Aus dem Institut für Phytopathologie
der Christian-Albrechts-Universität zu Kiel

Evaluation of Integrated Pest Management Systems for the Control of Fungal Diseases Under Consideration of Sustainable Wheat Production and Climate Change in a Long-Term Survey of 26 Years

Dissertation

zur Erlangung des Doktorgrades
der Agrar- und Ernährungswissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von

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Kiel, 2023

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Tag der mündlichen Prüfung: 28.06.2023

Gedruckt mit der Genehmigung der Agrar- und
Ernährungswissenschaftlichen Fakultät der Christian-Albrechts-Universität
zu Kiel

„Der Schlüssel zur Lösung gezielter, integrierter Pflanzenschutzmaßnahmen ist ausschließlich im Feld, unter den Bedingungen der Kulturführung und Umwelt, zu suchen und zu finden"

- Prof. Dr. Dr. H.C. Günter-Martin Hoffmann -
(TU München – Weihenstephan)

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE INDEX

FIGURE INDEX

ABBREVIATION INDEX

a.i.	Active ingredient
A_{F-x}	AUDPC of leaf layer F - x
ANOVA	Analysis of variance
AUDPC	Area under disease
cm	Centimetre
°C	Degree celsius
df	Degrees of freedom
DI	Disease incidence
DS	Disease severities
dt	Deci tons
EC	European Commission
e.g.	Example given
EPPO	European and Mediterranean Plant Protection Organization
EU	European Union
F	F-value
F	Flagleaf
Fin.	Final
GB	Glume blotch
GLA	Green leaf area
GS	Growth stage
h	Hours
ha	Hectare
HS	Healthy standard-treatment
Ini.	Initial
IPCC	International Panel of Climate Change
IPCC SR	IPCC Special Report
IPM	Integrated Pest Management
K	Kelvin
L	Litre
L/m²	Litre per square
LR	Leaf rust
LW	Leaf wetness
m	Meter
max.	Maximum
min.	Minimum
NEC	Necrotization
n-pycnidia	Number of pycnidia
OP	Observation period
OR	Oilseed rape
p	Significance Threshold
PF	Fungicide costs
PM	Powdery mildew
PP	Precipitation
PW	Wheat price
R^2	Coefficient of
RPC	Representative pathway concentrations
RWAUDPC	Relative WAUDPC
s	Seconds
SNK	Sönke-Nissen-Koog
SQL	Structured query language
STB	Septoria tritici blotch
t	Tons
T	Temperature
TFI	Treatment frequency index
TS	Tan spot
UC	Untreated control
SRES	Special Report on Emissions Scenarios
SR	Stripe rust
SUR	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
WAUDPC	Weighted AUDPC
WB	Winter barley
WW	Winter wheat
YLC	Year-Location-Cultivar
Z. tritici	*Zymoseptoria tritici*

Chapter I

General Introduction and Outline of the Thesis

Chapter I GENERAL INTRODUCTION AND OUTLINE OF THE THESIS

1.1 Plant Protection in Wheat Production

Cereals are the world's most important staple food, with wheat, rice, and maize accounting for 90% of world production. In the European Union, wheat is of major importance, as more than 50% of the food sold are wheat products. In terms of yield per hectare, Europe is above the world average. [1]. Northern Germany is one of the most productive wheat cultivation areas within the European Union due to fertile and clayey soils in a maritime climate with sufficient rainfall and moderate temperatures [2,3]. As the general conditions are extraordinary, agricultural practices have been optimised for wheat production and implemented in current agronomic practices on a supra-regional scale.

The combination of maritime climates [4,5] and fertile soils [6] provides excellent conditions for wheat cultivation. These conditions make northern Europe one of the most suitable and productive wheat growing areas in the world. However, these conditions are also conducive for the progression of fungal diseases, which are ubiquitous throughout the region [5]. Hence, losses of up to 50% of crop production can be attributed to yield-limiting foliar diseases [7–9]. In particular, 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*) are responsible for quantitative and qualitative losses. Of these diseases, Septoria tritici blotch is the most difficult to manage, because the point of infection is the only fungicide-sensitive stage in the cycle. However, as this infection point is not visible, the timing of applications is difficult to determine. Thus, the progression of fungal pathogens is largely determined by agronomic practices such as crop rotation, tillage systems or cultivar selection [10–12], and by prevailing weather conditions such as temperature or precipitation. Each pathogen has specific requirements in terms of agronomic factors and weather conditions [5,13–17]. These lead to year-to-year differences in the occurrence, course, and intensity of the epidemic.

As foliar diseases are highly influenced by weather conditions [18,19], climate change is expected to have an impact on disease development and severity.

According to the Intergovernmental Panel on Climate Change (IPCC), warmer and drier conditions during the main growing season can be expected due to climate change. Consequently, an influence on the productivity of wheat production in north-western Europe can also be expected [14,20]. Warmer temperature in combination with increased and more intensive rainfall events were simulated by the IPCC for the years up to 2030 [21]. As simulations were on a global scale, the impact of climate change can vary to a large extent on a regional scale. Hence, an increase in mean temperature of 0.4 to 0.5 °C and an increase in daily precipitation of 0.1 L/m² per decade can be expected in northern Germany [21,22]. Approaches in disease management must therefore be adapted to the varying environmental and bio-epidemiological conditions [23,24].

In disease management, adapting agronomic practices to manage prevailing fungal diseases is the basis of integrated pest management [11,25]. Thereby, the choice of cultivars, crop rotation, soil cultivation, sowing date, and the use of nitrogen fertilizers has an impact on disease progression [10,25–28]. Depending on the disease, modifications to agronomic practices can significantly reduce disease severity. However, adequate and integrated disease management through the production system is not always sufficient. As a result, despite advances in agronomic practices, epidemics of yield-limiting diseases can be expected, especially when conducive weather conditions occur. In this case, the use of fungicides is essential in order to provide adequate disease management. Historically, the superior performance of the European wheat production is largely based on pesticides [8,29]. During the growing season, fungicides primarily secure the yield potential at the respective location [7,30]. The utilization of fungicides for other potential side-effects other than pest control is not permitted in the EU [31,32]. The use of foliar fungicides is fundamental for the control of fungal diseases in wheat [11,13,33–35]. For typically agronomic practices, the use of fungicides is mostly carried out through routine applications based on plant growth stages. However, the use of pesticides is being critically discussed and there is a need to optimize the use of fungicides. According to Verreet et al. [36], a system based on biological-epidemiological thresholds can optimise the timing of applications, reduce number of pesticide applications as well as quantity, and maintain yield potential. In general, decision support systems (DSSs), which are based on biological-epidemiological thresholds, are available, but not holistically implemented into agronomic practices. The advantages of DSSs are enhanced, if implemented correctly and perform as promised, as prevailing diseases are controlled with reduced fungicide use.

The high potential in wheat production in northern Germany and the high impact of prevailing diseases on yield constitutes an increased pesticide use. Despite European Union's rather strict regulations on the authorisation and use of pesticides in a global comparison, pesticides remain a matter of controversy and public concern. Today, the use of pesticides is regulated by the Directive 2009/128/EC for sustainable use of pesticides [37]. Due to the increasing public pressure, the EU is currently repealing the Directive as a part of the "European Green Deal" and developing a new strategy for the sustainable use of pesticides. This "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", as part of the "Farm to Fork Strategy" under consideration claims to reduce the overall pesticide use as well as the use of environmentally hazardous pesticides by 50% in the EU by 2030 [38]. There are also plans to halve nutrient losses by reduced fertiliser use of at least 20%. Furthermore, 25% of farmland will be converted to organic production and at least 10% of farmland will be renaturalized. Consequently, the "Farm to Fork Strategy" can lead to a considerable drop in quality and quantity of yields, due to insufficient crop protection, lower yield potential, and reduction of arable land. By comparison, the current Directive 2009/128/EC for sustainable use of pesticides claims a reduction of risks caused by pesticides. However, the implementation of the Directives regulations into the EU member state legislation has been delayed and only a minor progress was observed since 2009 [39]. Considering the EU's demands on agricultural production to reduce the use of pesticides, a better approach would be to minimise unnecessary pesticide use. In general, 90% of the pesticides sold are classified as herbicides, fungicides, and insecticides [40]. Compared to herbicides, lower amounts of fungicides are used in total, and compared to insecticides, a smaller proportion of fungicides are used unnecessarily, but taking both factors into account, they have the highest potential to reduce total pesticide use, if efficacy increases [40–42].

1.2 Outline of the Thesis

As aforementioned, foliar diseases are a major threat to worldwide wheat production [5,7,8,29,35,43]. In the present dissertation, the threats by foliar diseases in wheat were determined. Furthermore, the effective use of fungicides was evaluated based on the data of a long-term survey from 1996 to 2021 in a highly productive wheat production area in northern Europe. The survey was conducted at eight trial locations evenly distributed across

Schleswig-Holstein, Germany's northernmost federal state, which is located between the Baltic Sea and the North Sea. The first objective was to investigate the impact of the six major foliar diseases Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust on wheat production. In addition, the potential of a biological-epidemiological fungal disease management system under maritime conditions was evaluated, in order to investigate the efficacy of the system in crop protection when used in agronomic practices. Therefore, epidemiological data from a 26-year long-term study with standardized conditions (same cultivar, same trial locations, same growing conditions) at eight locations in northern Germany was analysed **(Chapter II)**.

As Septoria tritici blotch is the most challenging disease to manage, the second objective was to investigate its disease progression in relation to the prevailing climate conditions. Therefore, the epidemiological behaviour and the agrometeorological conditions in dependence of growth stage and date were continuously assessed at a unique location in northern Europe without concomitant diseases during the survey period. As incidence, course, and severity of Septoria tritici blotch epidemics are primary determined by the prevalent weather conditions, an influence of climate change on the disease dynamics was additionally evaluated. In particular, possible effects for the agricultural production in northern Europe were analysed, and possible future risks caused by this major disease were discussed **(Chapter III)**.

Foliar diseases are primarily managed by applying fungicides at specified plant growth stages during the growing season. Thereby, Septoria tritici blotch is the most challenging disease in wheat, due to the prolonged latency period of the pathogen which renders applications by visual symptoms ineffective. This elucidates the importance of optimizing fungicide applications. Therefore, decision support systems of different origins, namely the IPM-Wheat Model Schleswig-Holstein (scientific), the ISIP system (federal government), and the xarvio© FIELD MANAGER (commercial), were evaluated under maritime climate conditions at three locations in a high-input area of wheat cultivation in northern Germany from 2019 to 2021, as a third objective. In addition, their function as possible tools for improving the sustainability of agriculture generally and whether the European Union's sustainability goals of a 50% reduction in pesticide use by 2030 can be achieved, have been examined **(Chapter IV).**

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CHAPTER II

EFFICIENCY AND EFFECTIVITY OF A BIOLOGICAL–EPIDEMIOLOGICAL FUNGAL DISEASE MANAGEMENT SYSTEM IN WHEAT —A STUDY OF 26 YEAR

The content of this chapter has already been peer reviewed and published in:
Klink, H. †; Prahl, K.C. †; Hasler, M; Verreet, J.-A.; and Birr, T.
Efficiency and Effectivity of a Biological–Epidemiological Fungal Disease Management System in Wheat—A Study of 26 Years. *Agriculture* **2022**, *11*, 1099.
doi: 10.3390/agriculture12081099

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Chapter II EFFICIENCY AND EFFECTIVITY OF A BIOLOGICAL–EPIDEMIOLOGICAL FUNGAL DISEASE MANAGEMENT SYSTEM IN WHEAT—A STUDY OF 26 YEARS

2.1 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, tan 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

2.2 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*) 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 [9,10,11], or by prevailing weather conditions such as temperature or moisture. Regarding the agronomic factors and weather conditions, each pathogen has specific environmental requirements [12,13,14,15,16,17]. 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.

2.3 Materials and Methods

2.3.1 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/m² [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 trial locations of the regional wheat disease monitoring in northern Germany from 1995 to 2021. WW = winter wheat, WB = winter barley, OR = oilseed rape. [1] Sönke-Nissen-Koog.

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

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).

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.

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.

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/m²; 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.

2.3.2 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.

2.3.3 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

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

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

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)).

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.

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

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:

$$TFI = \sum_i \frac{dose\ rate_i}{standard\ dose_i} \tag{3}$$

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:

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

where μ is the annual mean of all locations.

2.3.4 *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.

2.4 Results

2.4.1 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 S 1. 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.

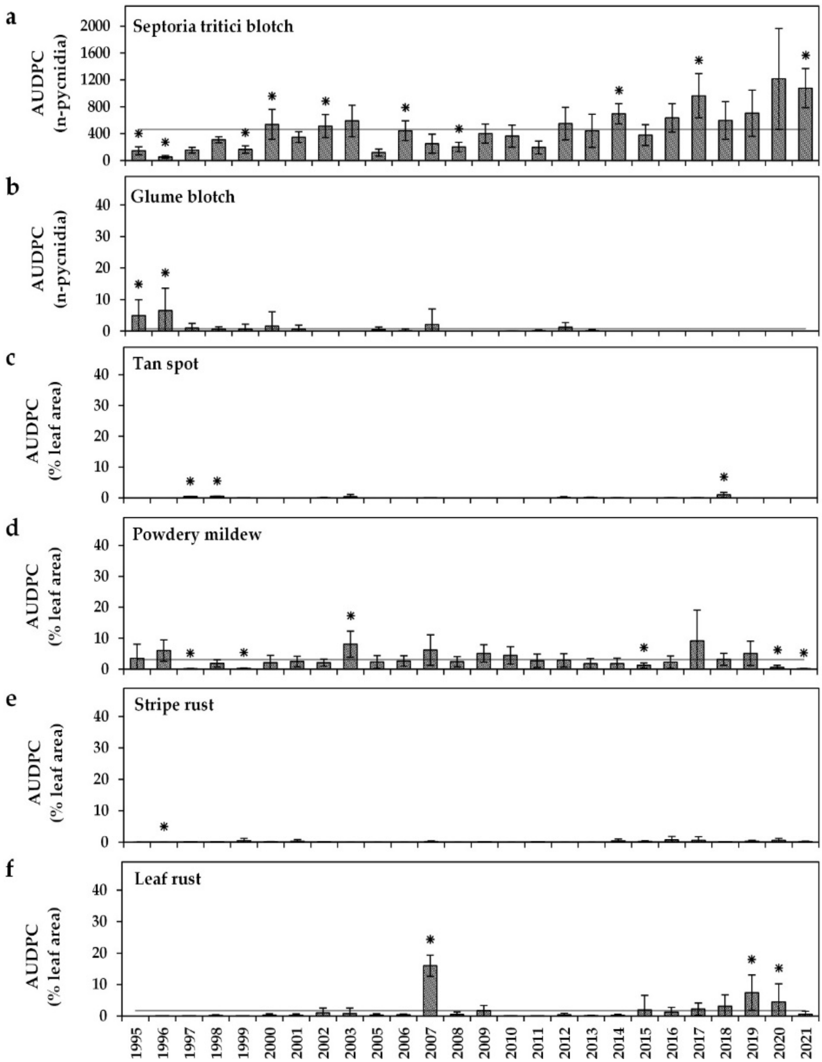

Figure 1. Average of disease severities from 1995 to 2021 (grey line) and annual disease severities (AUDPC; GS 30 to 77; bars) of (**a**) Septoria tritici blotch (number of pycnidia), (**b**) glume blotch (number of pycnidia), (**c**) tan spot (percentage of leaf area affected), (**d**) powdery mildew (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 *.

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 in 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.

2.4.2 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.

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$_{I}$). 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 2aII). 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.

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	25.736770	<0.0001
	Year (Y)	324	59.351940	<0.0001
	T x Y	324	23.681770	<0.0001
Glume blotch	Treatment (T)	324	9.288164	0.0009
	Year (Y)	324	11.220406	<0.0001
	T x Y	324	3.131020	0.2044
Tan spot	Treatment (T)	324	0.463364	0.4965
	Year (Y)	324	8.877909	<0.0001
	T x Y	324	0.441737	0.9917
Powdery mildew	Treatment (T)	324	2.567894	<0.0001
	Year (Y)	324	8.076783	<0.0001
	T x Y	324	1.810791	<0.0001
Stripe rust	Treatment (T)	324	18.671426	<0.0001
	Year (Y)	324	2.065552	0.0024
	T x Y	324	1.925722	0.0057
Leaf rust	Treatment (T)	324	18.671426	<0.0001
	Year (Y)	324	2.065552	0.0024
	T x Y	324	1.925722	0.0057

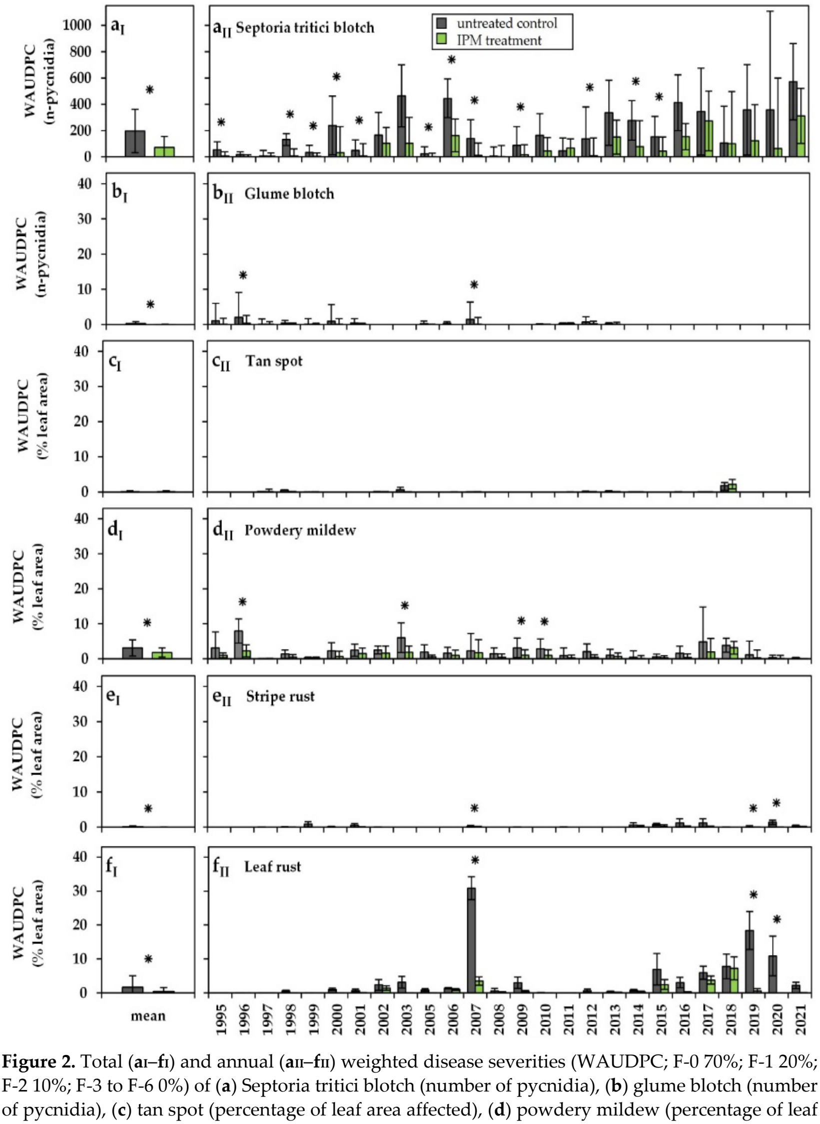

Figure 2. Total (**aI–fI**) and annual (**aII–fII**) weighted disease severities (WAUDPC; F-0 70%; F-1 20%; F-2 10%; F-3 to F-6 0%) of (**a**) Septoria tritici blotch (number of pycnidia), (**b**) glume blotch (number of pycnidia), (**c**) tan spot (percentage of leaf area affected), (**d**) powdery 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 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 2 d_{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.

2.4.3 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.

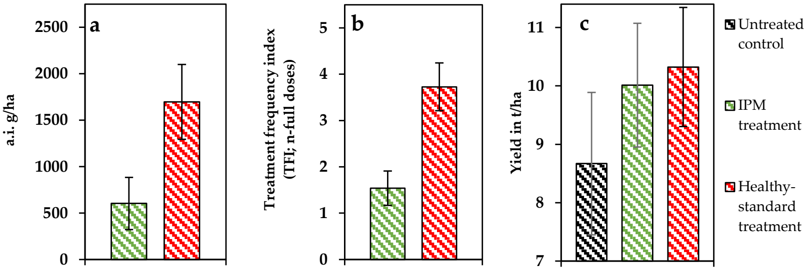

Figure 3. (**a**) Total use of fungicidal active ingredient (a.i.) in the healthy-standard treatment and the IPM treatment (average in g per litre), (**b**) total treatment frequency index of the healthy-standard treatment and IPM treatment and (**c**) total yield (t/ha) of the untreated control, IPM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

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.

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.

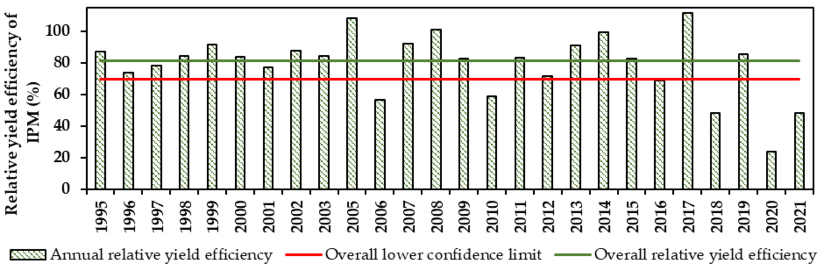

Figure 4. Overall relative yield efficiency (green line), overall lower confidence limit (red line; α = 0.05) and annual relative yield efficiency of the IPM treatment (green bars) in relation to the healthy-standard treatment adjusted by the untreated control from 1995 to 2021.

2.4.4 *Economic Analysis*

For further evaluation, the IPM efficiency was considered economically. According to the trial 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).

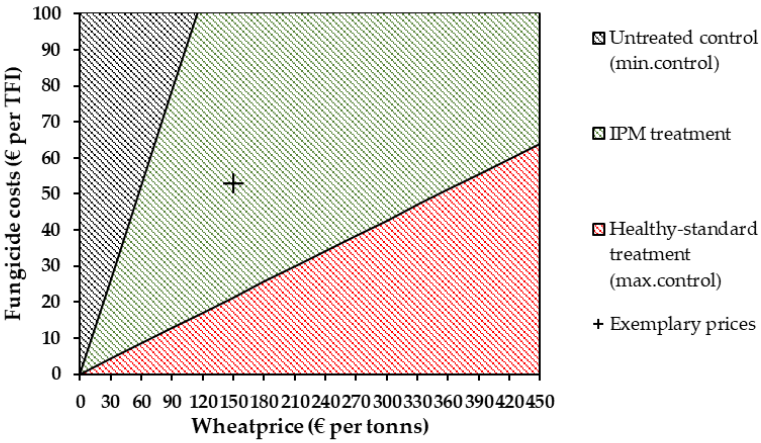

Figure 5 Equal Profit margin of untreated control versus IPM treatment and IPM treatment versus healthy-standard treatment from 1995 to 2021 as a function of wheat price (€/t) and fungicide costs (€/TFI). Exemplary wheat prices and fungicide costs of the survey area and period are shown as black cross.

2.5 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 [11,27,48,49,50,51]. Furthermore, crop rotation and soil cultivation can influence the infestation of foliar diseases, e.g., tan spot [10,47,52,53,54]. 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 [55,56,57,58]. 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% [59,60,61]. 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 *Zymoseptoria tritici* (*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 [18,66,67,68]. 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 *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 [70,71,72,73,74]. 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 [76,77,78,79]. 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) [61,82,83,84]. 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 favour 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 [85,86,87], 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 [88,89,90]. 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.

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Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

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2. This co-author declaration applies to the following article:
Efficiency an Effectivity of a Biological-Epidemiological Fungal Disease Management System in Wheat-A Study of 26 Years

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CHAPTER III

DISEASE DYNAMICS OF SEPTORIA TRITICI BLOTCH IN A LONG TERM SURVEY OF 25 JEARS

The content of this chapter has already been peer-reviewed and published in:
Prahl, K. C.; Klink, H.; Hasler, M.; Verreet, J.-A.; and Birr, T.
Will Climate Change Affect the Disease Progression of Septoria Tritici Blotch in Northern Europe?
Agronomy **2023**, 13(4), 1005. doi.org/10.3390/agronomy13041005

Chapter III WILL CLIMATE CHANGE AFFECT THE DISEASE DYNAMICS OF SEPTORIA TRITICI BLOTCH IN NORTHERN EUROPE?

3.1 Abstract

Septoria tritici blotch (STB) caused by the fungus *Zymoseptoria tritici* Desm. is the most important disease of wheat in Northern Europe. There is strong correlation between STB and weather variables, therefore research on climate change and epidemiology is essential. In a long-term survey of 25 years, we evaluated the epidemiological development of STB at a representative location under maritime climatic conditions. Surveys conducted between 1996 to 2021 showed an increase in disease severity of STB with respect to time. At the survey location, plants were also evaluated for other diseases, but other foliar diseases were observed only with negligible severities. A continuous increase in the severity of STB was observed throughout the survey. During the survey period, there was not a significant relationship between disease severity and single weather parameters (e.g., temperature and precipitation). However, seasonal change in the progress of conducive STB conditions within the season were observed during the survey. Thereby, STB infections occurred at increased temperatures due to later infections during the growth season. In general, the distribution of conducive weather conditions, which supports an infection, determine the epidemiological behaviour of STB during the growing season. By enhanced STB epidemics a decline in wheat production has been observed, especially in agronomic practices of maritime climates. This is particularly the case if temperature and precipitation during the growing season are affected by climate change.

Keywords: STB, *Zymoseptoria tritici*, climate change, AUDPC, sustainable wheat production, global warming, *Triticum aestivum* L., disease severity, foliar disease, long-term survey

3.2 Introduction

Septoria tritici blotch (STB), caused by *Zymoseptoria tritici* Desm., is one of the most serious and yield-limiting foliar diseases in global wheat production. In Europe, STB is responsible for annual yield losses of 5 - 10% under current agricultural practices, representing an annual economic loss of approximately €1500 million in Germany alone [1]. STB is particularly prevalent in regions with temperate humid climates, such as the EPPO "maritime zone" [2], which includes northern Europe. As described by Klink et al [3], in addition to agronomic practices (e.g., crop rotation, cultivar selection, or tillage systems), the conducive weather conditions, such as continuous precipitation, moderate temperatures, and high humidity, determine the incidence, course, and severity of STB's epidemics. In particular, sufficient precipitation with prolonged leaf wetness is essential for a successful infection. Thereby, the precipitation transports the inoculum on higher leaf layers and the leaf wetness periods ensure the infection of the pathogen [4,5].

According to Miedaner and Juroszek [6], climate change, as described in the International Council of Climate Change (IPCC) Special Report (SR) [7] is threatening the wheat productivity in north-western Europe by warmer and drier conditions during the main growing season. The recently published Sixth Assessment Report (AR6) of the IPCC [8] shows that exceeding 1.5 °C global warming is possible by 2030. As a result, an increased and more intense rainfall events are expected by the IPCC. In general, the development of the global climate is a dynamic process with large regional variations [9]. According to the IPCC [9] the effects of climate change are an increase in mean temperature of 0.4 to 0.5 °C and an increase in daily precipitation of 0.1 L/m^2 per decade in northern Europe, which includes Northern Germany.

Since STB is highly influenced by weather conditions [10,11], climate change is expected to have an impact on disease development and severity. Analyses of epidemics of a specific pathogen are usually carried out in greenhouses under artificial conditions with controlled abiotic and biotic factors. Since, it is usually not possible to quantify the influence of biotic factors, especially associated pathogens, on the disease progression of pathogens on plants [12]. In this study, unique circumstances were observed. For instance, the only disease observed was STB at the surveyed period. This allowed us to analyse the disease progression of STB in the field, without the biotic influences of the usually associated diseases glume blotch (caused by *Parastagonospora nodorum* Berk.), tan-spot (caused by *Pyrenophora tritici-repentis* Died.), powdery mildew (caused by *Blumeria graminis* f. sp. *tritici*), stripe rust (caused by *Puccinia* *striiformis* f. sp. *tritici*), or leaf rust (caused by *Puccinia triticina*) as described by Verreet et al. [4].

The present study investigated (i) the development of STB in wheat at a representative location from 1996 to 2021, and (ii) the possible influence of climate change on the disease progression of STB in northern Germany. Over this period of 25 years, the progression of STB was continuously evaluated using samples from an identical reference location and a uniform cultivar. Due to the influence of the weather variables to STB, the parameters temperature, precipitation, and leaf wetness were assessed directly from the reference location and associated with the climate change.

3.3 Materials and Methods

3.3.1 Area Surveyed and Survey Strategy

Since 1996, evaluations of major foliar diseases were conducted in Germany's northernmost federal state, Schleswig-Holstein (54°38′01′′N; 08°52′08′′E), proximal to the northern sea. The location is characterized by very fertile clay soils, high prevalence of wheat in crop rotations and is therefore one of the main producing areas in northern Germany [13]. Due to the proximity to the northern sea, maritime weather conditions with an average temperature of 9.2 °C, an annual precipitation of 846 L/m² and average humidity of 81% are prevailing at the trial location [14]. As described by Klink et al. [3] the foliar diseases powdery mildew, stripe rust, leaf rust, and STB are the prevalent foliar diseases in the surrounding region of the trial location. As a result of the continuous western winds, the disease powdery mildew was not observed at the trial location [15]. Additionally, Rust diseases were recorded sporadically the trial location and the only disease that was frequently recorded at the trial location was STB [3]. As a result of the climate conditions at trial site, disease pressure can be expected and is suitable for the evaluation of STB and weather variables in the field. Within the survey period, either winter wheat or oilseed rape preceded the evaluated winter wheat. According to the preceding crop the soil cultivation was reduced tillage when oilseed rape preceded or ploughing when wheat preceded. Throughout the survey period from 1996 to 2021, the cultivar "Ritmo" was analysed for foliar diseases in weekly intervals from growth stage (GS) 30 (begin of stem elongation) to 77 (late milk). The susceptibility of wheat cultivars to the major foliar wheat diseases is listed in the descriptive cultivar list by the Bundessortenamt, an independent senior federal authority under the supervision of the Federal Ministry of Food and Agriculture. The used cultivar "Ritmo" is classified as moderately to highly susceptible against STB. Additionally, it is classified as moderately susceptible against stripe rust, powdery mildew, tan spot, and glume blotch, and highly to very highly susceptible against leaf rust [16]. Klink et al. [3] described that glume blotch and tan spot do not occur under good agronomic practices. Accordingly, only STB occurred at the used location cultivar combination. In consequence, this combination is representative for the evaluation of STB's disease progression. In order to evaluate the development of STB at the location, four fungicide untreated plots were established every year. In the absence of fungicides, the untreated plots show the epidemiological disease behaviour. Every year plots were planted at 10 m² (2x5 m) and integrated in a farmer's field. Whereby, crop management as well as the application of herbicides, insecticides, and growth regulators was based on common agricultural practices, and was carried out comprehensively in cooperation with the Chamber of Agriculture of Schleswig-Holstein. To determine the weather conditions at the trial site, meteorological stations (Thies Clima, Göttingen, Germany) were installed at every trial location to measure precipitation (L/m²; measuring accuracy ± 3%), air temperature at 30 cm height (°C; measuring accuracy ± 0.1 K), and leaf wetness (%, measuring accuracy ± 3%) [5]. The assessed data was recorded in 15 second intervals and was given automatically as hourly values.

3.3.2 Sampling and Disease Assessment

Disease analyses was conducted from GS 30 to GS77 in weekly intervals. The samples contained at least ten main tillers and were taken arbitrarily from three separate plots. To assess disease incidence (DI) and disease severity (DS) the analyses followed an exact sequence corresponding to Verreet et al. [4]. Primarily the growth stage according to Zadoks et al. [17] was determined and simultaneously every leaf was rated at the main stem for disease incidence and percentage of necrotic leaf area and affected leaf area from the biotrophic foliar diseases. For the preceding steps, the leaves were then soaked in water to simulate leaf wetness, which leads to expanded pycnidia and ensures highest quality in rating. To assess the quantitative parameter for the disease severity, the pycnidia of STB were counted between eightfold to fiftyfold magnification for every single leaf. The result of the assessment is a DI and a DS from three plots with ten replicates per plot, resulting in an accurate DI and DS for each individual leaf layer. Additionally, notes such as rating date, and plot number were also recorded. The assessed epidemiological data was averaged for the leaf layers F-0 to F-6 separately after every weekly rating for each plot and stored in a SQL database.

3.3.3 Data Analyses

For data analyses and annual comparison of the disease severity, the area under disease progress curve (AF-x) of each leaf layer in every year was considered. This was calculated from the parameters necrotization and disease severity of STB from GS 30 to 77. For the estimation of the AF-x according to Madden et al. 2007 [18] the trapezoidal method has been used by discretizing the time variable and determining the average disease intensity between two neighbouring time points (Formula 1).

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

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 also a yield-directed comparison was performed, adjusting the AF-x to the weighted AUDPC (WAUDPC) by weighting disease severities separately for each leaf layer with the factors x_{F-0}, x_{F-1}, x_{F-2}, x_{F-3}, x_{F-4}, x_{F-5}, and x_{F-6}, (e.g. x_{F-0} = 70% for F-0, x_{F-0} = 20% for the F-1 and x_{F-0} = 10% for the F-2 and x_{F-3} to x_{F-6} = 0%) (nominator Formula 2) [19,20]). The result of the WAUDPC calculation was challenging 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.

$$\text{RWAUDPC} = \frac{x_{F-0}\, A_{F-0} + \ \dots + x_{F-6}\, A_{F-6}}{k+1} \qquad (2)$$

A_{F-x} = AUDPC of leaf layer F minus x, t = rating date; k = number of

neighbouring time intervals;

X = percentage of considered leaf layer

3.3.4 *Statistical analyses*

The statistical software R, Version 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria; 2022) [21] was used to evaluate the data. The data evaluation was based on linear regression models and corresponding analyses. The residuals of the models were all assumed to be normally distributed and to be homoscedastic. These assumptions are based on a graphical residual analysis.

3.4 Results

3.4.1 Occurrence of Foliar Diseases from 1996 to 2021

Disease severities were assessed for the major foliar diseases, namely Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust, from 1996 to 2021. As shown in Figure 6, except for STB, the severities of the foliar diseases averaged over every leaf layer remained on a minor level (RWAUDPC < 1). Only STB was rated with significant RWAUDPC's $_{(xF\text{-}0 - x\text{-}6 = 14\%)}$ with a total average of 55 pycnidia. In 1996, the lowest disease severities recorded had 8 pycnidia and in 2019 the highest disease severities were rated with 134 pycnidia. It is noticeable that in the first decade of the survey the disease severities of STB were above the total average in only two years. In contrast, in the last decade of the survey the disease severities were only two years below the total average (Table S 2).

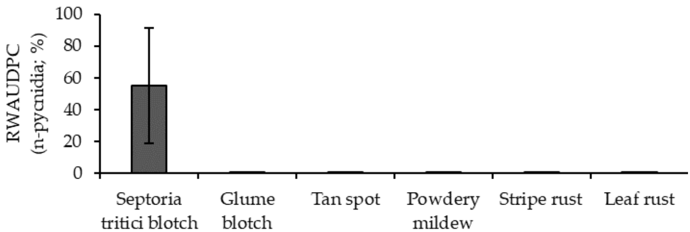

Figure 6. Occurrence of the major foliar diseases averaged from 1996 to 2021 at the trial location. RWAUDPC $_{(xF\text{-}0 - x\text{-}6 = 14\%)}$ of Septoria tritici blotch and glume blotch as n-pycnidia. RWAUDPC $_{(xF\text{-}0 - x\text{-}6 = 14\%)}$ of tan spot, powdery mildew, stripe rust, and leaf rust as % affected leaf area from GS 30 to GS 77.

3.4.2 Prevailing Weather Conditions and Occurrence of Septoria tritici blotch

In Figure 7, the disease severity of STB is shown as RWAUDPC$_{(xF\text{-}0 - x\text{-}F\text{-}2 = 33\%;\ xF\text{-}3 - x\text{-}F\text{-}6 = 0\%)}$ of the three uppermost leaf layers, thereby, the disease severity varied around an average of 54 pycnidia from 1 pycnidia in 1999 and 2008 to 162 pycnidia in 2013. Noticeably was that the disease severity was consistently underneath the total average in the first half of the survey and over above the average in the second half of the survey period. Thus, a significant ($p = 0.005$) annual increase of 3.5 pycnidia from 1996 to 2021 with a R^2 of 0.30 was observed. Concomitant to the disease severity of STB, the RWAUDPC from the necrotized leaf area increased significantly ($p \leq 0.05$) by 0.28% per year within the survey period from 1996 to 2021.

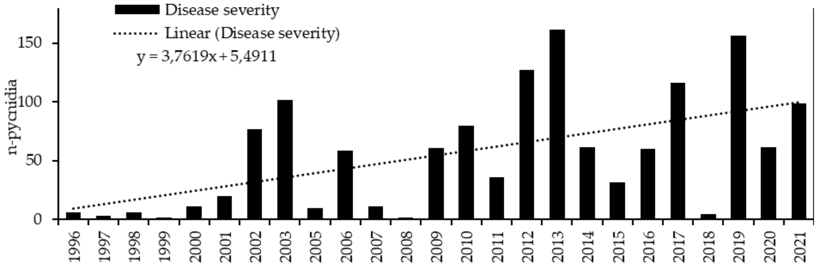

Figure 7. RWAUDPC (xF-0 – x-F-2 = 33%; xF-3 – x-F-6 = 0%) of STB (n-pycnidia) of the observation period (GS 30 to GS 77) from the survey period at the trial location. Dotted lines describe the linear regression of disease severity.

Considering the uniformity of agronomic practices during the survey period, a superordinate factor must determine the disease severities of STB in the field. Due to the superior dependency of STB to prevailing weather conditions in a first step, the development of temperature and precipitation during the growth season (GS 30 to 77) were analysed for every year in the survey. Additionally, monocausal influences of temperature and precipitation on the disease severity were evaluated.

Figure 8 shows the prevailing weather conditions during the growth season from 1995 to 2021 in combination with the disease severities of STB. The mean annual temperature varied from 9.3 °C in 2015 to 13.8 in 2018 and an averaged 11.0 °C with a standard deviation of 0.9 °C. Furthermore, regression analyses of the temperature development did not show a linear trend. Nevertheless, an increase in variation of the annual temperature in the growth season from the linear trend was observed in the last decade of the survey. The evaluation of the relationship between the severity of STB and temperature showed with an R^2 of 0.04 a minor correlation. The annual precipitation varied from 93 L/m² in 2000 to 302 L/m² with a standard deviation of 80 L/m² around a total average of 159 L/m² during the observation period (GS 32 to 77). In contrast to temperature, a slight non-significant (p = 0.47) linear trend of an annual increase of 1 L/m² was observed at the trial site. However, the linear regressions of precipitation and disease severity of STB showed an increase over the survey period, but the monocausal relationship between these two factors remained at a minor level ($R^2 = 0.10$).

Hence, the increase in the disease severities cannot be adequately explained monocausal by either precipitation or temperature. According to Verreet et al [4] the leaf wetness by Weihofen, as a combination of several weather factors, is a major factor on the disease severity of STB. The correlation between total hours of leaf wetness during the growth season and the disease severity of STB was also on a minor level ($R^2 = 0.08$). As STB disease progression correlate with the single factor's temperature, precipitation, and total hours of leaf wetness only on a minor level, the detailed epidemiological development on every single leaf layer of STB within a growth season was evaluated.

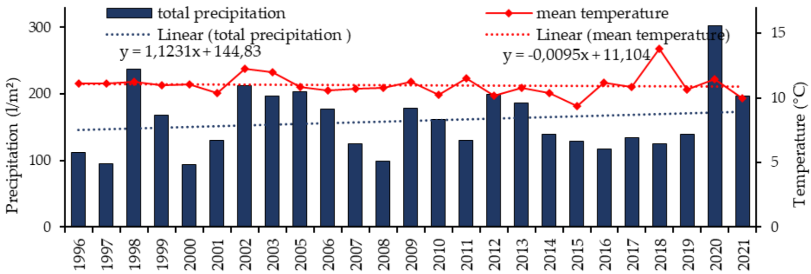

Figure 8. Averaged temperature (°C; red line), total precipitation (L/m²; blue bars) of the observation period (GS 30 to GS 77) from the survey period at the trial location. Dotted lines describe the linear regression of temperature, and precipitation.

3.4.3 Case Study of Septoria Tritici Blotch

Since STB disease progression correlated with the single factors' temperature, precipitation, and total hours of leaf wetness only on a minor level, the detailed epidemiological development on every single leaf layer of STB within a growth season was evaluated. In Figure 9, the disease severity of STB is shown for two representative years of the survey, together with the individual STB disease severity for each leaf layer in combination with the necrotization of 2018 and 2019. As no other diseases were observed at the site in the years shown, the necrotization can be considered as directly dependent of STB infections and abiotic factors.

In general, the average temperature in 2018 was increased during the growing season compared to 2019 by 3.0 °C, with 16.2 °C and 13.2 °C, respectively. In contrast, the total precipitation increased by 82 L/m² in 2019 as compared to 2018 during the growing season, with 62 L/m², and 144 L/m², respectively. Furthermore, similar initial infestations were observed on the lower leaf layers (F-4 to F-6) in both years.

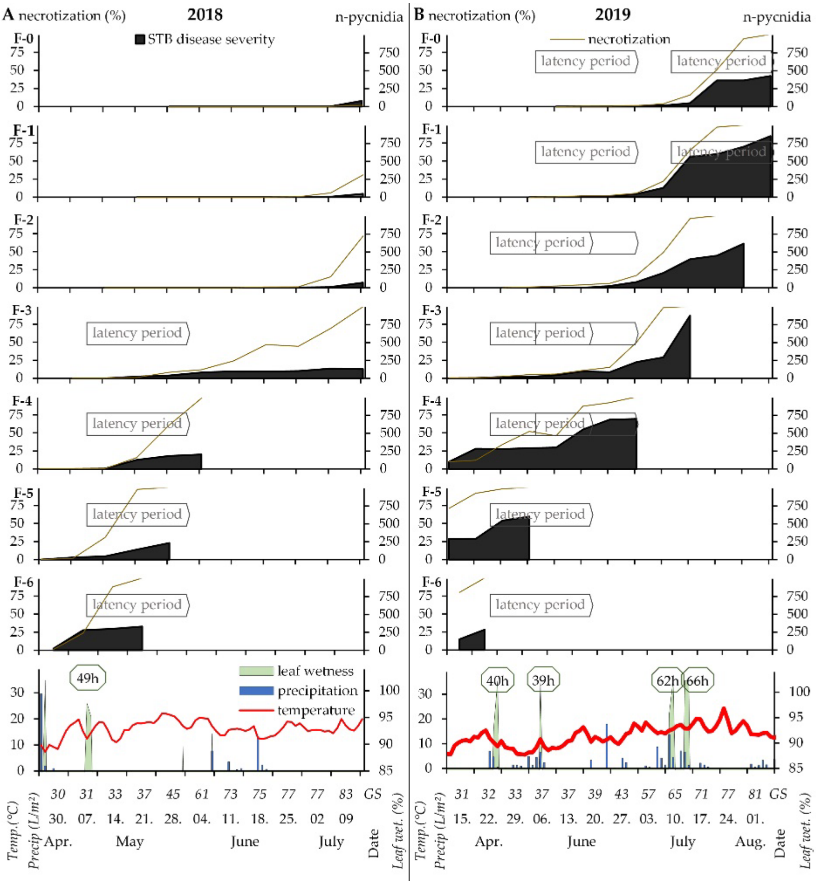

Figure 9. Epidemiological development of STB (n-pycnidia; black area) on the seven uppermost leaf layers in combination with the necrotized leaf area (%; gold line) and prevailing weather conditions (temperature as red line; precipitation as blue bars; leaf wetness (%) as green area (duration of leaf wetness ≥ 98% are given in hours) as a function of the date and growth stage of the survey years (A) 2018 and (B) 2019.

As shown in Figure 9, STB epidemics have their origin on the lower leaf layers and infest higher leaf layers when conducive weather conditions occur. Thereby, conducive conditions are present, if a rainfall event of at least 3 L/m² transports the spores of STB on higher leaf layers. On higher leaf layers, spores will need leaf wetness of at least 98% for 36 hours for the infection process including germination, growth of infection hyphen with appressorium development, and stomatal leaf penetration) [4,5,22]. Generally, an initial infestation of STB needs to be present at the location, and only visible leaf layers can be infected, if conducive conditions occur. In 2018, the 12th of May was the only day that conducive weather conditions for STB occurred at the trial site. Thereby, a plant GS of 31 was observed, thus the upper leaf layers (F-0 to F-2) were not completely developed and therefore not affected by STB after the latency period of approximately 28 days [4]. In particular, leaf layer F-3 was affected by this infection, as an increase in disease severity was observed 4 weeks after infection. In the absence of conducive conditions during the 2018 growing period, STB was not able to spread to the upper and yield relevant leaf layers. However, in 2019 colder and wetter weather persisted (Figure 9 B), four infection periods were observed, namely 29th of April (GS 32), 5th of May (GS 37), 10th of June (GS 65), and 19th of June (GS 71). Compared to 2018, plant development was advanced in 2019, therefore GS 32 was observed during the infectious conditions on the 29th of April. This resulted in an increase in disease severity after the latency period on leaf layers F-2 and a primary increase on F-1. The primary increase on leaf layer F-0 and the secondary increase on the leaf layer F- 1 is a result of conducive conditions during the infection period at the 5th of May at a plant GS of 37. Consequently, the epidemiological development of STB within the growing season depends on the distribution of conducive conditions on the one hand, and plant growth stage (leaves of interest need to be appeared) on the other hand.

3.4.4 Conducive Conditions of Septoria Tritici Blotch During the Survery Period

Epidemics of STB depend on the occurrence of initial infestation at a location and the interaction of visible leaf layers and distribution of conducive conditions during the growing season. In Figure 10, the initial and final infestation are shown relative to the highest observed initial and final infestation of STB, together with conducive conditions for STB including a classified temperature and precipitation during the corresponding leaf wetness period. Additionally, relevant growth stage periods are shown for every year of the survey to classify the visible leaves. To assess the epidemiological behaviour of STB the absolute RWAUDPC $_{(xF\text{-}0 - x\text{-}F\text{-}2 = 33\%;\ xF\text{-}3 - x\text{-}F\text{-}6 = 0\%)}$ is shown for every day in the growing season. The initial infestations varied from 2.81 pycnidia in 1996, 151 pycnidia in 2020 and averaged 50 pycnidia. The final infestations varied from 27.8 pycnidia in 1996 to 552 pycnidia in 2019 and averaged 261 pycnidia. The increase in pycnidia during the growing season from GS 32 to 77 differed with an average of 211 pycnidia. Thereby, the lowest increase was observed in 2008 (12.3 pycnidia) and the highest increase in 2012 (507 pycnidia). Even if a significant ($p < 0.05$) correlation between initial and final infestation was observed, over 60% of the final infestation could not be explained by the initial infestation ($R^2 = 0.36$; Figure 10 A). Considering the distribution of STB conducive conditions during the growing period the years 2008 and 2018 showed no infections between the GS 32 and GS 77. Thus, no significant increase in disease severities was observed during the growing season, even though the initial infestations were moderate with 32.5 in 2008 and 48.2 in 2018. In contrast, the years 2003 and 2013 also showed a low to moderate initial infestation with 7.86 and 62 pycnidia, respectively, but a major increase in disease severity of 330 in 2003 and 467 pycnidia in 2013.

Figure 10 B shows temperature and precipitation within 24 - 35, 36 - 47, and ≥ 48-hour periods of leaf wetness ≥ 98%. Over the 25 years survey, 94 STB infection periods were observed in the month of May, June, and July, which corresponds to an average of 3.76 infection conditions per year. Only in 1996 was a period of more than 24 hours and less than 36 hours observed in the three-month shown. In contrast, periods with 36 hours of leaf wetness ≥ 98% were observed 25 times (1.48 periods per year) and periods with more than 48 hours of leaf wetness ≥ 98% occurred 56 times (2.24 periods per year). In May 52 periods were observed, 36 periods in June, and 3 periods in July. Over the years, the number of infectious periods in May were consistent, whereas the number of infectious periods of STB in June increased from 1996 to 2021. The regression analysis showed a non-significant ($p = 0.65$) annual increase of 0.03 infections ($y = 0.031x + 3.24$). This was primary based on the non-significant ($p = 0.15$) increase of infections in June ($y = 0.044x + 0.86$), whereby the infections in May remained on a constant level ($y = 0.009x + 1.96$). Furthermore, in 1998, 2008, and 2018, no periods with leaf wetness ≥ 98% of more than 24, 36, and 48 hours were observed within growth stages 32 and 77, and apparently STB did not occur on the three uppermost leaf layers. The relationship between the severity of STB on the three uppermost leaf layers and the number of infection periods is at a minor level with an R^2 of 0.18.

In Figure 10 C the course of the total disease severity during the annual growing seasons of the three uppermost leaf layers is shown in n-pycnidia. Thereby, the STB disease severities increased after conducive conditions, if the observed leaf layers were visible (GS > 32). From 1996 to 2021, the required duration of leaf wetness for a successful infection with a concomitant increase in disease severity following decreased from 48 hours to 36 hours.

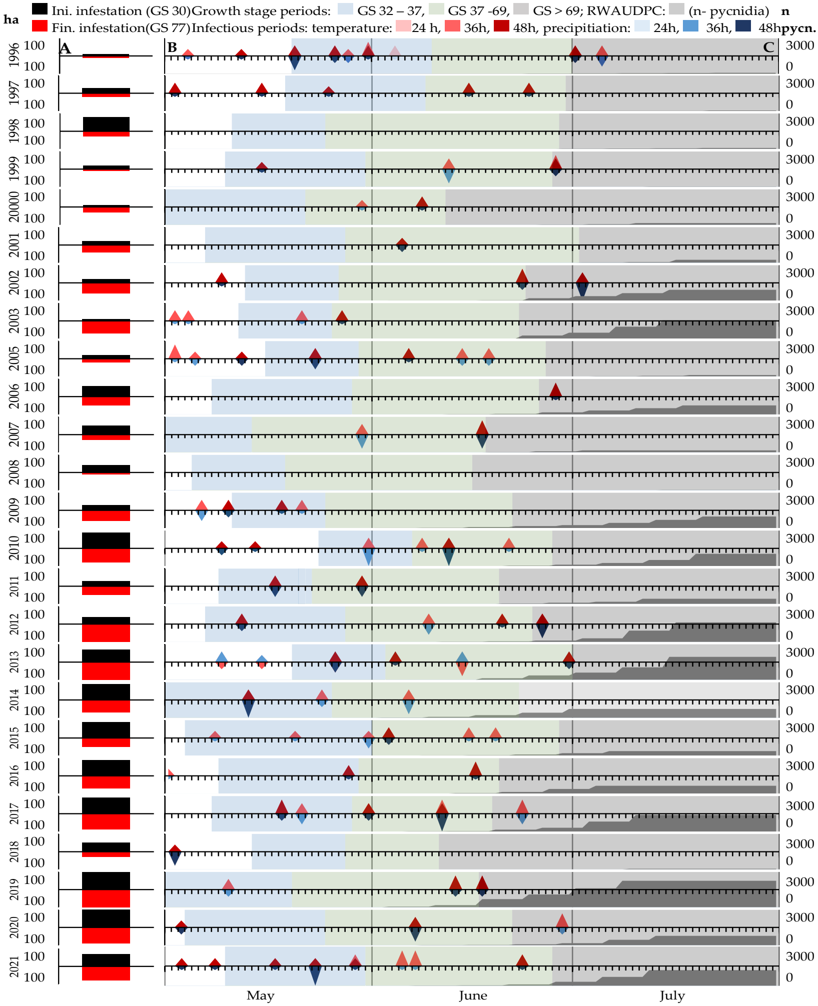

Figure 10. (**A**) Initial (Ini.) infestation and final (Fin.) infestation of STB at the trial location of every year of the survey. (**B**) Temperature (red) and precipitation (blue) during leaf wetness periods over 24 hours (light), 36 hours (medium), and 48 hours (solid) in four categories (Temperature <5 °C, 5-10 °C, 10-15 °C, 15-20 °C; precipitation <4 L/m²; 4-8 L/m²; 8-12 L/m²; 12-16 L/m²; 16-20 L/m²), and (**C**)disease severities of STB (grey area) in combination with plant growth stages from the month May, June, and July.

In particular, two infections occurred in 2000, the first at the 28th of May with a leaf wetness duration of more than 36 and less than 48 hours and one at the 8th of June with a duration of more than 48 hours, but an increase in disease severity was only observed after the second (longer) infection. In 2020, two infections also occurred at the location. The first was on the 7th of June with a leaf wetness duration of more than 48 hours and the second was on the 26th of June with a duration of more than 36 hours. In contrast to 2000, both infections showed an increase in disease severity.

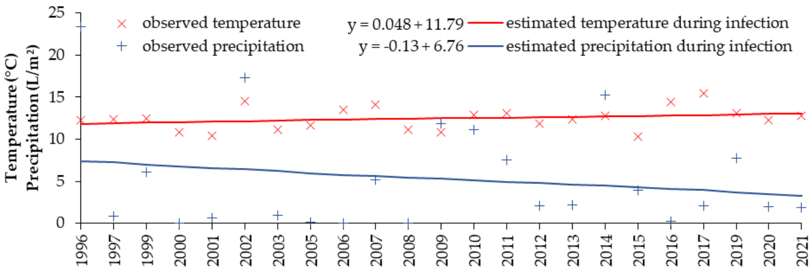

Figure 11. Averaged temperature (°C; red dots) and total precipitation (L/m²; blue dots) during the annual infection periods and estimated temperature (red line) and precipitation (blue line) of the regression analysis.

As conducive conditions shifted to later seasonal dates, it can be assumed that the corresponding temperature during the infection period increases by the seasonal change. At the observed location the multiannual temperature average from 1991 to 2020 was 3.1 °C higher in June (15.3 °C) as in May (12.1 °C). Considering the weather conditions during the infection, as shown in Figure 10 B, an increase in temperature was observed during the survey period. Regression analyses showed an estimated total increase during infection period of 1.2 °C from 1996 to 2021 (Figure 11). This equates to an annual temperature increase over the survey period of 0.1 °C. In contrast to temperature, the regression analysis showed an estimated seasonal decrease in precipitation during the infection periods of 3 L/m², which equates to an annual decrease of 0.1 L/m² from 1996 to 2021. Compared to the temperature, a significant increase in variation of the precipitation during the infection periods was observed during the survey.

3.5 Discussion

Septoria tritici blotch (STB) is one of the most important foliar diseases in global wheat production and is responsible for yield losses in all growing areas, particularly in maritime climates [1,3,10,23]. The occurrence of associated foliar diseases complicates the assessment of the progression of a single disease in the field [12,24,25]. In our field study, STB was the only disease observed at the trials site. Based on epidemiological data, the trial location was well suited to assess the influence of climate change on the disease progression of STB. This was particularly due to the consistent epidemics of STB at the trial location and the absence of other foliar diseases. In our study, there was a significant increase in the severity of STB during the survey period at the representative trial location.

A possible explanation for the increased disease pressure of STB is that the pathogen has potentially adapted to the cultivar selected, as described by McDonald and Mundt [26]. In contrast, Prahl et al. [27] showed in a comparable study with two different susceptible cultivars, "Ritmo" (moderate to highly susceptible) and "RGT Reform" (moderately susceptible), that high disease severities were also observed in the less susceptible cultivar "RGT Reform". In addition, the used cultivar "Ritmo" has become less important in the agronomic practices of the trial area during the long-term survey, so that "Ritmo" was barely grown in the region during the last decade of the survey. An adaptation of the pathogen to the cultivar used is therefore rather improbable. However, the consistent use of the cultivar "Ritmo" is a possible explanation for the increased disease severity during the survey period but does not explain the intensity of the STB progression during the survey.

A similar study using epidemiological data conducted by Volk et al. [28], predicts an increase in disease severity of STB in Western Germany by 2050, by using the empiric-statistical method "WettReg" (based on SRES-Scenario A1B). In contrast, a study by Goucahe et al [29] predicts a decrease in the disease severity of STB by 2-6% in France. A significant uncertainty in the predicted development was mentioned, in particular the probability of STB disease severity increasing rather than decreasing was 45% for the coastal location of the study.

Although the correlation between the disease severity and the weather parameters temperature, precipitation, and leaf wetness (R^2 = 0.19, R^2 = 0.31, R^2 = 0.28, respectively) was on a minor level, an influence of the prevailing weather condition was observed. As shown in the case study, precipitation with prolonged leaf wetness is essential for a successful infection (germination, growth of infection hyphae with appressorium development, stomatal leaf penetration). Thereby 3 L/m² of precipitation are sufficient to transport the inoculum and a 36-hour period of leaf wetness are sufficient to complete the infection. An increase in precipitation above 3 L/m², or an extension of the leaf wetness period, is not determining the expression of the corresponding infection [22]. The prevailing temperature, as it is not under 6.0 °C, is not involved in the success of the infection, but determines the expression of the respective infection [11,30,31]. As shown by Henze et al. [5], a direct influence of temperature, precipitation, and leaf wetness on the disease development was confirmed in northern Germany. Chungu et al [11] also showed a direct influence of the prevailing temperature on the development of STB in Manitoba, Canada. The influence of the prevailing climatic conditions was also confirmed by the change in the requirement for successful infection. As it was shown, in the first half of the study a leaf wetness ≥ 98% with a duration of ≥48 h was necessary for a successful infection with a subsequent increase in disease severity [4,32]. Whereas, in the second half of the study a reduced period of leaf wetness ≥ 98% with a duration of 36 - 48 h was necessary for a successful infection [5]. However, a seasonal extension in conducive STB conditions from May to June was investigated at the trial site. Thereby, an increase in conducive conditions of STB was observed for the entire growing season and in particular for the month June. This seasonal extension explains the increase in infestation during the survey period, as the average temperature in June (15.3 °C) was 3.1 °C higher than in May (12.1 °C) [14]. Beyer et al. [33] showed that increasing temperatures shortened the latency period between infection and epidemic outbreak. Shorter latency periods ensure that new STB pycnidia develop more quickly. Under increased temperatures, a stronger and faster epidemiological disease dynamic of STB can be expected. Even though climate change has so far only had a marginal influence on the temperature in the growth period, the seasonal expansion (periods of high precipitation in later months) has led to an increased temperature at the time of infection. Consequently, later STB infections occurred under warmer conditions with an increased epidemiological potential [31,34,35].

According to the IPCC special report (SR) [7] the global temperature increases since 1881 has been about 1.0 °C, with regional temperature changes differing from the global average. In Germany, the increase has been about 1.5 °C [36], due to higher temperatures after the year 2000. Climate change simulations suggest that this trend will continue, even without the projected reductions in greenhouse gas emissions. Jacob et al. [37] simulated an increase in air temperature (based on the period 1971 to 2000) in Europe of 1.0 to 4.5 °C by the end of this century under the IPCC Representative Concentration Pathway (RCP) 4.5 scenario [38], or 2.5 to 5.5 °C under the RCP 8.5 scenario. In contrast, the temperature of the coastal regions of Germany, the Netherlands, and France will be less affected by the climate change. The German National Meteorological Service (Deutscher Wetterdienst) predicted a regional temperature increase of 0.2 to 0.5 °C from 2021 to 2031 based on average temperatures from 1991 to 2020 [39]. Contrary to the predictions, no direct temperature increase was observed during the 25 -year survey period. According to the IPCC SR [7] a general increase in the risk of weather phenomena (e.g., heat waves, droughts) has been predicted, which is consistent with our results in the form of an increased variance of the measured temperature during the survey period at the trial site. As shown in our study, the initial infestation is of minor importance for the epidemiological development of STB. Consequently, it is not only the regionality of the climate, but rather the seasonality of the climate that is of major interest. In particular, the climate of the spring season (April to June) determines the epidemiological behaviour of STB [1,40,41]. Consistent with our results, seasonal and regional simulations, showed an increase in precipitation during the spring season in northern Europe [42–44]. In contrast, the same simulations also predicted an increase in temperature, which was not observed in our study. In conclusion, there is an influence of climate change on the disease progression of STB. Furthermore, if temperature and precipitation follow the trend shown, an increase in the severity of STB can be expected.

Assuming that epidemics of other diseases occur at this location, interactions between the occurring foliar diseases are possible, as described by Jesus Junior et al. [12]. As shown by Klink et al. [3] leaf rust competed primarily with STB in a long-term survey in a similar region. However, leaf rust was not recorded consistently from year to year. As described by Garin et al. [24], leaf rust and STB compete for the same leaf area, with STB inhibiting leaf rust development, but leaf rust not inhibiting STB development under current weather conditions. By shortening the rust latency period (e.g., by increased temperatures) leaf rust was more competitive. Furthermore, a strongly reduced growth rate of STB was observed when the temperature exceeded 25 °C under laboratory conditions [31]. In contrast, Klöhn [22] was able to show that increasing temperatures correlated linearly with the leaf wetness duration required for a successful infection by STB. However, the seasonal mean temperatures in northern Europe are significantly lower than those described by Chaloner [31] and Klöhn [22], and it is therefore expected that STB remains the most dominant disease in northern Europe under maritime conditions.

Fungal disease management in wheat is mainly based on fungicides, which are primarily used to control STB. Consequently, it can be expected, that the amount of fungicides needed for a proper disease management in wheat will increase as STB disease pressure increases in the future, and if current practices are maintained [27]. In addition, Birr et al. [45] and Klink et al. [46] observed a shift in the sensitivity of STB to most of the available fungicides from 1999 to 2020. The increased disease pressure and the reduced sensitivity to fungicides threaten future yields of wheat production. In the European Union, pesticides are of growing concern of the general public. Due to the public concern, the EU is trying to reduce the amount of pesticides used through regulations such as the reduction of authorised active substances by the ever-expanding list of candidates for substitution [47].

Additionally, the EUs plan 'Regulation of the European Parliament and of the Council on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115' envisions a 50% reduction in total pesticide sales by 2030 [48]. Taking into account the aforementioned increase in STB disease pressure and reduced fungicide sensitivity, combined with European Union regulations, yield losses due to STB in common practice can be expected to increase beyond the 5-10% of Fones and Gurr [1]. In conclusion, this will lead to a greater reliance on genetic resistance in wheat cultivars. Although several resistance genes are currently known [49,50], resistant individual wheat cultivars with sufficient yield are currently unavailable. The durability of the resistant cultivars is also questionable, especially if the disease pressure increases [51]. An interesting approach is to use a mixture of cultivars to extend the lifetime of resistance sources due to heterogeneity [52,53]. In general, appropriate agronomic production techniques, such as proper crop rotation, tillage systems, or cultivars, will not suppress STB sufficiently.

In summary, the disease severity at the location increased significantly at the representative location. Thereby the prevailing weather conditions, in particular temperature and precipitation, changed within the survey period. Thereby, a seasonal expansion of infectious periods to advanced dates of the growing season was observed. Consequently, the infections occurred under higher temperatures, which might have led to the increased disease progression.

3.6 Conclusions

The sustainable production of wheat, the most important crop in the EU, is primary threatened by foliar diseases, and especially by Septoria tritici blotch (STB). During the 25-year survey period, a significant increase in STB disease severity was observed at a unique location without accompanying diseases in a maritime climate. The epidemiological development of STB is highly dependent on conducive weather conditions during the growing season. In particular, a seasonal expansion of STB conducive weather conditions during the critical growing season from May to June was observed. Due to the higher temperatures and constant precipitation in the advanced growing season, an enhanced disease dynamic of STB was observed from 1996 to 2021. As STB disease progression is highly dependent on the prevailing weather conditions, changes in climate, e.g., global warming, has major impact on the disease progression of STB. In particular climate change can influence the disease dynamic of STB, if spring temperatures and precipitation will increase as predicted by several climate simulations. Under this assumption, STB will become a bigger issue as it already is and the control of STB will be the major challenge for agronomic practices in maritime climates. Thereby, the use of integrated approaches for disease management are effective, as the disease pressure is evenly distributed across all agronomic practices, including the proper use of pesticides.

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Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

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2. This co-author declaration applies to the following article:
Will Climate Change Affect the Disease Progression of Septoria Tritici Blotch in Northern Europe?

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CHAPTER IV

CAN DECISION SUPPORT SYSTEMS HELP IMPROVE THE SUSTAINABLE USE OF FUNGICIDES IN WHEAT?

The content of this chapter has already been peer-reviewed and published in:
Prahl, K.C.; Klink, H.; Hasler, M.; Hagen, S.; Verreet, J.-A.; and Birr, T.
Can Decision Support Systems Help Improve the Sustainable Use of Fungicides in Wheat?
Sustainability **2022**, 14, 15599. doi: 10.3390/su142315599

Chapter IV CAN DECISION SUPPORT SYSTEMS HELP IMPROVE THE SUSTAINABLE USE OF FUNGICIDES IN WHEAT?

4.1 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

4.2 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 [3,4,5] 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.

4.3 Materials and Methods

4.3.1 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 5). 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/m² [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 5). 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.

Table 5. 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-WW-OR	Plough
Futterkamp	54°17′31′′N	10°38′04′′E	WW-WB-OR	Reduced tillage
Kluvensiek	54°19′38′′N	09°48′25′′E	WW-WB-OR	Reduced tillage

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 5). Corresponding to the preceding crop, the soil was cultivated with reduced tillage when oilseed rape preceded and by ploughing when winter wheat preceded.

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 6)[16].

Table 6. 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

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 6) [17].

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 7). 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/m² 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 7. 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 hours leaf wetness of > 98%
Glume blotch	37 - 39 41 - 47 51 - 69	F-5 or F-4 F-4 or F-3 F-3 or F-2	DI > 12%
Tan spot	32 33 - 39 41 - 49 51 - 69	F-6 or F-5 F-5 or F-4 F-4 or F-3 F-3 or F-2	DI > 5%
Powdery	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 8) 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 8. 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 hours 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	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 9) 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 9).

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.

Table 9. 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] (€/l)	Active ingredient (a.i.)	GS	Indicating diseases
T0, T1	Input® Classic[5]	1.00 / 1.25	33.60 €	Spiroxamine (300 g/l) Prothioconazole (160 g/l)	30-37	STB, GB, TS
T1	Talius®[2, 5]	0.20 / 0.25	28.00 €	Proquinazid (200 g/l)	30-59	PM
T2	Ceriax®[6]	2.50 / 3.00	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	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	16.00 €	Spiroxamine (250 g/l) Tebuconazole (133 g/l)	30-59	PM
RD solo	Folicur®[4,5]	0.80 / 1.00	16.60 €	Tebuconazole (250 g/l)	30-59	SR, LR

[1] Prices were investigated in Germany before 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.

4.3.2 *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.

4.3.3 *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)):

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

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:

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

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.

4.3.4 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)).

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

μ = annual mean of every location

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.

4.4 Results

4.4.1 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 10. 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.

Thereby, the 30-year average of Schleswig-Holstein is 127 L/m² [14] in the observed month; within the survey period, the precipitation varied between 75 L/m² in Barlt in 2020 and 236 L/m² 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/m² 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 S 3. At every location and in every year, conducive weather conditions for STB prevailed throughout the survey.

Table 10. 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.
OP = Observation period; T = Temperature; PP = Precipitation; LW = Leaf wetness

Location	OP	T (°C)	PP (l/m²)	h of LW ≥ 98% h	h of LW ≥ 98% n	STB infection conditions Date (hours of leaf wetness ≥ 98%)
Barlt	22.04.19 01.07.19	14 (6/24)	114	433	4	01.05. (108); 10.05. (64); 13.06. (64); 17.06. (54)
	20.04.20 29.06.20	14 (7/24)	75	336	3	03.05. (113); 24.05. (42); 10.06. (163)
	26.04.21 05.07.21	14 (5/25)	154	605	5	08.05. (111); 19.05. (207); 27.05. (42); 29.05 (56); 22.06. (63)
Futterkamp	15.04.19 24.06.19	13 (5/22)	172	449	7	10.05. (41); 23.05. (32); 10.06. (163); 01.06. (45); 09.06. (37); 17.06. (155); 23.06. (105)
	20.04.20 05.07.20	13 (6/22)	114	324	4	02.05. (98); 14.05. (50); 15.06. (62); 21.06. (56)
	26.04.21 05.07.21	14 (5/25)	164	428	5	06.05. (73); 19.05. (27); 25.05. (94);29.05. (113); 31.06. (66)
Kluvensiek	15.04.19 24.06.19	13 (4/21)	89	190	6	14.05. (120); 24.05. (61); 30.05. (91); 12.06. (58); 16.06. (42); 21.06. (79)
	27.04.20 06.07.20	14 (6/23)	127	205	5	02.05. (87); 14.05. (37); 05.06. (26); 14.06. (46); 19.06. (35)
	26.04.21 05.07.21	14 (4/23)	236	461	5	01.05. (58); 07.05. (129); 16.05 (143); 06.06. (66); 24.06. (112)

4.4.2 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 12A). 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 12A).

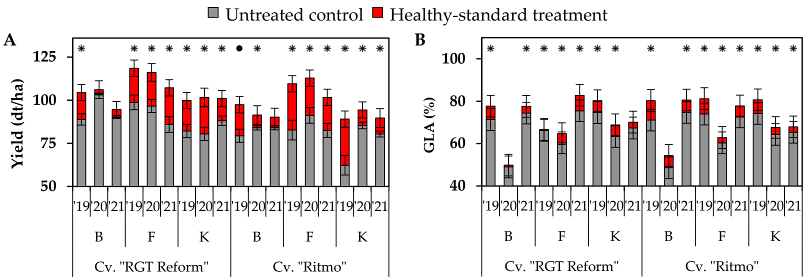

Figure 12. Annual (**A**) yield (dt/ha) and (**B**) green leaf area (GLA; RWAUDPC of percentage of leaf area) of the UC (grey bars) and the healthy-standard treatment (red bars) of the wheat cultivars "RGT Reform" and "Ritmo" at the locations Barlt (B), Futterkamp (F), and Kluvensiek (K) from 2019 and 2021. Significant ($p \leq 0.05$) 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 12B). 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 13, 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 13 A).

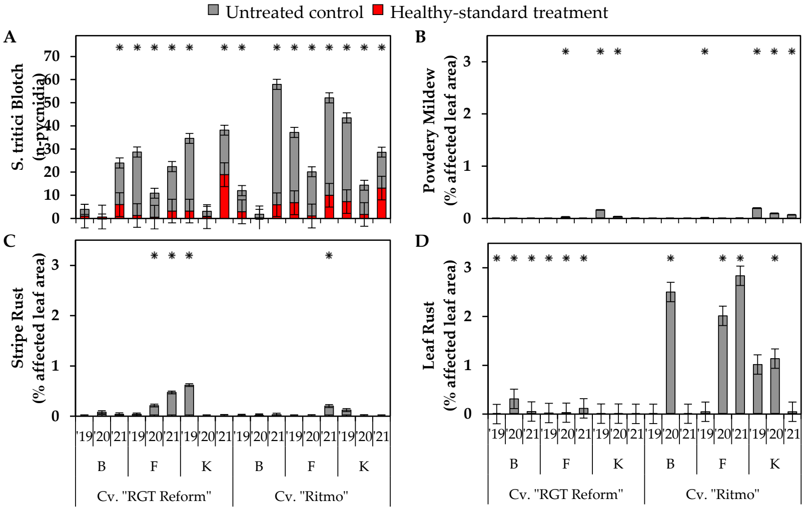

Figure 13. Annual disease severities (RWAUDPC; F-0 70%; F-1 20%; F-2 10%) of (**A**) Septoria tritici blotch (number of pycnidia), (**B**) powdery mildew (percentage of leaf area), (**C**) stripe rust (percentage of leaf area), and (**D**) leaf rust (percentage of leaf area) of the untreated control (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 *.

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 13 B-D). As shown in Figure 13 B 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 13 B).

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 13 C).

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 13D).

4.4.3 Performance of Decision Support Systems to 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 S 4). 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 14.

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 14) A 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 14 B).

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 14C, 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 14 D 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.

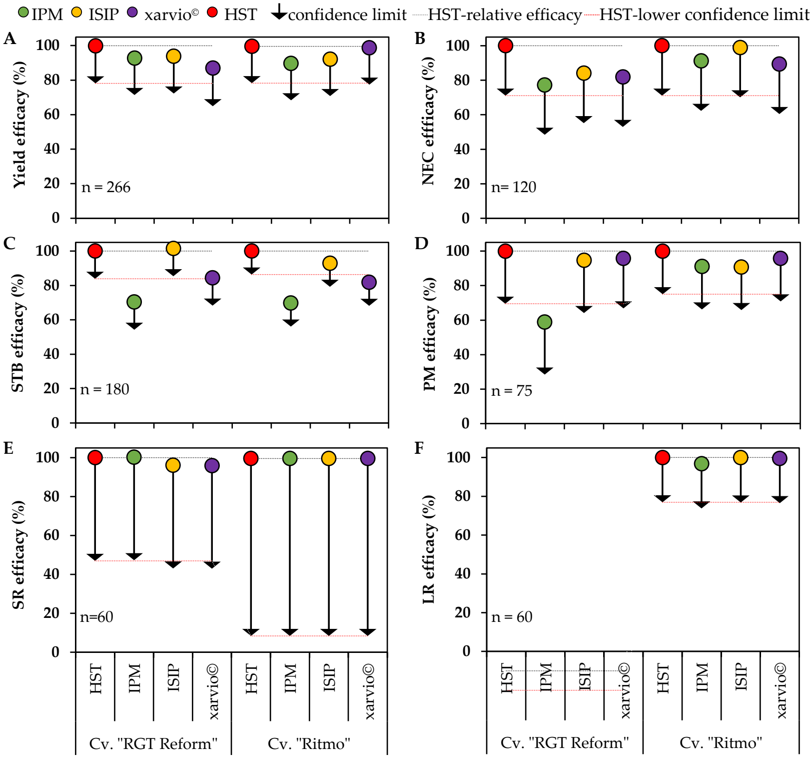

Figure 14. Relative efficacy and lower confidence limit (whisker, α = 0.05) of the healthy-standard treatment (red dots), IPM treatment (green dots), ISIP treatment (yellow dots), and xarvio© treatment (purple dots) in relation to the healthy-standard treatment adjusted by the untreated control for the 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.

4.4.4 Efficacy of DSSs

For evaluation of the efficacy of the subjected DSSs, the average yield and TFI of the cultivars "RGT Reform" (Figure 15 A) and "Ritmo" (Figure 15 B) were used. 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 15 A_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 15 B_I).

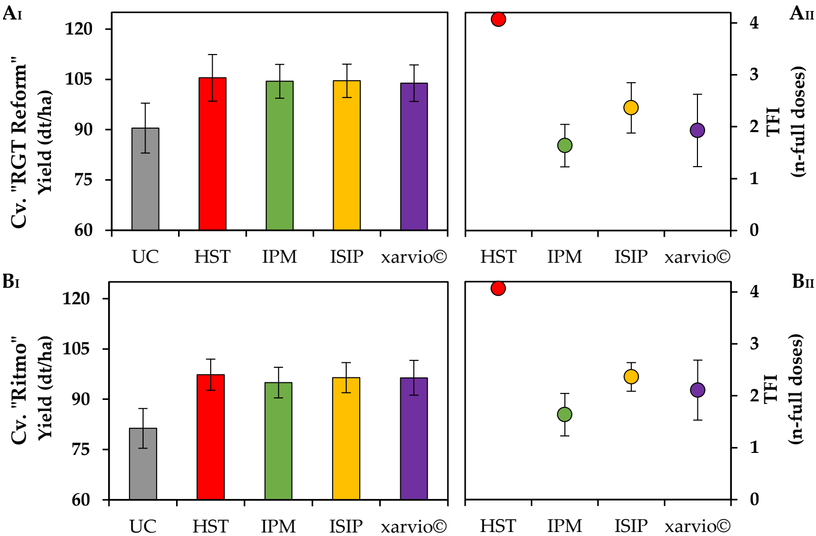

Figure 15. Yield (dt/ha; bars) and treatment frequency index (TFI; n-full doses; dots) of the untreated control (UC), healthy-standard treatment (HST; red), IPM treatment (green), ISIP treatment (yellow), and xarvio© treatment (purple) of the wheat cultivars (**A**) "RGT Reform" and (**B**) "Ritmo" averaged 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 15 A_{II}, BII. 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 15 A_{II}; B_{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.

4.4.5 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 11).

Table 11. 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	6.33 €	126.14 €	$p(x) = 104.43x - 88.22$
	ISIP	9.03 €	104.00 €	$p(x) = 104.58x - 127.34$
	xarvio©	7.76 €	71.89 €	$p(x) = 103.86x - 103.79$
"Ritmo"	UC			$p(x) = 81.33x$
	HST			$p(x) = 97.32x - 219.15$
	IPM	6.47 €	55.17 €	$p(x) = 94.95x - 88.22$
	ISIP	8.41 €	107.12 €	$p(x) = 96.47x - 127.34$
	xarvio©	7.54 €	113.97 €	$p(x) = 96.40x - 113.57$

4.5 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) [36,37,38] 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 [40,41,42,43]. 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 [45,63,64,65]. 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 significantly enhance 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.

4.6 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.

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Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

1. Doctoral candidate
Name: Ketel Christian Prahl

2. This co-author declaration applies to the following article:
Can Descisssion Support Systems Help to Improve the Suistainable Use of Fungicides in Wheat?

The extent of the doctoral candidate's contribution to the article is assessed on the following scale:

A. Has contributed to the work (0-33%)
B. Has made a substantial contribution (34-66%)
C. Did the majority of the work independently (67-100%)

3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
Concept: Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	C
Planning: Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	B
Execution: Involvement in the analysis or the concrete experiments/investigation	C
Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form	C

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Chapter V

General Discussion & Future Perspectives

Chapter V GENERAL DISCUSSION AND FUTURE PERSPECTIVES

The ultimate goal of agriculture is to provide food in sufficient quantity and quality, hence 95% of the global production value are food products and two thirds of the foods are contributed on cereals. Their production is primarily based on the three major crops, namely wheat, rice, and maize, which are the most important staple foods worldwide and account for over 90% of the world cereal production. In the European Union, 99% of the total value of agricultural production is sold as food product, with wheat accounting for more than 50% [1]. Within the European Union, the area harvested has shown a decreasing trend. At the same time, wheat yields have constantly increased since 1961. [2]. The increase in yield is primarily due to the use of fertilizers and pesticides [3]. Despite the strict regulations on pesticides in the European Union, the use of plant protection products is of major concern and the public is demanding more sustainable agricultural production [4–10]. Therefore, the European Union is amending the existing Directive 2009/128/EC [11] on the sustainable use of pesticides with the ‘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’ (SUR) [12]. The most incisive change regarding pesticides is that instead of reducing the risk from pesticides, the amended regulation aims to reduce the total amount of pesticide used by 50%.

In general, sustainability is encompassing the economic, social, and environmental (or ecological) dimensions equally [13–18]. In terms of the three dimensions, sustainable agriculture must provide eco-friendly food in adequate quality and quantity at reasonable prices for producers and consumers [19]. In the case of agricultural production, the dimensions are in direct conflict, with the use of pesticides in particular affecting the balance between the dimensions.

Wheat production in general, and in Europe in particular, is severely affected by the occurrence of fungal diseases. The epidemiological progression of foliar diseases is highly dependent on the prevailing weather conditions on the one hand and the agricultural production system on the other [20–22]. The primary objective of an agricultural production system according to integrated pest management (IPM) is to maintain the quality and quantity of the harvested products by preventing diseases. The production system must be adapted to all abiotic (e.g., soil, climate) and biotic (e.g., pathogens, weeds) factors at the location [23,24]. In particular, rust diseases and powdery mildew, as wind-borne diseases, can be reduced by selecting tolerant or resistant cultivars in northern Europe [25–30]. In contrast, diseases which persist on crop residues, such as tan spot, glume blotch, or Septoria tritici blotch can be reduced by appropriate crop rotation and tillage systems [22,31–34]. For example, tan spot can be expected when reduced tillage and continuous wheat are used simultaneously [22,32,35]. The dilemma for agricultural production systems is that ploughing has a negative effect on soil structure, water balance, or earthworm populations [36–39]. Furthermore, early sowing increases the risk of high initial inoculum of soil-borne diseases, due to increased temperatures and consequently increased fungal activity before winter. In addition, an increase in initial inoculum at the beginning of the growing season in spring can be expected, due to mild winters in maritime weather conditions [40,41]. In contrast, a positive effect on yield can be expected by early sowing, if sufficient precipitation during the late summer is available. Therefore, early sowing is a common agricultural practice [42–46]. The selection of crop rotation, cultivar, tillage system, and sowing date shows the complexity of an agronomic production system. In conclusion, adapting the production system to the prevailing foliar diseases can prevent epidemics to a certain extent. In particular, agronomic prevention of powdery mildew, leaf rust, stripe rust and tan spot is more reliable than the prevention of Septoria tritici blotch which can be reduced, but not avoided.

5.1 Occurrence of Wheat Foliar Diseases

The occurrence of foliar wheat diseases was monitored in a long-term study from 1995 to 2021. Thereby, the agronomic production system was adapted to the eight investigated trial locations in every year of the survey. In Chapter II, the epidemiological data is presented for the major foliar diseases of wheat in northern Germany, namely Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust. The results demonstrate that Septoria tritici blotch and powdery mildew were consistently present throughout the survey period. In contrast, glume blotch, tan spot, stripe rust, and leaf rust occurred rather inconsistently throughout the 26-year survey. Therefore, the management of foliar diseases by adapting the production system is not sufficient, as conducive weather conditions can lead to high severities of these diseases. The importance of the major diseases has also been shown by other studies in maritime wheat growing areas of central and northern Europe [19,20,47–49]. Within the survey, Septoria tritici blotch was the most predominant disease as it occurred frequently with high disease severity in every year and at every location of the long-term survey (Chapter II).

Under maritime climatic conditions, Septoria tritici blotch is the most important foliar disease of global wheat production and is responsible for significant yield losses in all wheat growing areas [21,40,50,51]. During the survey period, a significant increase in disease severity of Septoria tritici blotch was observed. In order to identify possible reasons for the continuous increase, the disease progression was analysed at a location without any occurrence of other foliar diseases [52–54]. Due to the absence of associated diseases and exactly recorded weather parameters (e.g., temperature, precipitation, leaf wetness) at this trial location a possible influence of climate change on the Septoria tritici blotch disease progression was analysed. A significant increase in the severity of Septoria tritici blotch was observed during the survey period, with a corresponding increase in necrosis, confirming the yield limiting influence of Septoria tritici blotch. According to the trial design, the increase in the severity of Septoria tritici blotch during the study period could be caused by the consistent use of the cultivar "Ritmo" and an adaptation of the pathogen to the cultivar [55], whereas in Chapter IV the less susceptible cultivar "RGT Reform" also showed high disease severity compared to the cultivar "Ritmo". Therefore, an adaptation during the survey is possible, but does not explain the extent of the increase in disease severity of Septoria tritici blotch. Due to the high dependency of Septoria tritici blotch on prevailing weather conditions, a change in climatic conditions at the survey locations is a more plausible explanation for the increase in disease severities during the survey period.

5.2 Impact of Climate Change on Septoria Tritici Blotch Disease Progression

In contrast to our results, Gouache et al. [56] simulated a 2-6% decrease in the severity of Septoria tritici blotch in France due to climate change, but with high uncertainty. In contrast, Volk et al. [57] simulated an increase in disease progression. Both scenarios were based on IPCC scenarios. In Chapter III, low correlations were observed between the disease severity and the weather parameters temperature, precipitation, and leaf wetness. The case study demonstrated the importance of precipitation followed by leaf wetness for successful infection (germination, growth of infection hyphae with appressorium development, stomatal leaf penetration). Thereby, the results of the case study are based on assessments under natural field conditions and are therefore influenced by realistic agronomic and environmental conditions, which increases the general validity of the results. As a result, 3 L/m² of precipitation followed by a 36-hours duration of leaf wetness is sufficient to transport the inoculum on the upper leaf layers and complete the infection process. Interestingly, higher amounts of precipitation and longer periods of leaf wetness did not determine the expression of the corresponding infection [58]. During the infection process, the primary influence of temperature is indirect, as the leaf wetness period is shortened, and the infection process is exposed at temperatures below 6 °C and above 25 °C. However, after a successful infection, the temperature during the latency period determines the strength of the corresponding Septoria tritici blotch infection, as the activity of Septoria tritici blotch increases under higher temperatures and decreases under lower temperatures [50,59,60]. Therefore, Septoria tritici blotch is highly dependent on the prevailing weather conditions and conducive conditions are primarily found in maritime climates [44,50]. In Chapter III, a temporal expansion of conducive Septoria tritici blotch conditions from May to June was observed. The number of conducive conditions in May remained constant over the survey period, but an increase was observed in June. Due to obviously higher temperatures in June as in May, Septoria tritici blotch infections showed an increased severity, which resulted consequently in higher disease severities. Therefore, the enhanced expression of Septoria tritici blotch throughout the survey period can be attributed to the temporal extension of conducive conditions. In addition to the increased strength of Septoria tritici blotch infections, higher temperatures shorten the latency period between infection and epidemic outbreak [61], allowed more infections to occur during the growing season. Consequently, Septoria tritici blotch infections occurred later in the growing season under warmer conditions with an increased epidemiological potential [59,62,63]. As a result, a higher temperature after a successful infection increases the disease pressure of Septoria tritici blotch in northern Europe and therefore an impact of climate change cannot be excluded.

Since 1881, the global temperature increase has been about 1.0 °C with regional temperature changes differing from the global average [64]. The temperature increase in Germany was 1.5 °C due to higher temperatures after the year 2000 [65]. According to climate change simulations, a further increase in temperature can be expected even if greenhouse gas emissions are not taken into account [66]. In the simulations the extent of the temperature increase is linked to the emitted greenhouse gases in the future. Four Representative Concentration Pathways (RCP), namely RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 were presented for climate modelling and research in the Fifth Assessment Report of the IPCC [67]. Depending on the RCP, air temperature increases of 1.0 to 5.5 °C have been simulated for northern Europe by 2100 (based on the period 1971 to 2000) [66]. According to the German National Meteorological Service (Deutscher Wetterdienst) the coastal regions of Germany, the Netherlands and France will be less affected by the climate change, with a calculated increase of 0.2 to 0.5 °C [68]. In addition, there is a general increase in the risk of weather phenomena (e.g., heat waves, droughts), which is consistent with our results in the form of an increased variance of the measured temperature during the survey period at the trial location. As shown in Chapter III, the initial infestation is of minor importance for the overall epidemiological development of Septoria tritici blotch. For Septoria tritici blotch, not only the regionality of the climate, but rather the seasonality of the climate is of major importance. In particular, the climate of the spring season (April to June) determines the epidemiological behaviour of Septoria tritici blotch [40,69,70]. IPCC climate simulations showed a seasonal and regional increase in precipitation and temperature during the spring season in northern Europe [71–73], although only the increase in precipitation was observed in the study. Therefore, there is an influence of climate change on the progression of Septoria tritici blotch, and if temperature and precipitation follow the IPCC predictions, an increase in the severity of Septoria tritici blotch can be expected.

Under the assumption that temperature and precipitation increase during the spring growing season, diseases adapted to higher temperatures may become more important. A similar shift was observed at the beginning of the long-term survey. Glume blotch was the most predominant disease in German wheat production in the 1980s [23,74]. At the beginning of the 1990's Septoria tritici blotch displaced glume blotch as the most predominant disease [75–77]. This shift has been attributed to susceptible cultivars, early sowing, increased nitrogen fertilisation, increased summer precipitation and a differential response to certain fungicides [77–79]. This has been confirmed in the survey, as glume blotch occurred with low but relevant disease severities in the very first years of the survey. Only very low disease severities were recorded thereafter and since 2012 glume blotch has not been observed at all (Chapter II). A similar shift is conceivable as interactions between the occurring foliar diseases are possible, as described by Jesus Junior et al. [52]. As shown in Chapter II, leaf rust severity increased in the last years of the survey and was the most important concomitant disease after Septoria tritici blotch during the survey, while leaf rust was inconsistently assessed from year to year. In contrast to the interaction between Septoria tritici blotch and glume blotch, leaf rust is a biotrophic pathogen and is dependent on green leaf tissue. Therefore, Septoria tritici blotch inhibits the disease development of leaf rust. Similar to Septoria tritici blotch, leaf rust disease progression is expected to increase with temperature [58]. However, at temperatures above 25°C inhibition of Septoria tritici blotch growth has been observed under laboratory conditions [59]. Consequently, a shift in dominance from Septoria tritici blotch to leaf rust is unlikely, as even under the most intense RCP 8.5 scenario the mean daily temperature in northern Europe will not exceed 25°C during the growing season [71,80]. Therefore, Septoria tritici blotch is expected to remain the most important disease under maritime conditions. In addition, a further increase in disease pressure of Septoria tritici blotch in wheat production can be expected, if the development of temperature and precipitation follows the climate change simulations.

5.3 Efficacy of Disease Management under Maritime Climatic Conditions

As aforementioned, foliar disease epidemics are possible under conducive weather conditions, despite optimized agronomic practices [22]. In order to maintain yields and thus sustainability, the use of chemical crop protection products (in this case fungicides) is essential. Therefore, according to the principles of IPM, pesticides as part of an agronomic production system should only be used as a last option to control pests [23,24,81]. Furthermore, the use of pesticides is essential for the economic and social sustainability of agricultural products, as the quality (e.g., mycotoxin contamination) and quantity (e.g., yield) of the harvested crop can only be achieved cost-effectively with the appropriate use of chemical pesticides [19–21,82–84]. The total amount of pesticides sold in the European Union has remained stable over the last decade [85]. About one third (33%, 10464 tons) of all pesticides sold annually in Germany (31314 tons) were fungicides (excluding inert gases; herbicides 52%, insecticides 3%, others 12%) [86]. Of these, 13% of fungicides, 30% of insecticides and 6% of herbicides were used unnecessarily, mainly due to non-optimised application timing [87–89]. As a result, the highest potential in pesticide reductions is on fungicides, as they are unnecessary used in high quantities, considering both the total amount used and unnecessary use. In the case of fungicides, use should then be based on threshold to avoid significant yield losses [61,63,90,91]. In conclusion, fungicides have the greatest potential to reduce overall pesticide use.

In Chapter II, the biological-epidemiological thresholds of Verreet et al. [80] were evaluated from 1995 to 2021 for their effectiveness in reducing the severity of foliar diseases. The WAUDPC values of the threshold-based application system for Septoria tritici blotch, powdery mildew, stripe rust and leaf rust were significantly reduced over the entire survey period. Due to the lack of agronomic tools such as resistant cultivars, fungicides were primarily used for the control of Septoria tritici blotch during the survey period. This suggests that threshold-based fungicide applications were effective, which also has been confirmed by other studies [19,21,92–94]. However, there has been a decline in the control of Septoria tritici blotch. Compared to earlier periods of this long-term study, no significant control of this pathogen has been achieved in recent years (Chapter II). This development must be of concern to agricultural practice, as there has been an apparent change in the disease behaviour [95–98]. Reduced fungicide efficacy may be due to loss of sensitivity of the pathogen to the different fungicide classes. A long-term study by Birr et al [99] showed a significant loss of fungicidal efficacy of triazoles against Septoria tritici blotch in the same region, which has now stabilized at a lower efficacy level. This has been confirmed in studies from other countries and must be considered a global effect [100–103]. In contrast, Klink et al [94] was able to demonstrate a stable sensitivity of Septoria tritici blotch to mefentrifluconazole with its flexible isopropanol group over the last decades. It appears to be less affected by the mutation in the CYP51 gene of Septoria tritici blotch [98], which is important for resistance management in current agricultural practices. Septoria tritici blotch has achieved complete resistance to the fungicide group of quinone outside inhibitors [104,105]. Similarly, the carboxamides (succinate-dehydrogenase inhibitors), as a relatively new group of fungicides, are subject to a continuing loss of efficacy [82]. Thus, the loss of sensitivity to Septoria tritici blotch towards several fungicide groups must be considered critical, as both the number of available fungicides [106] and the efficacy of the remaining fungicides are continuously decreasing. Similar trends in loss of sensitivity have recently been observed for other diseases such as powdery mildew [107].

In order to assess the effectiveness of a biological-epidemiological threshold-based system, the impact on yield must be assessed in addition to the impact on leaf diseases. This has been shown in Chapter II for the threshold-based system according to Verreet et al. [24] for the period from 1995 to 2021 at eight locations in northern Germany. The yield of the biological-epidemiological treatment was compared to the yield of an untreated control and a healthy standard treatment. Due to the continuous foliar protection throughout the growing season, it can be assumed that the standard healthy treatment represents the yield potential of the cultivar at the location. In addition, the untreated control was an indicator of disease progression at each location and in each year of the study. Averaged over the 26 years of the study, under standardised conditions (same variety, same location), a 20% reduction in yield was observed in the untreated control compared with the standard healthy treatment. Furthermore, the biological-epidemiological system was not statistically inferior to the healthy standard treatment. As aforementioned, Septoria tritici blotch was the most predominant disease throughout the study and consequently accounted for the highest yield losses. In studies from other regions with maritime conditions, such as northern France, Ireland or the UK, Septoria tritici blotch was also the most important yield-reducing disease with even higher losses of up to 50% in wheat production recorded [40,44,108–111]. Due to the high yield levels in northern Europe compared to the rest of the world, yield losses caused by foliar diseases are comparable to Australian yields [2]. In summary, the use of a biological-epidemiological system has archived an adequate reduction in the occurrence of foliar diseases, while utilizing the yield potential of the sites evaluated.

For the control of foliar diseases during the survey period, the agronomic production system was optimized for the suppression of foliar diseases, therefore powdery mildew, stripe rust, and leaf rust occurred in minor disease severities, hence the use of fungicides during the growing season was primarily for the control of Septoria tritici blotch. Despite of non-inferiority in yield to the healthy standard treatment, the biological-epidemiological system showed a significant reduction in the amount of fungicide active ingredient (a.i./ha) by two-thirds compared with the healthy standard treatment averaged over the survey period of 26 years (Chapter II). This demonstrates the excellence of biological-epidemiological approaches for foliar disease control. The reduction of fungicides has been achieved due to an optimal timing of fungicide application at the most sensitive stages of the disease epidemic. As a result, applications applied too early reduce the protective performance, while applications applied too late reduce the curative performance of fungicides [24,93,112,113]. Consequently, either early or late applications reduce the efficacy of fungicides, leading to the use of higher doses to compensate for the loss of efficacy. Optimizing the timing and effectiveness of fungicide applications is a major challenge for current farming practices [24,93,114]. As shown in Chapter IV, the use of biological-epidemiological decision support systems (DSS) for optimized timing of fungicide applications is recommended, but not comprehensively established [88,93,109,115]. Over the past decades, numerous DSSs for foliar disease control have been published by universities, federal institutions, or companies

[109]. However, the published DSSs vary considerably in their degree of transparency, which is one of the reasons for the non-comprehensive establishment of DSSs in common agricultural practice [109]. In general, the thresholds and algorithms of scientific and governmental institutions provide a high degree of transparency compared to commercial systems. As also shown in Chapter IV, the scientific and federal DSSs (IPM and ISIP) showed full transparency compared to the commercial DSS (xarvio©) [24,116,117]. In addition, the requirements for disease diagnosis vary considerably between DSSs [109,118]. Therefore, all DSS considered implemented diagnosis by regional observation in the study area. In general, any fungicide use in the European Union is only justified if an indicator disease occurs [11], and therefore disease diagnosis is required in farm practice. Nevertheless, diagnostic problems are a common reason for refusal of DSS [109,118]. Another reason for the low implementation of DSS in common farm practice may be the additional workload for farmers in terms of sampling, diagnosis and effort [119]. Apart from the above reasons, the major concern of farmers is yield-stability when DSSs determine the timing of their fungicide application [120].

In Chapter IV, three DSS were evaluated for their ability to control foliar diseases and protect yield potential in two different susceptible cultivars (cv. "RGT Reform" and cv. "Ritmo") under maritime conditions at three locations in northern Germany from 2019 to 2021. As expected, cultivar susceptibility varied, as indicated by the data from the foliar disease evaluations (Chapter IV). In particular, the cultivar "RGT Reform" was less susceptible to foliar diseases than the cultivar "Ritmo" with the exception of stripe rust. The different susceptibilities to foliar diseases were therefore confirmed from the untreated control. Disease severities of stripe rust and leaf rust were significantly reduced due to the selection of a less susceptible cultivar, confirming the importance of an optimized agronomic production system [49,121–125]. In contrast, the suppressive effect of cultivar resistance on disease severities of Septoria tritici blotch was only rudimentary in the study. Other commercially available cultivars with low susceptibilities to all diseases are either not adapted to local conditions and therefore less productive or have lower yield potential [126]. Therefore, fungicides are essential to maintain quality and quantity of yield, as long as aforementioned cultivars are not available.

Current legislation only allows the use of fungicides when there is evidence of considerable disease in the crop. Determining such a yield-limiting infection is a major challenge for agronomic practice. Biological-epidemiological thresholds have been developed to indicate the level of infestation required to break even [23,24,93]. In general, DSSs are based on these biological-epidemiological thresholds. As shown in Chapter IV, all DSSs showed high efficacy in reducing foliar diseases at each location and in each year of the study. Despite their minor inferiority in disease suppression compared to the healthy standard treatment, no significant differences in yield were observed between the DSS and healthy-standard treatments. This suggests that the full potential of the crop was utilized, even when disease severity was low. By applying pathogen-specific fungicides during most sensitive phase, the highest efficacy in fungicide use can be achieved. Therefore, low disease severities are tolerable in the disease suppression strategy in common farm practice. In Chapter IV, minor deviations were observed in the disease suppression efficacy of the DSS treatments compared to the healthy-standard treatment. In the trial, efficacy in suppressing necrosis, powdery mildew and Septoria tritici blotch varied constantly from the healthy-standard control with differences at a low level. As a result, all DSS tested adequately reduced disease severities of all foliar diseases and the full yield potential of location and cultivar in each year of the study was shown. Additionally, the amount of fungicide used to control foliar diseases was halved with the use of DSSs compared to healthy-standard treatment. As the purpose of the healthy standard treatment was to show the full yield potential, compared to common farm practices a relatively high amount of fungicides was used to ensure a maximum in disease protection. Therefore, the active ingredients used in the healthy-standard treatment are not directly transferable to common farm practices. Dachbrodt-Saaydeh [87] showed in a 10-year study in Germany that a treatment frequency index (TFI) of 2.5 full doses was necessary to control prevailing foliar diseases. The use of DSSs resulted in a further reduction in the TFI with observed TFIs ranging from 1.65 to 2.36. This shows that a further optimization of the fungicides used in common farm practices is possible, in particular by the use of DSSs to determine the optimal application dates. In conclusion, the number of fungicide applications was reduced significantly compared to the healthy-standard treatment and to common north German farm practices by avoiding unnecessary treatments due to optimized timing of fungicide application by DSSs. In addition, the yield potential has been exploited to a degree that maximizes revenue.

5.4 Resistance Management by DSS

In general, reducing the number of sprays also reduces the risk of resistance development due to extension of fungicide activity [115,127–129]. As the amount of fungicides used and the number of sprays to control foliar diseases was significantly reduced by DSS, it can be assumed that the use of DSS also reduces the risk of fungicide resistance. This was achieved by optimising the timing of applications through the use of DSSs. In the long-term study, a continuous decline in efficacy was observed throughout the study period, particularly in the control of Septoria tritici blotch (Chapter II). A possible explanation for the decline in efficacy is that the efficacy of DSS is directly related to the efficacy of commercial fungicides. As the amount of fungicides used to control foliar diseases was significantly reduced by DSS, it can be assumed that the use of DSS reduces the risk of fungicide resistance. In the long-term study, a continuous decline in efficacy was observed throughout the study period, particularly in the control of Septoria tritici blotch. A possible explanation for the decline in efficacy is the increased disease pressure of Septoria tritici blotch as described in Chapter III. Another possibility is that the efficacy of DSS is directly related to the efficacy of commercial fungicides. The sensitivity of rust diseases to commercial fungicides is still at a sufficient level [130], but a decrease in efficacy against Septoria tritici blotch and powdery mildew has been observed [94,99,107]. This was confirmed by the results in Chapter IV, which showed high efficacy in controlling rust diseases compared to Septoria tritici blotch and powdery mildew. It can therefore be assumed that the lack of efficacy is due to both reduced fungicide efficacy and increased disease pressure. With the EU Regulation 2015/408 [106] establishing a list of candidates for substitution of plant protection products on the market, the number of available fungicides is decreasing, leading to increased disease pressure on the remaining fungicides, which increases the risk of loss of sensitivity. As a result, fungicides need to be applied earlier in the disease development process to maintain efficacy. Biological-epidemiological thresholds must therefore be adjusted, resulting in earlier DSS recommendations and consequently an increase in total fungicide use. The restrictions imposed by the European Union are therefore contrary to their original purpose.

5.5 Improved Sustainability of Fungicide Use by Decision Support Systems

As mentioned at the beginning of this chapter, sustainability encompasses economic, social, and environmental considerations [13–18]. With regard to pesticides as used currently in agriculture, an improvement of sustainability is possible. Historically, pesticides have already improved the sustainability of agriculture, particularly in Europe. Since the 1960's, the productivity of the European agriculture has increased continuously based on the implementation of fertilisers and pesticides into agronomic practices. As a result, the productivity of wheat, the most widely grown and important staple crop in Europe, has increased. Consequently, the social sustainability dimension was increased by providing food in adequate quantities and quality using chemical crop protection. Fungicides have made a major contribution to this increase in productivity by protecting crops from the emergence of diseases which adversely affect yields and quality. Today, approximately 10% (770 million people) of the total population were undernourished worldwide [131]. As a result of the worldwide trade flows, the agricultural production in Europe has an impact on the nutrition status of the global population [132]. Due to which political restrictions regarding plant protection products also affect the global food supply.

In contrast, each application of plant protection products results in the release of active substances into the ecosystems of the application site, which has an impact on the environmental sustainability dimension of agricultural production [133–138]. Although pesticides are a highly regulated group of chemicals in terms of environmental risk, there is increasing evidence of their detrimental ecological effects (e.g., biodiversity in agricultural landscapes) [133,138]. Insecticides (e.g., neonicotinoids), herbicides (e.g., glyphosate), and fungicides (e.g., chlorothalonil) are the majority of pesticides in use that are considered to have adverse ecological effects [138–142]. In general, pesticides are deposited into ecosystems in agricultural regions and are subsequently metabolised in the ecosystem to various metabolites. The effects of all emerging metabolites, and in particular the effects of interacting metabolites, are not yet fully understood. For this reason, the planned reduction of pesticides by EU Regulation 2021/2115 [12] is beneficial for the environmental dimension of sustainability. However, the social and economic dimensions of sustainability have not been taken into account, as there will be a loss of productivity [19]. As described in Chapter II [21], a system based on biological-epidemiological thresholds can optimize the use of fungicides.

At present, agricultural commodity prices are highly volatile, so a large increase in wheat price could lead to a similar increased fungicide rate to maximize productivity. In Chapter II and IV most profitable treatments for different scenarios with different fungicide cost structures and wheat prices for all tested DSSs, the untreated control, and the healthy standard treatment are shown. In these different scenarios the benefits of DSS over the untreated control and the healthy standard treatment is evident for a very high range of costs and wheat prices. Economic benefits of DSSs have also been shown by Verreet et al. [24] and Jørgensen et al. [109]. Due to the use of fungicides the efficacy of agricultural production increases and higher margins can be achieved, which improves the ecological dimension of sustainability. In addition, the quality and quantity of food can remain on the current level, which preserves the social sustainability dimension on its high level. Furthermore, the release of active substances into the environment is decreased to a minimum extent, which increases the environmental dimension of sustainability. In conclusion, the use of biological-epidemiological decision support systems can improve the sustainability of fungicide use in all three sustainability dimensions.

5.6 Future Perspectives

As part of the planned 'Farm to Fork' strategy, a component of the European 'Green Deal', the SUR envisages a general 50% reduction in total pesticide use by 2030 [12]. As shown in chapter II and IV, productivity losses can be expected in the future if the planned proposal is implemented in the EU [143]. With an expected loss of 20% in European wheat production the resulting gap will lead to a decrease in exports and even an import of wheat in Europe. To close the gap new farmland or increased productivity is needed to maintain production, but this is not possible for European agriculture as there is already a shortage of farmland and important tools for increasing productivity in agricultural production are regulated [3,143,144]. Furthermore, the use of pesticides in general has an impact on the quality of the harvested products. This can be the contamination of the crop by the pesticide itself or by natural contamination (e.g., mycotoxins). Thereby, the problems, such as mycotoxin contamination of cereals, making them unsuitable for human or animal consumption [82,83]. Additionally, the 'Farm to Fork' strategy has a negative impact on aggregate consumer surplus and a net increase or decrease in producer surplus, resulting in an overall net welfare loss [145]. In conclusion, the general reduction of pesticides by 50% in the EU will have an impact on global nutrition and a negative impact on the sustainability of agricultural production in Europe.

Rather than reducing pesticides across the board, improved land use and optimised agricultural practices can sustainably reduce pesticide inputs to the environment. In particular, solutions should be based on critical biological and economic 'leverage points' in agricultural systems, where with the least effort and cost, major improvements in food production or environmental performance can be achieved. As shown in Chapter IV, improvements such as DSSs effectively reduce the use of pesticides without compromising food safety. With better data, e.g., meteorological-, epidemiological- and biological-data, DSSs can further be developed in order to improve management decisions, productivity, and environmental performance [146]. Understanding the biological-epidemiological disease behaviour under agronomic and environmental conditions in the field is essential for effective and sustainable disease management and wheat production.

5.7 References

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SUPPLEMENTARY MATERIAL

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SUPPLEMENTARY OF: EFFICIENCY AND EFFECTIVITY OF A BIOLOGICAL–EPIDEMIOLOGICAL FUNGAL DISEASE MANAGEMENT SYSTEM IN WHEAT—A STUDY OF 26 YEARS

Table S 1. 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.

Foliar disease	**Effect**	***df***	***F***	***p***
Septoria tritici blotch	Treatment (T)	324	295.616500	< 0.0001
	Year (Y)	324	50.573800	< 0.0001
	T x Y	324	2.096100	0.002
Glume blotch	Treatment (T)	324	9.854726	0.0018
	Year (Y)	324	3.411725	< 0.0001
	T x Y	324	1.241881	0.1996
Tan spot	Treatment (T)	324	0.463364	0.4965
	Year (Y)	324	8.877909	< 0.0001
	T x Y	324	0.441737	0.9917
Powdery mildew	Treatment (T)	324	0.001637	< 0.1950
	Year (Y)	324	8.594131	< 0.0001
	T x Y	324	1.665901	< 0.0032
Stripe rust	Treatment (T)	324	18.671426	<0.0001
	Year (Y)	324	2.065552	0.0024
	T x Y	324	1.925722	0.0057
Leaf rust	Treatment (T)	324	2.764142	0.0974
	Year (Y)	324	21.769113	< 0.0001
	T x Y	324	10.004208	< 0.0001
Necrotization	Treatment (T)	324	180.925	< 0.0001
	Year (Y)	324	22.757	< 0.0001
	T x Y	324	1.634	0.0305

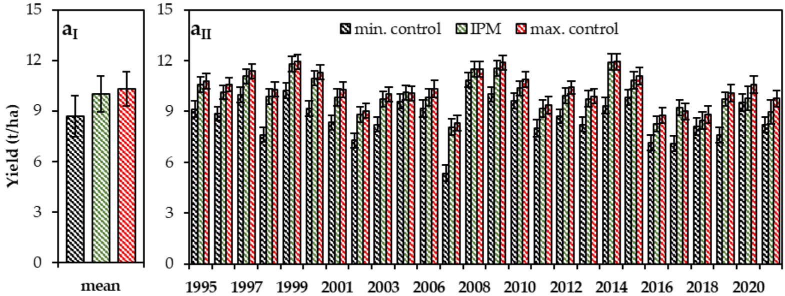

Figure S 1. Total yield (t/ha; **a**I) and annual yield (t/ha; **a**II) of the min. control, IPM and max. control of winter wheat (cultivar "Ritmo") of the eight trial locations in northern Germany from 1995 to 2021.

SUPPLEMENTARY OF: WILL CLIMATE CHANGE AFFECT THE DISEASE DYNAMICS OF SEPTORIA TRITICI BLOTCH IN NORTHERN EUROPE?

Table S 2. RWAUDPC of all observed foliar diseases from 1996 to 2021 at the trial location of the survey.

Year	Septoria tritici blotch	glume blotch	tans spot	powdery mildew	stripe rust	leaf rust
1996	7.84	0.00	0.00	0.03	0.00	0.00
1997	19.71	0.10	0.09	0.01	0.00	0.00
1998	22.65	0.00	0.01	0.01	0.00	0.01
1999	11.64	0.00	0.00	0.00	0.18	0.00
2000	24.85	0.00	0.00	0.00	0.00	0.02
2001	31.17	0.00	0.00	0.00	0.00	0.00
2002	56.48	0.00	0.01	0.00	0.00	0.08
2003	64.43	0.00	0.00	0.00	0.00	0.03
2005	12.87	0.00	0.00	0.00	0.00	0.03
2006	51.13	0.00	0.00	0.00	0.00	0.02
2007	22.33	0.00	0.00	0.00	0.01	1.78
2008	11.27	0.00	0.00	0.05	0.00	0.02
2009	64.67	0.00	0.00	0.01	0.00	0.05
2010	61.02	0.00	0.00	0.00	0.00	0.00
2011	44.19	0.07	0.00	0.00	0.00	0.00
2012	111.20	0.40	0.00	0.00	0.00	0.02
2013	92.71	0.00	0.00	0.00	0.00	0.00
2014	64.70	0.00	0.00	0.00	0.01	0.01
2015	46.27	0.00	0.00	0.00	0.00	0.01
2016	79.49	0.00	0.00	0.00	0.02	0.01
2017	90.36	0.00	0.00	0.00	0.00	0.06
2018	36.60	0.00	0.00	0.00	0.00	0.05
2019	133.53	0.00	0.00	0.00	0.01	1.64
2020	122.67	0.00	0.00	0.00	0.00	0.02
2021	86.47	0.00	0.00	0.00	0.00	0.00

SUPPLEMENTARY OF: CAN DECISION SUPPORT SYSTEMS HELP IMPROVE THE SUSTAINABLE USE OF FUNGICIDES IN WHEAT?

Table S 3. Temperature, precipitation, hours of leaf wetness and STB infection conditions (leaf wetness by "Weihofen" sensor ≥ 98% over more than 36h) in detail for the month May and June of the observed vegetation period at the trial locations Barlt, Futterkamp and Kluvensiek from 2019 to 2021.

		May					June				
	Year	T (°C)	PP (L/m²)	h of LF ≥ 98%	STB inf. n (h of LW ≥ 98%)		T (°C)	PP (L/m²)	h of LF ≥ 98%	STB inf. n (h of LW ≥ 98%)	
Barlt	2019	11	38	172	[illegible]	01.05. (108); 10.05. (64)	18	66	2	2	13.06. (64); 17.06. (54)
	2020	11	23	155	[illegible]	03.05. (113); 24.05. (42)	17	41	1	1	10.06. (163)
	2021	10	91	416	[illegible]	08.05. (111); 19.05. (207); 27.05. (42); 29.05 (56)	17	57	1	1	22.06. (63)
Kluven-siek	2019	10	30	73	[illegible]	10.05. (41); 23.05. (32)	18	56	3	3	12.06. (58); 16.06. (42); 21.06. (79)
	2020	12	31	148	[illegible]	02.05. (98); 14.05. (50)	17	63	3	3	05.06. (26); 14.06. (46); 19.06. (35)
	2021	10	108	307	[illegible]	06.05. (73); 19.05. (27); 25.05. (94); 29.05. (113)	18	118	2	2	06.06. (66); 24.06. (112)
Futter-kamp	2019	10	67	272	[illegible]	14.05. (120); 24.05. (61); 30.05. (91)	18	76	4	4	01.06. (45); 09.06. (37); 17.06. (155); 23.06. (105
	2020	11	29	124	[illegible]	02.05. (87); 14.05. (37)	16	100	2	2	15.06. (62); 21.06. (56)
	2021	11	108	330	[illegible]	01.05. (58); 07.05. (129); 16.05 (143)	18	66	1	1	31.06. (66)

T = Temperature; PP = Precipitation; LW = Leaf wetness

Table S 4. Analyses of variance (ANOVAs) for the effect of treatment (untreated control, IPM, ISIP, xarvio©, HST), cultivar ("RGT 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.

	Effect	***df***	***F***	***p***
Yield	Cultivar	26	0.1187	0.7332
	Treatment	203	56.3937	< 0.0001
	Cultivar x Treatment	203	0.2732	0.8950
Green leaf area	Cultivar	8	1.0137	0.3435
	Treatment	88	25.7087	< 0.0001
	Cultivar x Treatment	88	0.1995	0.9380
Septoria tritici blotch	Cultivar	14	0.3976	0.5385
	Treatment	136	101.6270	< 0.0001
	Cultivar x Treatment	136	0.1950	0.9406
Powdery mildew	Cultivar	5	0.5804	0.4805
	Treatment	52	31.5724	< 0.0001
	Cultivar x Treatment	52	0.9869	0.4229
Stripe rust	Cultivar	2	0.0035	0.9578
	Treatment	40	6.6905	0.0003
	Cultivar x Treatment	40	0.0033	1.0000
Leaf rust	Treatment	44	19.7410	< 0.0001

SUMMARY

SUMMARY

Wheat (*Triticum aestivum* L.) is one of the world's most important crops, providing food for a significant part of the world's population. Productivity varies considerably from one growing region to another due to differences in climate and soil conditions. Heavy clay soils and climates with sufficient rainfall and radiation, like large parts of northern Europe, are particularly productive. However, these maritime climates are equally conducive to yield-limiting pathogens, in particular the foliar diseases Septoria tritici blotch (*Zymoseptoria tritici* Desm.; STB), 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*).

In the present study, disease progressions of the six most important foliar diseases were recorded at eight trial locations in Schleswig-Holstein over a period of 26 years using an untreated control. Based on the epidemiological surveys, the efficacy and effectiveness of a biological-epidemiological threshold concept (BESK) for the control of emerging foliar pathogens was also evaluated. This was done using a positive control with complete foliar protection by fungicide application during the growth period from the beginning of stem elongation to flowering (Chapter II). The study showed that STB was the most important disease with high infestations observed every year since 1995 at all locations of the long-term study. In addition to STB, powdery mildew and rust pathogens were determined with lower relevance, as powdery mildew was rated continuously with low severity at the eastern sites and rust pathogens were rated with moderate severity at all sites in individual years. Glume blotch and tan spot were very sporadically detected at some locations and in some years, but the BESK threshold was not exceeded in any year of the study, which can be attributed to the adapted cropping system used in the trials. STB was thus the dominant disease in the trial area throughout the survey period and consequently the most economically important disease. The importance of STB was also evident in the evaluation of BESK with STB accounting for the majority of application recommendations. By applying the biological-epidemiological thresholds, emerging diseases were suppressed to a reasonable extent with high efficacy, as yields were equivalent to the healthy standard treatment, but only half the fungicides were applied.

In addition to the importance of STB in the survey area, a continuous increase of disease severities of STB was also observed during the survey period. Due to the special conditions at the location Sönke-Nissen-Koog (only STB occurred during the entire study period), a possible influence of climate change on STB was investigated (Chapter III). This showed a temporal extension of conductive STB conditions from originally early May to early June to early May to late June. A cumulative analysis of these conducive weather conditions showed an increase in temperature during the critical infection period, which explains the increase in intensity of STB infections. If climate change leads to a further increase in temperature or a further shift in conducive conditions for an infection, a further increase in the intensity of STB can be expected.

Disease control is therefore essential in wheat production, especially under maritime climatic conditions. At the current state of research, the use of plant protection products, in this case fungicide use, is indispensable for the control of fungal pathogens. Despite excellent training in practical farming, the optimisation of fungicide applications is possible with the use of decision support systems (DSSs). In Chapter II, a 50% reduction compared to the positive control was shown. Therefore, three DSSs from different sources (scientific, governmental, industrial) were evaluated in terms of their effectiveness in controlling emerging foliar diseases over three years at three locations in two wheat cultivars (Chapter IV). All DSSs equally halved the amount of fungicide needed to maintain equivalent yields compared to the positive control and significantly reduced the fungicide use compared to agronomic practices in the survey area. This confirms the effectiveness of biological-epidemiological decision support systems. The use of DSSs as a tool for fungicide optimisation could be of great importance in the future for agricultural practice, especially in view of the political objective of reducing pesticide use by 50% by 2030 (EU Farm to Fork strategy).

Irrespective of the economic benefits of agricultural practice using DSS, the sustainability of agricultural production is improved by DSSs in the sense that, on the one hand, food can continue to be provided in adequate quantities and quality. On the other hand, there will be a reduction in the emission of foreign substances into the agro-ecosystems. Thus, all three dimensions of sustainability are improved by optimising the use of fungicides.

ZUSAMMENFASSUNG

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Weizen (*Triticum aestivum* L.) ist weltweit eine der wichtigsten Kulturarten und bildet die Ernährungsgrundlage für einen erheblichen Teil der Weltbevölkerung. Aufgrund unterschiedlicher Rahmenbedingungen wie Klima- oder Bodenbedingungen variiert die Produktivität zwischen den Anbaugebieten in einem erheblichen Maße. Schwere tonhaltige Böden und Klimate mit ausreichend Niederschlägen und Strahlung, wie sie in weiten Teilen Nordeuropas vorherrschen, sind dabei besonders produktiv. Diese sogenannten maritimen Klimate fördern aber auch in gleichem Maße ertragslimitierende Krankheitserreger, insbesondere die in Nordeuropa ubiquitär auftretenden pilzlichen Blattkrankheiten wie die Septoria-Blattdürre (*Zymoseptoria tritici* Desm.; STB), Blatt- und Spelzenbräune (*Parastagonospora nodorum* Berk.), DTR (*Pyrenophora tritici-repentis* Died.), Echter Mehltau (*Blumeria graminis* f. sp. *tritici*), Gelbrost (*Puccinia striiformis* f. sp. t*ritici*) und Braunrost (*Puccinia triticina*).

Mit der vorliegenden Arbeit wurde zunächst überregional die Populations- und Schadensdynamik der sechs wichtigsten Blattpathogene an acht Standorten in Schleswig-Holstein über 26 Jahre anhand einer unbehandelten Kontrolle erfasst. Aufgrund der epidemiologischen Erhebungen wurde zusätzlich die Effizienz und Effektivität eines biologisch-epidemiologischen Schwellenwertkonzeptes (BESK) zur Kontrolle auftretender Blattpathogene unter Zuhilfenahme einer Positivkontrolle mit lückenlosem Schutz von Schoßbeginn bis zur Blüte durch den Einsatz von Fungiziden evaluiert (**Kapitel II**). Die Untersuchungen zeigten, dass insbesondere STB als überregional bedeutendster Erreger seit 1995 auftrat. Dabei wurde in jedem Jahr und an jedem Standort der Langzeitstudie ein epidemischer Befall beobachtet. Neben STB wurden auch die Erreger des Echten Mehltaus und der Rostkrankheiten beobachtet, wobei der Echte Mehltau kontinuierlich an den östlichen Standorten mit geringen Befallsstärken und die Rostkrankheiten in Einzeljahren in epidemischen Befallsstärken an allen Standorten beobachtet wurden. Die Erreger der Blatt- und Spelzenbräune als auch der DTR-Blattfleckenkrankheit wurden nur sehr sporadisch an einzelnen Standorten in einzelnen Jahren beobachtet. Dabei wurde in keinem Jahr ein Schwellenwert des BESK überschritten, was auf das in den Versuchen genutzte angepasste Anbausystem zurückzuführen ist. STB war somit die dominierende Krankheit im Erregerspektrum des Versuchsgebiets über die gesamte Versuchsdauer und folglich auch die wirtschaftlich bedeutendste Krankheit. Die Bedeutung von STB zeigte sich auch bei der Evaluierung des

BESK, wobei der Großteil an Behandlungsempfehlungen auf STB zurückzuführen war. Durch die Anwendung der Schwellenwerte wurden auftretende Erreger mit hoher Effizienz unterdrückt, da der Einsatz von Fungiziden auf ein unbedingt notwendiges Maß reduziert wurde, ohne dass dabei Ertragseinbußen gegenüber der Positivkontrolle mit maximalem Fungizideinsatz entstanden.

Neben der Bedeutung von STB konnte ein kontinuierlicher Anstieg der Befallsintensität von STB über die letzten 26 Jahre festgestellt werden. Aufgrund der besonderen Voraussetzungen am Standort Sönke-Nissen-Koog, an dem ausschließlich STB über die gesamte Versuchsdauer auftrat, wurde ein möglicher Einfluss des Klimawandels auf STB untersucht (**Kapitel III**). Dabei zeigte sich eine temporale Erweiterung der STB-fördernden Bedingungen von ursprünglich Anfang Mai bis Anfang Juni auf Anfang Mai bis Ende Juni. Bei kumulierter Betrachtung dieser Witterung konnte ein Anstieg in der Temperatur zu den kritischen Zeitpunkten der Infektion gezeigt werden, was den o.g. Anstieg in der Befallsintensität von STB erklärt. Wird es durch den Klimawandel zu einer weiteren Erhöhung der Temperatur bzw. einer weiteren Verschiebung der befallsfördernden Bedingungen kommen, kann ebenfalls mit einem weiteren Anstieg in der Intensität von STB gerechnet werden.

Die Kontrolle von Schaderregern ist im Weizenanbau, insbesondere in maritimen Klimaten, von entscheidender Bedeutung. Ein Einsatz von Pflanzenschutzmitteln zur Kontrolle dieser Erreger, in diesem Fall von Fungiziden, ist nach heutigem Stand der Forschung unabdinglich. Trotz hervorragender Ausbildung der praktischen Landwirtschaft ist eine Optimierung des Fungizideinsatzes durch Entscheidungshilfesysteme (DSS) möglich. In Kapitel II wurde eine Reduktion von 50% durch den Einsatz von DSS gegenüber der Positivkontrolle (Vierfach-Applikation orientiert an den Entwicklungsstadien der Pflanze) gezeigt. Dazu wurden drei DSS unterschiedlicher Herkunft (Wissenschaft, Offizialberatung, Wirtschaft) auf deren Effizienz in der Kontrolle auftretender Blattkrankheiten über drei Jahre an drei Standorten in zwei Weizensorten evaluiert (**Kapitel IV**). Im Rahmen der Untersuchungen wurde durch alle DSS, verglichen zur Positivkontrolle, der Fungizideinsatz auf ein notwendiges Maß reduziert, ohne dabei Ertragseinbußen hinnehmen zu müssen. Hierdurch wird die Effizienz und die Effektivität biologisch-epidemiologisch basierter Entscheidungshilfen bestätigt. In Anbetracht der politisch angestrebten Reduktion des Einsatzes von Pestiziden um 50% bis 2030 ("Farm to Fork-Strategie" der EU) kann der

Einsatz von DSS als Instrument der Fungizid-Optimierung für die landwirtschaftliche Praxis zukünftig von großer Bedeutung sein.

Ungeachtet der wirtschaftlichen Vorteile des Einsatzes von DSS wird die Nachhaltigkeit der landwirtschaftlichen Produktion durch DSS in dem Sinne verbessert, als dass zum einen Lebensmittel weiterhin in adäquaten Mengen und Qualitäten bereitgestellt werden können und zum anderen Belastungen der Agrarökosysteme verringert werden. Dementsprechend kommt es zur Verbesserung aller drei Nachhaltigkeitsdimensionen durch die Optimierung des Fungizideinsatzes.

EXTENDED MATERIALS & METHODS

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Materials

Table M1 Coordinates and agronomic practices (crop rotation, soil tillage) of the eight regional wheat disease monitoring sites in northern Germany from 1995 to 2021. WW = winter wheat, WB = winter barley, OR = oilseed rape.

Location	Coordinates Latitude Longitude		Crop Rotation	Soil Cultivation
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
Sönke-Nissen-Koog	54°38′01′′ N	08°52′08′′ E	WW-WW-OR	Plough

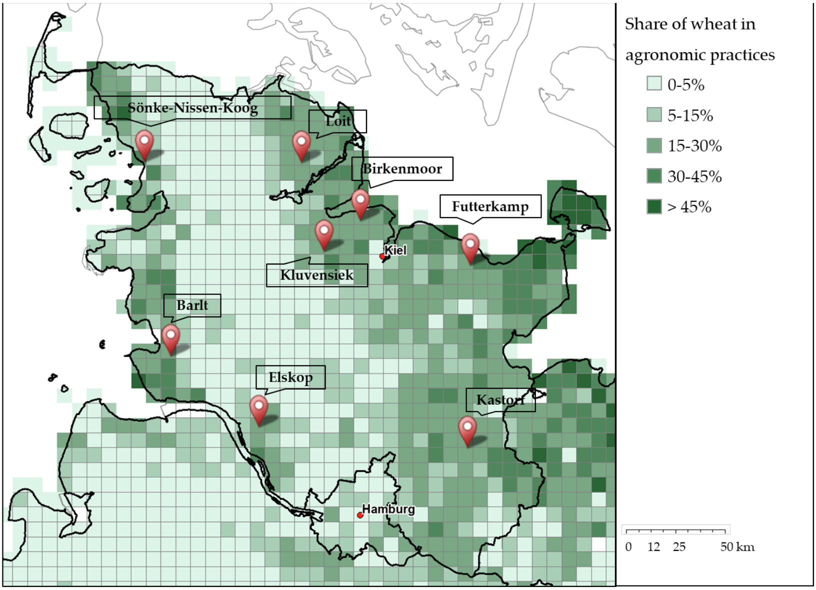

Figure M1. Locations of the long-term survey in combination with the share of Wheat in the survey area of 2020 [1].

Table M2 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)

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

Table M3 Fungicides used in the long-term study from 1995 to 2021.

Fungicde	Max. Dose/ha	Max. a.i/ha	Date of expir.	Compound I	a.i/L	Classific.	Compund II	a.i/L	Classific.	Compund III	a.i/L	Classific
Acanto	1.00	250.0	11/17	Picoxystrobin	250.0	C3 Qol						
Adexar	2.00	250.0	04/20	Fluxapyroxad	62.5	C2 SDHI	Epoxiconazol	62.5	G1 DMI			
Agent	1.00	575.0	06/19	Propioconazol	125.0	G1 DMI	Fenpropidin	450.0	G2 Amine			
Amistar	1.00	250.0	12/24	Azoxystrobin	250.0	C3 Qol						
Ascra Xpro	1.50	390.0	07/23	Fluopyram	65.0	C2 SDHI	Bixafen	65.0	C2 SDHI	Prothioconazol	130.00	G1 DMI
Aviator Xpro	1.25	281.3	07/23	Bixafen	75.0	C2 SDHI	Prothioconazol	150.0	G1 DMI			
Bravo 500	2.00	1.000.0	10/16	Chlorthalonil	500.0	M5 M. s.						
Capalo	2.00	675.0	04/19	Epoxiconazol	62.5	G1 DMI	Fenpropimorph	200.0	G2 Amine	Metrafenone	75.00	U8 M. s.
Ceriax	3.00	449.4	04/20	Fluxapyroxad	41.6	C2 SDHI	Pyraclostrobin	66.6	C3 Qol	Epoxiconazol	41.60	G1 DMI
Champion	1.50	450.0	04/20	Boscalid	233.0	C2 SDHI	Epoxiconazol	67.0	G1 DMI			
Colt	1.00	500.5	12/02	Triadimenol	125.1	G1 DMI	Tridemorph	375.4	G2 Amine			
Credo	2.00	1.200.0	11/17	Picoxystrobin	100.0	C3 Qol	Chlorthalonil	500.0	M5 M. s.			
Diamant	1.75	649.3	04/19	Pyraclostrobin	114.0	C3 Qol	Epoxiconazol	43.0	G1 DMI	Fenpropimorph	214.00	G2 Amine
Eleando	3.00	574.8	04/20	Epoxiconazol	41.6	G1 DMI	Prochloraz	150.0	G2 Amine			
Fandango	1.50	300.0	07/23	Fluoxastrobin	100.0	C3 Qol	Prothioconazol	100.0	G1 DMI			
Flamenco FS	2.30	524.4	01/15	Fluquinconazol	54.0	G1 DMI	Prochloraz	174.0	G2 Amine			
Flexity	0.50	150.0	04/23	Metrafenone	300.0	U8 M. s.						
Folicur	1.00	250.0	08/22	Tebuconazol	250.0	G1 DMI						
Fortress	0.30	75.0	04/19	Quinoxyfen	250.0	E1 Chinol.						
Gladio	0.80	500.0	06/19	Propioconazol	125.0	G1 DMI	Fenpropidin	375.0	G2 Amine	Tebuconazol	125.00	G1 DMI
Input Classic	1.25	575.0	12/22	Prothioconazol	160.0	G1 DMI	Spiroxamine	300.0	G2 Amine			
Input Xpro	1.50	600.0	07/23	Bixafen	50.0	C2 SDHI	Prothioconazol	100.0	G1 DMI	Spiroxamine	250.00	G2 Amine
Juwel	1.00	250.0	04/20	Kres.-methyl	125.0	C3 Qol	Epoxiconazol	125.0	G1 DMI			
Juwel Top	1.00	400.0	04/19	Kres-methyl	125.0	C3 Qol	Epoxiconazol	125.0	G1 DMI	Fenpropimorph	150.00	G2 Amine
Magnello	1.00	350.0	12/25	Tebuconazol	250.0	G1 DMI	Difenoconazol	100.0	G1 DMI			
Opera	1.75	560.9	12/14	Pyraclostrobin	233.0	C3 Qol	Epoxiconazol	87.5	G1 DMI			
Opus Top	1.50	750.0	05/19	Epoxiconazol	125.0	G1 DMI	Fenpropimorph	375.0	G2 Amine			
Orius	1.25	250.0	08/22	Tebuconazol	200.0	G1 DMI						

Fungicde	Max. Dose/ha	Max. a.i/ha	Date of expir.	Compound I	a.i/L	Classific.	Compund II	a.i/L	Classific.	Compund III	a.i/L	Classific
Osiris	3.00	195.0	04/22	Epoxiconazol	37.5	G1 DMI	Metconazol	27.5				
Proline	0.80	200.0	07/23	Prothioconazol	250.0	G1 DMI						
Pronto Plus	1.50	574.5	08/23	Tebuconazol	133.0	G1 DMI	Spiroxamine	250.0	G2 Amine			
Prosaro	1.00	250.0	07/22	Prothioconazol	125.0	G1 DMI	Tebuconazol	125.0	G1 DMI			
Soleil	1.20	328.8	12/25	Tebuconazol	107.0	G1 DMI	Bromuconazol	167.0				
Sportak Delta	1.25	510.0	12/03	Cyproconazol	48.0	G1 DMI	Prochloraz	360.0	G2 Amine			
Stratego	1.00	312.0	08/04	Trifloxystrobin	187.0	C3 Qol	Propioconazol	125.0	G1 DMI			
Talius	0.25	50.0	12/22	Proquinazid	200.0	E1 Chinol.						
Twist	0.50	125.0	12/15	Trifloxystrobin	250.0	C3 Qol						
Unix	1.00	750.0	04/23	Cyprodinil	750.0	D1 Ap Fun.						
Vegas	0.50	375.0	12/20	Cyfluenamid	750.0	U6 Amidox.						
Zenit M	0.75	562.5	12/17	Fenpropidin	750.0	G2 Amine						

Date of expir. = Date of Expiration; Classification according to Fungicide Resistance Action Committee; M.s. = Multisite inhibitors

Methods

This chapter includes protocols for selected key procedures used in this thesis. A comprehensive register of all methods used as well as experimental specifications are included in each chapter, respectively.

Trial design

In each year and at all locations, the field trials were conducted in a fully randomized block design with four replicated blocks containing three different treatments, namely untreated fungicide control, IPM treatment and healthy standard treatment. Using destructive sampling for disease diagnosis throughout the growing season of the untreated control and IPM treatments, the plots of the untreated control and IPM treatments were duplicated to assign the purpose of harvesting and sampling to each plot, resulting in five plots per replicated block. Each field plot was 10 m² (2 × 5 m). At all sites, the field trials were integrated into the farmers' fields. Crop management and the application of herbicides, insecticides and growth regulators were based on good agricultural practice and were carried out in cooperation with the Schleswig-Holstein Chamber of Agriculture.

Fungicide Application

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.

Table M3. 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	ISIP – Disease Control Threshold
Septoria tritici blotch	32 - 69	F-6 to F-0	DI > 50% + 36 hours leaf wetness of > 98%	DI > 30% DI > 10%; + 48 hours leaf wetness
Glume blotch	37 - 39 41 - 47 51 - 69	F-5 or F-4 F-4 or F-3 F-3 or F-2	DI > 12%	DI > 30%

Tan spot	32	F-6 or F-5	DI > 5%	DI > 5%
	33 - 39	F-5 or F-4		
	41 - 49	F-4 or F-3		
	51 - 69	F-3 or F-2		
Powder	30 - 69	F-6 to F-0 *	DI > 70%	DI > 60%
Leaf rust	37 – 69	F-6 to F-0	DI > 30%	DI > 30% or
Stripe	30 – 69	F-6 to F-0	DI > 30% or	DI > 30% or

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

Sampling and Disease Assessment

At weekly intervals from GS 30 to 77, ten main tillers per plot were randomly sampled from three of the four sampling plots for foliar disease analysis of the untreated control and IPM treatments. To assess disease severity, plant samples were analysed macroscopically and microscopically in a defined order. First, the growth stage was determined separately for each site. Simultaneously, each leaf on the main stem was rated for disease incidence and percentage of leaf area affected by the biotrophic foliar diseases, powdery mildew, stripe rust and leaf rust. Leaves were then separated from the main stem and directly assessed for the incidence and percentage of leaf area affected by tan spot. To ensure the highest quality of Septoria tritici blotch and glume blotch assessments, the leaves were soaked in water to simulate leaf wetness, resulting in pycnidia expansion, and thus better visibility of Septoria tritici blotch and glume blotch symptoms. After soaking for at least 5 min, Septoria tritici blotch and glume blotch pycnidia were counted as a quantitative parameter of disease severity under 8- to 50-fold magnification for each individual leaf. The exact disease incidence and severity for each individual leaf layer, date of assessment and location per plant and plot were recorded from the assessment. The scored data were averaged separately for leaf layers F-0 to F-6 after each weekly assessment for each location and stored in an SQL database.

Data Preparation

In order to prepare the data for further analysis and to compare disease severity from year to year, the area under the disease progression curve (AUDPC) of each year from 1995 to 2021 was calculated from all disease severities assessed from F-0 to F-6 from GS 30 to 77 (corresponding to 11 observed weeks in each year) separately as a quantitative summary for each year and site. The trapezoidal method according to Madden et al. 2007 [2] was used to estimate the AUDPC (formula (1))by discretising the time variable and determining the average disease intensity between two adjacent time points For a yield-oriented comparison, the AUDPC was adjusted to the WAUDPC (Weighted AUDPC) by weighting the disease severity separately for each leaf layer with the factors xF-0, x_{F-1}, x_{F-2}, x_{F-3}, x_{F-4}, x_{F-5} and x_{F-6} (formula (2)). However, dividing the WAUDPC by the number of time points (k+1 in formula 3) gives the relative WAUDPC (RWAUDPC), which represents disease severity in realistic terms (formula (3)).

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

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

$$\text{RWAUDPC} = \frac{0.7A_{F-0} + 0.2A_{F-1} + 0.1A_{F-2}}{k+1} \tag{3}$$

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

To compare fungicide use in general and with agronomic practices, the amount of active ingredient (A.I.) and the treatment frequency index (TFI) were determined according to Bürger et al. 2008 [3]. The annual amount of active ingredient was the sum of all active ingredients applied within a year and at the site of the survey. The TFI is the annual summed dose rate proportional to the recommended dose of each fungicide applied. For each year, site and treatment, the TFI was defined as follows:

$$TFI = \sum_i \frac{dose\ rate_i}{standard\ dose_i} \tag{4}$$

where *i* is the application number per year.

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ACKNOWLEDGEMENTS

At this point I would like to express my sincere thanks to all those without whose help and curiosity the writing of this dissertation would not have been possible.

First and foremost, I would like to express my deep gratitude to my supervisor, Professor Dr Joseph-Alexander Verreet, for giving me the invaluable opportunity to work in the fascinating field of Integrated Pest Management. Thank you also for your time, patience, trust, advice, and encouragement over the past years.

I would like to extend my sincere thanks to Dr Tim Birr and Dr Holger Klink. Thank you for your unwavering support and guidance, for the time you have taken to review this thesis and also for the motivation you have both given me during the difficult days. I would also like to express my gratitude for the constructive and extremely valuable revisions of the manuscripts of this thesis. I will always be grateful for your unconditional mentorship.

I would also like to thank Dr Jens Aumann and Brandt Berghuis for proofreading all the manuscripts.

Furthermore, I want to thank Dr Mario Hasler for his excellent statistical advice.

I am pleased to mention that I have had the privilege of working with fantastic colleagues. First of all, I would like to thank all my colleagues in Kiel for the excellent working atmosphere. In particular, I would like to mention Wilken Boie, Jannika Drechsel, Markus Schemmel, Thomas Bergmann, Hendrik Seide and Severin Einspanier. Thank you for your encouragement and support, for your helpful advice, for your friendship and also for the good times we spent together outside the university!

I would also like to thank all the former PhD students who worked on this long-term survey, namely Holger Klink, Christian Busse, Arndt Friedrich Wittrock, Imme Finger, Alke Wittrock, Matthias Henze, Henning Klöhn and Christian Engel, for their consistent evaluation of the epidemiological data by managing the supra-regional field studies.

Furthermore, I would like to thank the Schleswig-Holstein Chamber of Agriculture for the excellent cooperation throughout the study, especially Mathies Müller, Hans Joachim Gläser and Susanne Hagen. I would also like to thank the technical staff at the survey sites for their excellent and persistent work in the fields.

I am also very grateful to Heino Hansen and Dr. Christoph Algemissen for selflessly providing trail locations during the long-term study and for the organisation of the IPS training events on your farms.

I would also like to thank the technical Staff of the Institute. Bettina Bastian, Susanne Kleingarn, Susanne Herrmann, Andrea Ulrich, and Michael Wingen for their sincere and continuous support during my time at the Institute.

I am extremely grateful to the 'Stiftung Schleswig-Holsteinische Landschaft' for funding Integrated Pest Management Schleswig-Holstein and this PhD project for so many years!

Outside the university, I am deeply indebted to all my friends for their unconditional support, listening, care, encouragement, understanding and patience during this long and challenging journey.

Last but not least, my parents and Steffi deserve a special mention for their immense support through the good, bad and very bad days, as well as their constant encouragement and care over the years! Thank you for always being there for me!