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Economics of a decision–support system for managing the main fungal diseases of winter wheat in the Grand-Duchy of Luxembourg

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ABSTRACT

We evaluated the cost effectiveness of a decision–support system (DSS) developed for assessing in real time the risk of progression of the main fungal diseases (i.e., Septoria leaf blotch, powdery mildew, leaf rusts and Fusarium head blight) of winter wheat in the Grand-Duchy of Luxembourg (GDL). The study was conducted in replicated field experiments located in four agricultural locations (representative of the main agro-ecological regions of the country) over a 10-year period (2003–2012). Three fungicide spray strategies were compared: a single DSS-based system and two commonly used spray practices in the GDL, a double- (2T) and a triple-spray (3T) treatment; there was also a non-treated control. In years with a high disease pressure, the DSS-based recommendation resulted in protection of the three upper leaves comparable to that achieved with the 2T and 3T treatments, with significant grain yield increases ($P > 0.05$) compared to the control (a 4 to 42% increase, depending on the site and year). Overall, the financial gain in treated plots compared with the control ranged from 3 to 16% at the study sites. Furthermore, in seasons when dry weather conditions precluded epidemic development, the DSS recommended no fungicide spray, reducing use of fungicide, and thus saving the cost of the product. The gain in yield for the 2T and 3T plots (compared with control) did not necessarily result in a financial gain during the duration of the experiment. This study demonstrates the potential advantages and profitability of using a DSS-based approach for disease management.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is the most important grain crop grown in the Grand-Duchy of Luxembourg (GDL). The area under winter wheat in 2013 was 13,410 ha, with a total production of circa 86,433 metric tons (Ministère de l'Agriculture, 2014). Wheat protection in the GDL largely relies on early fungicide applications before appearance of severe symptoms that might reduce yield. Fungicides are routinely applied to control fungal diseases so as to prevent yield losses due to pathogens, to delay the senescence of the upper leaves or in some cases, to comply with the recommendations from the mill industry, thereby maximising economic returns. Generally, two to three fungicide treatments are applied during crop growth. The first spray is applied early in the season (during stem elongation), and aims to control early season diseases including powdery mildew (WPM, caused by *Blumeria graminis* DC. f. sp. *tritici* em. Marchal) and eyespot (caused by *Pseudocercosporella herpotrichoides* (Fron) Deighton). This fungicide application is often done in combination with herbicide or fertilizer applications. A second fungicide application typically aims to protect the flag leaf from Septoria leaf blotch (SLB, caused by *Zymoseptoria tritici* (Desm.) Quaedvlieg & Crous). Since early-developing epidemics of *Z. tritici* (approximately 245 days after sowing) are more destructive than late epidemics (with epidemic outbreaks around 270 days after sowing (approximately 270 days after sowing), an accurate forecast of infection for early epidemics is of particular concern (Beyer et al., 2012). A third application is sometimes applied at early flowering in order to protect the wheat crop against infection by *Fusarium* head blight (FHB, primarily caused by *Fusarium graminearum* Schwabe). Apart from these targeted fungal diseases, rusts [i.e., leaf rust (WLR) and stripe rust (WSR), caused by *Puccinia triticina* Roberge ex Desmaz. and *P.*

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striiformis Westend, respectively] have become of increasing economic concern over the last decade (El Jarroudi et al., 2009b, 2012b).

Decision–support systems (DSS) based on plant disease forecast models are increasingly used in integrated disease management programs (Knight, 1997; Moreau and Maraite, 2000; Verreet et al., 2000; Wegulo et al., 2011; El Jarroudi et al., 2014b). DSS help by limiting potentially harmful side effects of fungicide applications while ensuring economic benefits (Fabre et al., 2007; Shtienberg, 2013). Indeed, a major incentive in adoption of DSS by farmers is related to the cost advantages over conventional strategies (Wearing, 1988; Langvad and Noe, 2006; Fabre et al., 2007). Decision rules (i.e., tactical models) designed to provide farmers with binary advice ("treatment is needed" or "it is not worth the cost") are considered to be cornerstones for the implementation of DSS in integrated disease management programs (Hughes, 1999; Way and van Emden, 2000; McCown, 2002).

In Europe, including the GDL, the main fungicide groups used to control foliar fungal pathogens of wheat include the strobilurins and triazoles (EUROSTAT, 2007), both of which have a broad spectrum of activity. Chlorothalonil (a nitrile) has multi-site activity and good efficacy against the main pathogen *Z. tritici* (Beyer et al., 2011), and it is used in tank mixtures to delay the emergence of fungicide resistance. Recently, a new generation of succinate dehydrogenase inhibitors with excellent efficacy towards *Z. tritici*, but poor performance against *F. graminearum* (Dubos et al., 2013) and *Fusarium culmorum* (Pasquali et al., 2013), became available. A DSS based on different models for infection and progress was developed and validated for the main fungal diseases in the GDL [e.g., SLB (El Jarroudi et al., 2009a), WPM (El Jarroudi et al., 2011), and WLR (El Jarroudi et al., 2014a,b)]. This DSS determined (1) whether fungicide use was needed at all, and if so determined, (2) the best application time for a single treatment based upon the models' outputs and expert knowledge. Considering public awareness concerning environmental pollution (water quality, ecosystem sustainability, environmental pressure exerted by agriculture, climate change), and the increasing regulatory demand from national and international institutions and policy makers (national governments, non-governmental organisations, The European Commission, etc.), the assessment of the profitability of any crop protection strategy is of great importance. The main objective of this study was to assess the profitability of a single fungicide treatment recommended through the DSS, by protection provided to the three upper leaves of winter wheat, compared with conventional two or three spray fungicide regimes.

2. Materials and methods

2.1. Overview of the decision–support system

The DSS relies on (i) the mechanistic PROCULTURE model to simulate the emergence of the five last leaves as well as the availability of *Z. tritici* inoculum to infect those leaves (Moreau and Maraite, 1999, 2000; El Jarroudi et al., 2009a); (ii) an approach for predicting WLR and WSR infection and progress based on night weather variables (El Jarroudi et al., 2004, 2014a), and (iii) a model for simulating the progress of WPM (El Jarroudi et al., 2011). The inputs used for simulating the infection periods and progress of SLB, WLR, WSR and WPM are hourly meteorological data (i.e. maximum and minimum air temperatures, relative humidity, and rainfall) and observed disease incidence and severity. Meteorological variables were collected during the growing season using automatic meteorological stations located near each study site ($\leq$1 km). The assessment of severity of fungal diseases was conducted weekly throughout the growing season. The need for and timing of the single fungicide spray using the DSS was based on the observed disease severity earlier in the cropping season [i.e., at growth stages (GS) 31–37 (Zadoks et al., 1974), or on the lower leaves L5–L4, L1 being the flag leaf], the susceptibility of the cultivars, past and forecasted weather conditions, and the predicted development of leaves based on the output of the PROCULTURE model. Furthermore, historical data (weather and disease incidence and severity) were used as a basis for similarity analysis to further evaluate the risk of severe disease development. Given a threshold level of observed disease severity (on the lower leaves) and weather conditions (actual and forecasted), an advice for fungicide treatment was taken and fungicides applied if required to protect the upper leaves. For example, for 5% emergence of L3 coinciding with SLB symptoms on L5 and a rainfall event, there is an increased risk that L3 will become diseased with SLB by full emergence. Thus a fungicide treatment for SLB is recommended if 75% of a latency period is completed combined with favourable weather conditions forecasted. When different fungal diseases are observed, the relative importance in severity of each of the diseases is first evaluated. A combined treatment (i.e. tank mixtures) is recommended for protecting the upper leaves against the predominant diseases, if required. For example, if SLB and WLR are observed on L5 at the emergence of L3, or moderate to high severity of SLB is observed on L5, associated with at least 5% severity of WLR on L3, a tank mixture (triazoles and strobilurins in this case) is advised and should be applied to susceptible cultivars when forecasted weather is favourable for disease. If different diseases develop at different times, or there is a second outbreak, a risk assessment is made based on the field management practices (previous crop), the susceptibility of the cultivar to the disease, and historical examples, taking into account any effect of the remaining fungicide from the first application. If there is a high risk of the new disease outbreak affecting grain yield, a second fungicide treatment may be advised (thus in this situation two treatments will be recommended using the DSS).

2.2. Experimental fields and data collection

Experiments were carried out in fields of winter wheat at four locations in the GDL [Burmerange (50°3′N, 6°1′E), Christnach (49°47′N, 6°15′E), Everlange (49°29′N, 6°19′E), and Reuler (50°11′N, 5°15′E)] during the 2003–2012 growing seasons. Agronomic details of the trials are given in Table 1. The experimental design was a complete randomized block with four replicates (one replicate plot = 12 m^2). Each fully randomized replicate block consisted of fungicide treated and non-treated (control) plots. The different fungicides applied, and the wheat GS when treated (each treatment was associated with a specific GS) are given in Table 2. The GS were assessed according to the Zadoks' decimal code (Zadoks et al., 1974). The fungicides used were commercially available and applied according to the manufacturer's recommendations. Crop management (sowing and harvest methods, fertilisation and weed control) was done as described previously (El Jarroudi et al., 2009a, 2012a).

During the 2003–2012 cropping seasons, two to three fungicide treatments were tested at each site (Table 2). They included a single DSS-based treatment, a double (2T) spray treatment, and a triple (3T) spray treatment. The 2T and 3T treatments represent common practice for fungicide use in winter wheat in the GDL (Guy Reiland, Personal comm.). Note that 3T was included after the 2005 cropping season in order to protect the wheat crop against infection by FHB and was not tested during the 2003–2005 period.

The meteorological data, recorded at 10 min intervals, were automatically retrieved from a web-based database system (www.agrimeteo.lu) and processed using an automatic data processing chain for quality check and gap filling. As hourly intervals were needed for running the disease forecast models, the 10-min

Table 1
Agronomic information for the winter wheat fields used at the four experimental sites in the Grand Duchy of Luxembourg, 2003 to 2012.

Locations	Year	Cultivar	Sowing date	Previous crops	Nitrogen (kg N ha^{-1})	Harvest date
Burmerange	2003	Dekan	4 Oct. 2002	Oilseed rape	185	11 Jul. 2003
	2004	Cubus	1 Oct. 2003	Oilseed rape	185	2 Aug. 2004
	2005	Cubus	13 Oct. 2004	Oilseed rape	185	4 Aug. 2005
	2006	Cubus	30 Sep. 2005	Oilseed rape	192	19 Jul. 2006
	2007	Cubus	11 Oct. 2006	Oilseed rape	192	26 Jul. 2007
	2008	Cubus	6 Oct. 2007	Oilseed rape	228	5 Aug. 2008
	2009	Cubus	6 Oct. 2008	Oilseed rape	228	29 Jul. 2009
	2010	Cubus	1 Oct. 2009	Oilseed rape	228	6 Aug. 2010
	2011	Cubus	1 Oct. 2010	Oilseed rape	228	4 Aug. 2011
	2012	Cubus	14 Oct. 2011	Maize	228	3 Aug. 2012
Christnach	2003	Flair	2 Oct. 2002	Oilseed rape	200	23 Jul. 2003
	2004	Flair	13 Oct. 2003	Oilseed rape	200	12 Aug. 2004
	2005	Rosario	27 Oct. 2004	Maize	200	2 Aug. 2005
	2006	Flair	12 Oct. 2005	Maize	200	25 Jul. 2006
	2007	Tommi	12 Oct. 2006	Maize	200	26 Jul. 2007
	2008	Flair	23 Oct. 2007	Maize	200	5 Aug. 2008
	2009	Boomer	23 Oct. 2008	Maize	200	7 Aug. 2009
	2010	Cubus	15 Oct. 2009	Oilseed rape	200	23 Aug. 2010
	2011	Event	15 Oct. 2009	Oilseed rape	200	19 Aug. 2011
	2012	Matrix	7 Oct. 2011	Maize	200	15 Aug. 2012
Everlange	2003	Achat	4 Oct. 2002	Oilseed rape	165	19 Jul. 2003
	2004	Achat	14 Oct. 2003	Oilseed rape	195	6 Aug. 2004
	2005	Akteur	22 Oct. 2004	Oilseed rape	190	2 Aug. 2005
	2006	Achat	10 Oct. 2005	Fallow	225	7 Aug. 2006
	2007	Achat	10 Oct. 2006	Pea	195	26 Jul. 2007
	2008	Tommi	8 Oct. 2007	Fallow	195	5 Aug. 2008
	2009	Privileg	13 Oct. 2008	Oilseed rape	195	6 Aug. 2009
	2010	Achat	15 Oct. 2009	Oilseed rape	195	7 Aug. 2010
	2011	Achat	15 Oct. 2010	Oilseed rape	195	6 Aug. 2011
	2012	Achat	18 Oct. 2011	Oilseed rape	195	5 Aug. 2012
Reuler	2003	Flair	6 Nov. 2002	Oilseed rape	213	5 Aug. 2003
	2004	Bussard	16 Oct. 2003	Oilseed rape	200	16 Aug. 2004
	2005	Flair	5 Oct. 2004	Oilseed rape	200	13 Aug. 2005
	2006	Dekan	13 Oct. 2005	Maize	200	8 Aug. 2006
	2007	Akteur	7 Oct. 2006	Maize	200	3 Aug. 2007
	2008	Schamane	10 Oct. 2007	Oilseed rape	200	14 Aug. 2008
	2009	Schamane	10 Oct. 2008	Oilseed rape	200	18 Aug. 2009
	2010	Manager	28 Oct. 2009	Oilseed rape	200	23 Aug. 2010
	2011	Arktis	28 Oct. 2009	Oilseed rape	200	20 Aug. 2011
	2012	Arktis	15 Oct. 2011	Oilseed rape	200	18 Aug. 2012

measurements were resampled to provide an hourly resolution (Junk et al., 2008). In addition, from the beginning of the disease monitoring period, the forecasted weather conditions (over the following seven days) were provided weekly by the Centre de Recherche Public-Gabriel-Lippmann, Luxembourg.

Assessments of the main fungal diseases were made weekly from GS 29–30 to GS 85. Estimates of disease severity (% of leaf area diseased) were made on the same 10 plants in the control plots throughout the growing season, and bi-weekly on 10 randomly selected plants in each of the treated plots after applying the DSS treatment. Disease estimates were made to minimize errors by training raters using standard area diagrams (James, 1971) and disease assessment software (DISTRAIN, Tomerlin and Howell, 1988), and ensuring the same raters assessed the same experiments in each season (El Jarroudi et al., 2014c).

2.3. Analysis of the impact of fungicide sprays on grain yield

The winter wheat was harvested in mid-July in southern Luxembourg (Burmerange) and in the beginning of August at the other sites (Table 1). The marketable yield (Y_g, the total weight of grain) for each plot was determined automatically during the harvest in the field using an automated reaper (Wintersteiger AG, Austria), which has an overall accuracy ± 100 g. Humidity content (H, expressed in %) of the grain was determined in the laboratory on a sample of 500 g for each plot. The net grain yield for each plot (Y_n) was calculated at 14% humidity (typical humidity percentage in marketed winter wheat in the GDL) as follows:

$$Y_n = \frac{(1-H)\,Y_g}{0.86} \tag{1}$$

For each cropping season we calculated the difference between the yields (average net grain yield of the four repetitions) of fungicide treatment (i.e., DSS-based, 2T and 3T) and the control.

2.4. Assessment of the economic impact of different fungicide treatments

The economic impact of the different fungicide treatments focused on analysis over the whole study period. Thus, the financial return of each of the fungicide treatment strategies, including that of the control, was calculated as follows:

$$R_n = Y_N \times P - (F_c + A_c) \tag{2}$$

where R_n is the financial return (€ ha^{-1}); Y_N refers to the average Y_n of the four repetitions for a given treatment (dt ha^{-1}, 1 dt ha^{-1} = 0.1 t ha^{-1}); P is the wheat price (€ dt^{-1}); F_c is the fungicide cost (€ ha^{-1}), and A_c is the field fungicide application cost (fixed at 15 € ha^{-1} during the study period).

The financial gain was then determined as the difference between the financial return of a given fungicide treatment (DSS-based, 2T and 3T) and the control. Fungicide application and fungicide costs involved in the calculation of financial returns

Table 2

Wheat growth stages (Zadoks et al., 1974), fungicides (commercial brands and rates), and costs of fungicides used in the field experiments in the Grand-Duchy of Luxembourg (2003–2012), and wheat prices over the same period.

Year	Treatment[a]	Growth stage (GS) at fungicide application	Fungicide[b]	Fungicide cost/unit (€ ha^{-1})	Total fungicide cost (€ ha^{-1})	Wheat price (€ dt^{-1})
2003	DSS-based	R[c]	1.50 l ha^{-1} Opera®	111.4	111.4	10.3
	2T	GS 31	1.50 l ha^{-1} Sphere®	97.3	132.9	
		GS 59	1.00 l ha^{-1} Horizon®	35.6		
2004	DSS-based		1.50 l ha^{-1} Opera®	111.4	111.4	10.3
	2T	GS 31	0.75 l ha^{-1} Opera®	55.7	111.4	
		GS 59	0.75 l ha^{-1} Opera®	55.7		
2005	DSS-based	NR[d]				11.6
	2T	GS 31	0.75 l ha^{-1} Opera®	55.7	111.4	
		GS 59[a]	0.75 l ha^{-1} Opera®	55.7		
2006	DSS-based	R	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9	81.9	15.3
	2T	GS 31	0.75 l ha^{-1} Opus team® + 1.00 l ha^{-1} Bravo®	31.5	113.4	
		GS 59[a]	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	25.1	138.5	
		GS 37	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9		
		GS 59	0.75 l ha^{-1} Opus team® + 1.00 l ha^{-1} Bravo®	31.5		
2007	DSS-based	R	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9	81.9	26.0
	2T	GS 31	0.75 l ha^{-1} Opus team® + 1.00 l ha^{-1} Bravo®	31.5	113.4	
		GS 59[a]	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9		
	3T	GS 31	0.70 l ha^{-1} Stereo + 1.00 l ha^{-1} Bravo®	25.1	138.5	
		GS 37	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9		
		GS 59	0.75 l ha^{-1} Opus team® + 1.00 l ha^{-1} Bravo®	31.5		
2008	DSS-based	R	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9	81.9	14.5
	2T	GS 31	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9	160.4	
		GS 59[a]	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	189.3	
		GS 37	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9		
		GS 59	1.5 l ha^{-1} Swing Gold® + 1 l ha^{-1} Bravo®	58.5		
2009	DSS-based	R	1.6 l ha^{-1} Input® pro set + 1 l ha^{-1} Bravo®	81.9	81.9	13.1
	2T	GS 31	0.75 l ha^{-1} Opera® + 0.8 l ha^{-1} Input® pro set + 1 l ha^{-1} Bravo®	101.9	160.4	
		GS 59[a]	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	189.3	
		GS 37	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9		
		GS 59	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
2010	DSS-based	NR				20.0
	2T	GS 31	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9	160.4	
		GS 59[a]	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	189.3	
		GS 37	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo	101.9		
		GS 59	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
2011	DSS-based	R	1.50 l ha^{-1} Swing Gold + 1.00 l ha^{-1} Bravo®	58.5	58.5	21.5
	2T	GS 31	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9	160.4	
		GS 59[a]	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	189.3	
		GS 37	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9		
		GS 59	1.50 l ha^{-1} Swing Gold + 1.00 l ha^{-1} Bravo®	58.5		
2012	DSS-based	R	1.60 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	81.9	81.9	24.4
	2T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	87.4	
		GS 59[a]	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		
	3T	GS 31	0.70 l ha^{-1} Stereo® + 1.00 l ha^{-1} Bravo®	28.9	189.3	
		GS 37	0.75 l ha^{-1} Opera® + 0.80 l ha^{-1} Input® pro set + 1.00 l ha^{-1} Bravo®	101.9		
		GS 59	1.50 l ha^{-1} Swing Gold® + 1.00 l ha^{-1} Bravo®	58.5		

The cost of a fungicide application was fixed at 15 € ha^{-1} during the study period as per the average cost in the Grand-Duchy of Luxembourg over the same period. Fungicide costs and wheat prices were communicated by Mr. Guy Reiland (Lycée Technique Agricole, Ettelbruck) based on the annual surveys of Luxembourgish farmers.

[a] DSS-based: Decision support system; 2T and 3T: double and triple fungicide treatments, respectively.

[b] The products Opera®, Input® pro set, Bravo®, Opus team®, Stereo®, and Swing Gold® contain the active ingredients epoxiconazole (50 g/l) + pyraclostrobin (133 g/l), prothioconazole (250 g/l) + spiroxamine (500 g/l); chlorothalonil (500 g/l); epoxiconazole (84 g/l) + fenpropimorph (250 g/l); cyprodinil (250 g/l) + propiconazole (62.5 g/l); epoxiconazole (50 g/l) + dimoxystrobine (133 g/l), respectively.

[c] R: DSS-based treatment recommended. See details in Table 3 for each site.

[d] NR: No DSS-based treatment recommended.

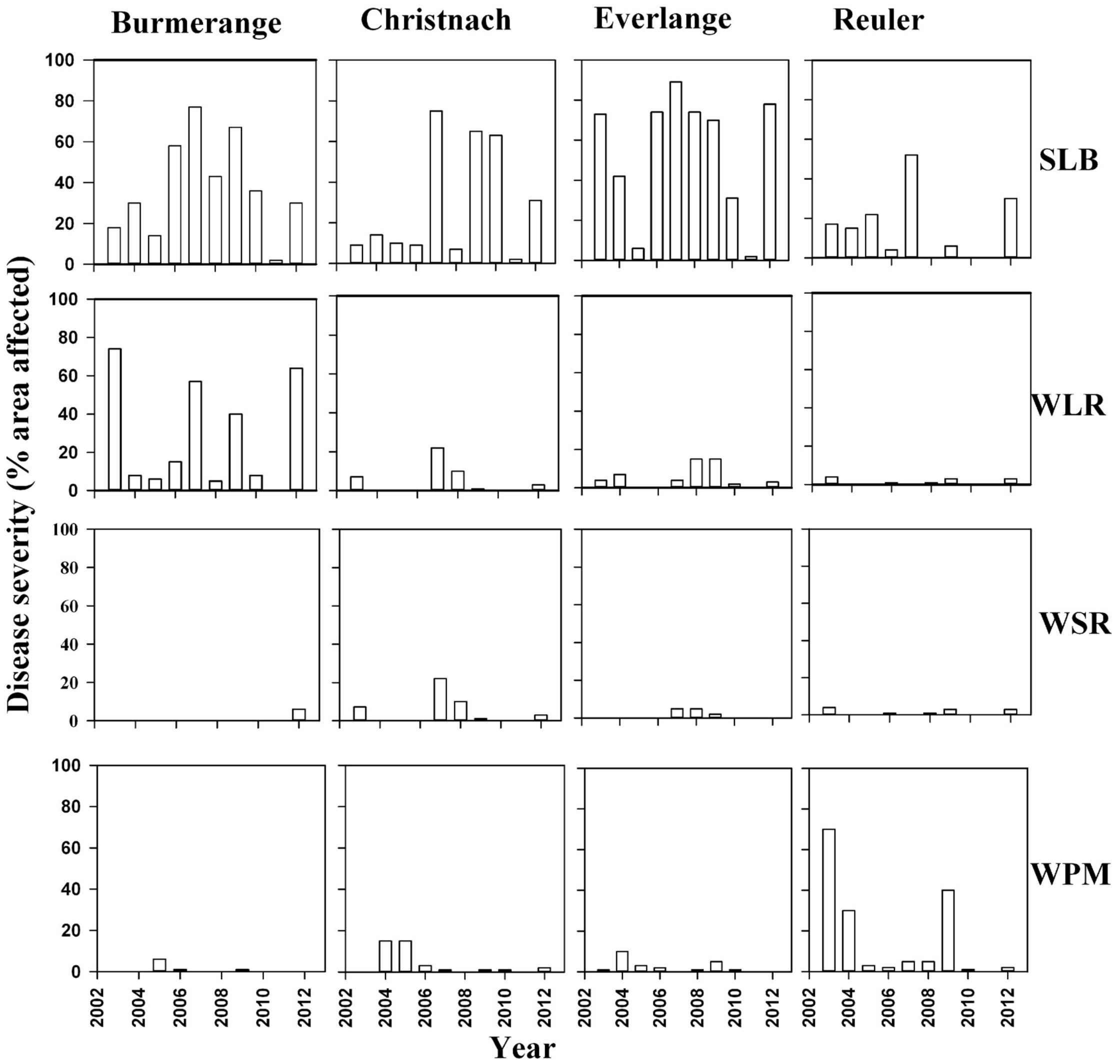

Fig. 1. Mean disease severity of Septoria leaf blotch (SLB), wheat leaf rust (WLR), wheat stripe rust (WSR), and wheat powdery mildew (WPM) between GS 77 and GS 87 (Zadoks et al., 1974) at four experimental sites in the Grand-Duchy of Luxembourg over the 2003–2012 period. The mean value was calculated on the two upper leaves L1 and L2, L1 being the flag leaf.

(Table 2) were provided by the Lycée Technique Agricole in Ettelbruck, GDL. Wheat prices (Table 2) were provided by the Administration des Services Techniques de l'Agriculture, GDL. In our analysis, machinery and machinery maintenance costs, as well as other costs related to fertilisation and weed control, were omitted because they could be considered the same across all plots.

2.5. Statistical analysis

All analyses were done in SAS® V9.2 (SAS Institute Inc., Cary, NC) or MS Excel (Microsoft, Redmond, WA). The replicate effects on grain yield and financial return at each location and year were subjected to analysis of variance (ANOVA) using the PROC GLM procedure. To assess the effects of year and fungicide treatment on winter wheat grain yield the PROC GLM procedure was run for the entire 2003–2012 period considering 3 years (2003–2005) of missing data for the 3T. This was found acceptable to summarize the results in Table 4 since independent analyses for the 2003–2005 and 2006–2012 periods yielded the same statistical conclusions (data not shown). PROC UNIVARIATE was used to determine the outliers based on residuals. Outliers were excluded based on residual values compared to the other values observed. The number of outliers removed from the analysis ranged from 0 to 2 depending on the experiment site. All outliers corresponded to low yield values from plots with harvested areas lower than the average (small harvested areas most often due to wind damage). Grain yield and financial gain were considered dependant variables, and year and fungicide treatment were independent variables. A Tukey's post hoc means separation test ($\alpha = 0.05$) was used to compare the means. Any pairwise P-values < 0.05 (2-sided) were considered significant.

3. Results

3.1. Fungal disease severities and fungicide spray recommendations

Data (2003–2009 period) on the severity of fungal diseases were published previously by El Jarroudi et al. (2012b) and will not be described in detail. The severity of the main fungal diseases (i.e., SLB, WLR, WSR, and WPM) on the two upper leaves (in control plots) between GS 77 and GS 87 revealed that the disease pressure varied according to the disease involved, site and year (Fig. 1). Significant differences in severity among all diseases between the four sites and between years ($P < 0.05$) was observed. SLB was the most prevalent and important disease with the highest severity occurring in 2007 at all experimental sites (a mean of 70% leaf area

Table 3
Fungicide treatment recommendations based solely on the Decision support system (DSS) at each of the four experimental sites in the Grand-Duchy of Luxembourg during the 2003–2012 period (the growth stage and the date of the fungicide spray are indicated when the treatment is recommended).

Year	Burmerange		Christnach		Everlange		Reuler		Total of recommendations	
	Status	Date	Status	Date	Status	Date	Status	Date	NR[a]	T[b]
2003	GS 59[c]	27 May	NR		GS 59	2 June	GS 37	27 May	1	3
2004	NR		GS 45	2 June	GS 45	2 June	NR		2	2
2005	NR		NR		NR		NR		4	0
2006	GS 37	11 May	NR		GS 37	16 May	NR		2	2
2007	GS 45	15 May	GS 59	23 May	GS 37	3 May	GS 45	24 May	0	4
2008	NR		GS 37	20 May	NR		GS 45	30 May	2	2
2009	GS 45	27 May	GS 37	13 May	GS 37	13 May	NR		1	3
2010	GS 59	2 June	GS 40	2 June	GS 45	2 June	NR		1	3
2011	GS 69	9 June	GS 67	9 June	GS 67	9 June	NR		1	3
2012	GS 42	25 May	GS 40	25 May	GS 40	25 May	GS 37	25 May	0	4
Total									14	26

[a] NR: no fungicide treatment recommended by the DSS.
[b] T: Treated (i.e. a single DSS-based fungicide treatment applied).
[c] DSS-based treatment recommended and applied at a specified plant growth stage (GS).

diseased recorded between GS 77 and GS 87 on the two upper leaves in 2007, Fig. 1). In addition, the most frequent incidence and severity of WLR was recorded namely at Burmerange; while Reuler had the lowest incidence and severity, but the highest incidence and severity of WPM. At the other sites the severity of WPM did not exceed 20% leaf area diseased between GS 77 and GS 87 (Fig. 1). The severity of FHB (% of infected grains by spike) was highest in 2007 and 2008 with a mean severity of 21% and 13% across the experimental sites, respectively (with a predominance at the Everlange and Christnach locations). FHB was not severe in the other seasons.

Over all 40 experiments (four sites × 10 years), a single fungicide treatment was advised based on the DSS in 65% of the time; conversely, 35% of the time no treatment was recommended (Table 3). At all sites receiving DSS advised treatment, even in years with severe SLB symptoms (2007), only the single fungicide application was made. However, in the 2005 cropping season no DSS-based treatment was recommended at any site despite the presence of fungal diseases at early crop development stages. These were not considered as threatening crop yield by the DSS because of a series of sequential forecasts for sunny and dry weather for the remaining of the 2005 cropping season. The 2T was not profitable in 2005 (see below in Section 3.4) and therefore the DSS, including weather forecast (Junk et al., 2008), appeared sensitive enough to tackle the relation between disease severity at early stages and risks of disease progress in terms of yield losses. Of the four sites, Reuler had the fewest occasions with DSS-advised treatment (6 out of 10 years, Table 3).

Overall, the latest timing of the DSS-based fungicide application was GS 59 at all sites over the 10-year period, except in 2011 when the DSS-based treatment was applied at GS 67–69 at Burmerange, Christnach and Everlange to protect the crop against SLB and an outbreak of WLR, and avoid the consequent effects on grain yield.

3.2. *Comparisons of grain yield during the 2003–2012 period*

The highest grain yield at each site was recorded in 2004 at Burmerange, Christnach and Everlange, and in 2005 at Reuler. The grain yield was lowest in 2012 at all sites. Overall, Burmerange had the highest grain yields: with 70% greater yield compared with the mean yield of all sites and years. Everlange and Reuler had the lowest annual yields (Fig. 2).

For each site, the effect of year and fungicide treatment on grain yield and financial return was analysed separately for (i) the years when the DSS recommended treatment (comparing the three fungicide treatment strategies DSS-based, 2T and 3T to the control), and (ii) years when it was not recommended (comparing the two fungicide treatment strategies 2T and 3T to the control).

Comparing all three treatment strategies, the ANOVA (Table 4) showed significant year and fungicide treatment main effects over the study period on grain yield at all locations ($P \leq 0.0001$ to 0.0003), with a significant year × fungicide treatment interaction only at Burmerange ($P = 0.016$). However, in years when no DSS-based treatment was recommended, the two-treatment strategies showed no fungicide treatment or interaction (year × fungicide treatment) effects on grain yield at any sites except Christnach (where only the fungicide treatment effect was significant, $P = 0.015$). This result suggests the DSS is a highly effective tool for recommending fungicide sprays throughout the agricultural region of the GDL. The Reuler site was unique over the study period in years when no DSS-based treatment was recommended, as there was no significant effect of year, fungicide treatment or their interaction on grain yield ($P > 0.05$).

3.3. *Year by year comparisons of grain yield at each study location*

At all sites for years with fungicide treatment recommended by the DSS, a significant difference was observed in wheat grain yield between the control and the treated plots in 17 out of 26 situations ($P < 0.05$, Table 5). However, in some cropping seasons when the DSS-based recommendation was applied (Table 3), no difference was noted in the mean grain yield of the control and treated plots. These years were 2003 and 2010, 2008–2011, and 2009–2012 for Burmerange, Christnach, and Everlange, respectively. The comparisons among treated plots for years with DSS-based recommendation showed that most often there was no significant difference between the 2T or 3T treatment strategies at all sites, except Christnach in 2007 (where there was a significant difference between the DSS-based and 2T and 3T treated plots, $P < 0.05$).

3.4. *Profitability of the decision support system (DSS)*

The overall ranges of gain in grain yield due to fungicide treatment were 1 to 81%, 3 to 52%, 3 to 28% and 2 to 45%, respectively, for Burmerange, Christnach, Everlange and Reuler; the highest gains being recorded in the 3T treated plots (Fig. 3). Irrespective of the site, the use of the DSS-based recommendation most often resulted in a grain yield gain over the control during the 10-year period, except at the Christnach site in 2011. Gains in grain yield using

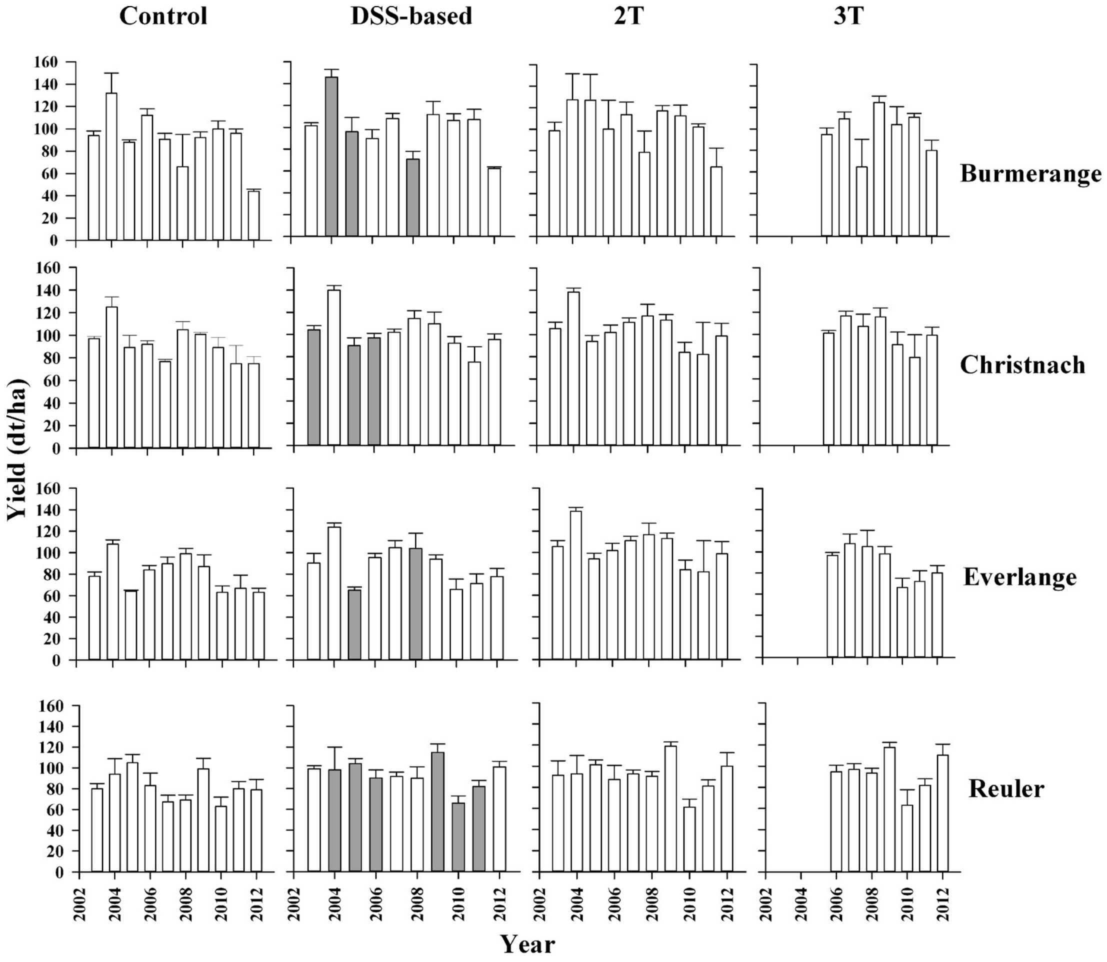

Fig. 2. Mean winter wheat grain yields (white columns) for control, DSS-based, double- (2T) and triple- (3T) fungicide treated plots at four experimental sites in the Grand-Duchy of Luxembourg over the 2003–2012 period. Error bars represent the standard deviation. The triple fungicide treatment was included from 2005–2006 cropping season onwards. The grey columns for the DSS-based strategy corresponded to yields obtained in years when no treatment was recommended (see Table 3). The yield was calculated at 14% humidity. Note: 1 dt ha^{-1} = 0.1 t ha^{-1}.

the DSS-based recommendation varied from 6 to 42%, 3 to 33%, 5 to 23%, and 23 to 37% on average at Burmerange, Christnach, Everlange and Reuler, respectively (Fig. 3). Similar trends were observed for the 2T and 3T treatments. However, the ANOVA using yield gain as a dependant variable revealed no significant differences between the three fungicide strategies at any site, except for Christnach in 2007 (significant difference between the DSS-based and 3T treated plots, $P < 0.05$). In years when no DSS-based

Table 4

General linear model (GLM) analysis of the effects of year and fungicide treatment on winter wheat grain yield during the 2003–2012 period at each of four experimental sites in the Grand-Duchy of Luxembourg (the analysis was performed separately on data including years when the decision support system (DSS) based treatment was recommended and years when it was not).

Site	Effect	Years when a DSS-based treatment was recommended			Years when no DSS-based treatment was recommended		
		DF[a]	*F*-value	*Pr* > *F*[b]	DF	*F*-value	*Pr* > *F*
Burmerange	Year	6	59.83	<0.0001	2	12.13	0.0005
	Treatment	3	23.45	<0.0001	2	0.04	0.958
	Year × treatment	16	2.11	0.016	2	1.01	0.383
Christnach	Year	6	46.05	<0.0001	2	5.15	0.01
	Treatment	3	12.54	<0.0001	2	5.77	0.015
	Year × treatment	17	1.69	0.062	2	0.55	0.582
Everlange	Year	7	75.35	<0.0001	1	87.1	< 0.0001
	Treatment	3	17.91	<0.0001	2	1.09	0.361
	Year × treatment	19	0.76	0.74	1	1.14	0.302
Reuler	Year	3	7.65	0.0003	5	35.94	0.138
	Treatment	3	33.64	<0.0001	2	2.06	0.138
	Year × treatment	8	0.65	0.73	8	1.13	0.358

[a] Degrees of freedom.

[b] *Pr* > *F* indicates the probability that the *F*-value for the model is significant. *P*-values < 0.05 were considered significant.

Table 5

General linear model (GLM) analysis of the effects of fungicide treatment on winter wheat grain yield by experimental site and year during the 2003–2012 period in the Grand-Duchy of Luxembourg. During the 2003–2005 period, only one to two fungicide strategy (i.e., DSS-based and double fungicide treatment) were analysed, along with the control. The triple fungicide treatment was included from 2005 to 2006 cropping season onwards.

Site	Burmerange			Christnach			Everlange			Reuler		
Year	DF[a]	*F*-value	*Pr* > *F*[b]	DF	*F*-value	*Pr* > *F*	DF	*F*-value	*Pr* > *F*	DF	*F*-value	*Pr* > *F*
2003	2	1.56	0.262	1	8.94	0.024	2	8.72	0.008	2	4.62	0.042
2004	1	0.96	0.371	2	18.30	0.0007	2	14.92	0.001	1	0.01	0.932
2005	1	0.78	0.411	1	0.47	0.52	1	1.37	0.286	1	0.67	0.443
2006	3	7.12	0.005	2	6.73	0.016	3	9.69	0.002	2	1.10	0.373
2007	3	7.10	0.005	3	105.02	<0.0001	3	5.71	0.012	3	30.70	<0.0001
2008	2	0.05	0.951	3	1.56	0.251	2	1.00	0.407	3	10.47	0.001
2009	3	13.93	0.0003	3	3.20	0.063	3	3.32	0.057	2	10.62	0.004
2010	3	0.90	0.469	3	0.51	0.685	3	0.50	0.689	2	0.05	0.949
2011	3	4.87	0.019	3	0.10	0.956	3	0.22	0.879	2	0.15	0.859
2012	3	5.64	0.030	3	9.09	0.002	3	2.91	0.078	3	7.00	0.006

[a] Degrees of freedom.

[b] *Pr* > *F* indicates the probability that the *F*-value for the model is significant. *P*-values < 0.05 were considered significant.

treatment was recommended at Burmerange (see Table 3 and indicated on Fig. 3), the 2T treatment assured a yield gain only in 2005 and 2008, while the 3T treatment (2008) did not ensure a yield gain (Fig. 3). At Christnach and Everlange, all the 2T and 3T treatments led to a yield gain in those years when no DSS-based treatment was recommended. These gains compared to the control ranged from 3% to 11% for both sites in 2005 and 2008. At Reuler no yield gain was observed in 2006 and 2010 with the 2T treatment, and no noticeable gain (gain $\leq$ 3%) was observed in 2010 and 2011 with the 3T treatment. Slight losses (<2%) in yield compared with the control were observed in 2T treated plots in 2004 at Burmerange, in 2010 at Christnach, and in 2005 and 2010

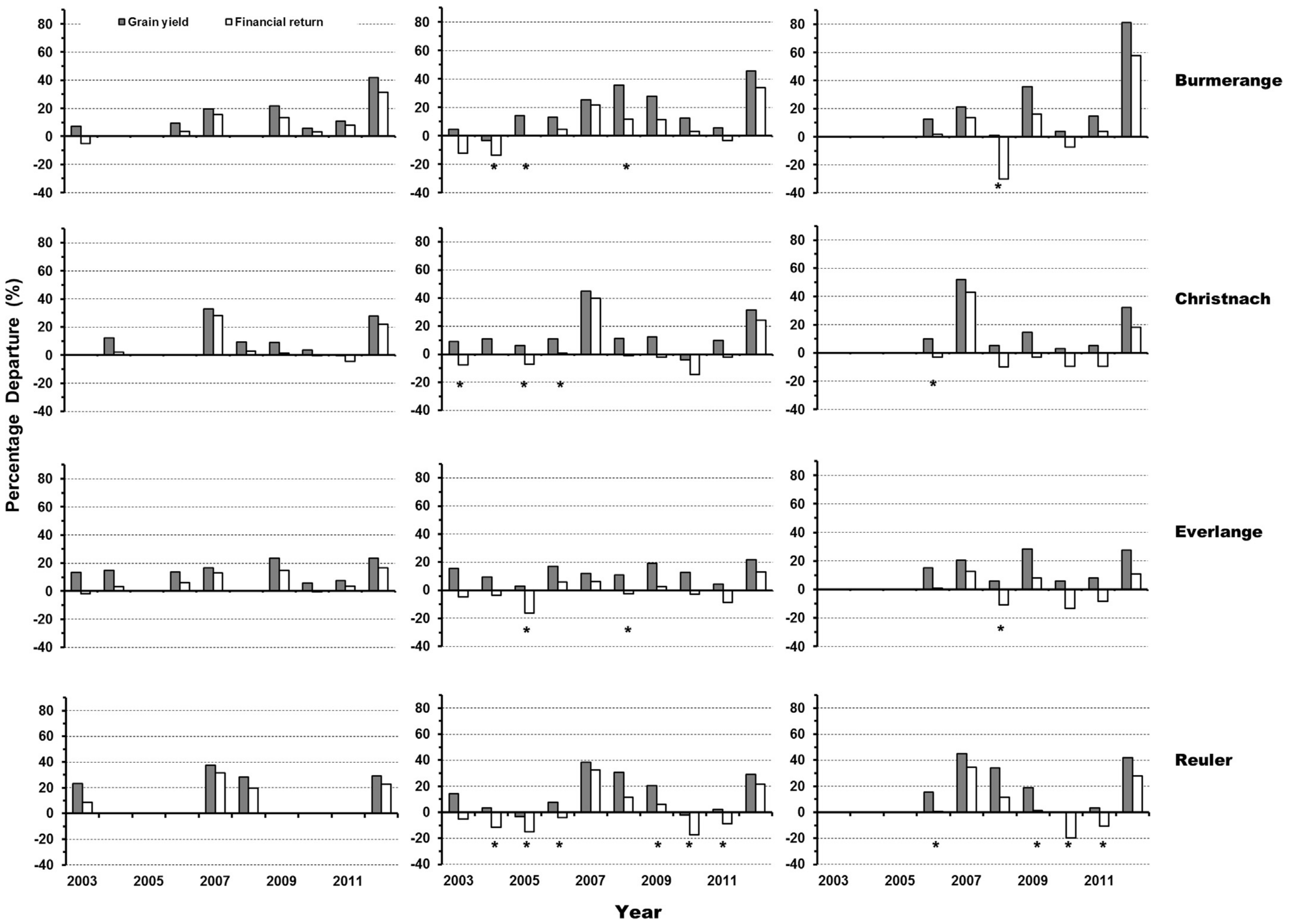

Fig. 3. Mean percentage departure of winter wheat grain yield (grey bars) and financial return (white bars) between the fungicide-treated and control plots at four experimental sites in the Grand-Duchy of Luxembourg over the 2003–2012 period. Negative values indicate that the fungicide treatment was not profitable. DSS-based, 2T and 3T refer to the single decision support system based-fungicide treatment, and the double and triple fungicide treatments, respectively. The missing bars in the DSS-based figures (left column) correspond to years with no DSS-based fungicide treatment recommended (corresponding years indicated by an asterisk for 2T and 3T related graphs). There were no 3T plots during the 2003–2005 growing seasons.

at Reuler. The overall yield gains in treated plots at all sites during the study period suggest that those losses might be related to undefined factors linked to field-scale experiments such as wind damages. Additionally, in years when no DSS-based treatment was recommended, the grain yield in these DSS-based untreated plots did not differ significantly from that observed in the control plots ($P > 0.05$, Fig. 2), as might be expected.

With respect to the financial return, the maximum gains over the study period were ≤58%, 43%, 17% and 34% for the Burmerange, Christnach, Everlange, and Reuler sites, respectively (Fig. 3). Regardless of the site, following the DSS-based recommendations resulted in a financial gain at all sites over the 2003–2012 period, except in 2011 at Christnach and in 2003 at Burmerange and Everlange. At Reuler, the DSS-based recommendations resulted in a financial gain in the four years when it was used (as did the 2T, except in 2003, and 3T treatments). Slight (≤3%) to relatively important (>10%) financial losses were observed in 2T and 3T treated plots at all sites during the study period, with the largest financial loss being 30% recorded in 2008 for the 3T plots at Burmerange. In years when no DSS-based treatment was recommended (see Table 3 and indicated on Fig. 3), the financial gain in fungicide treated plots was contrasted according to the year and site. Financial gains were observed only in 2009 at Reuler for the 2T and 3T treatments (a 1 to 5% increase, respectively, when compared with the control), and for the 2T treatment at Christnach in 2006 and at Burmerange in 2008 (∼1% and 12% increase, respectively, when compared with the control). An overall picture of the financial return at all sites during the study period revealed that in 33% to 60% and 30% to 70% of cases, there was a financial loss in the 2T and 3T treated plots, respectively. The gain in yield in those treated plots did not necessarily result in a financial gain. Particularly at Christnach and Everlange, in two to five years out of the seven years financial losses were recorded for 3T (Fig. 3). Such losses could be related to the application timing and/or its effectiveness in controlling the main diseases using a systematic scheduled spray approach, and possibly to the side-effects of their application (e.g. perturbation of reproductive organ development, alteration of nitrogen metabolism, etc.) eventually leading to a low yield gain and a financial loss.

4. Discussion

The European Union issued a directive (directive 2009/128/CE; Commission Européenne, 2009) that requires the member states to set up advice, training and scientific support for growers to ensure a healthy, sufficient and consistent food supply, which also limits potentially harmful side effects of pesticide applications. Optimising fungicide sprays by risk analysis and early warning systems is thus of great importance. The profitability of a crop protection strategy for diseases depends on various factors, namely the basic biological parameters of the pathosystem, the technical details of management tools, and historical and real-time information, so as to provide the basis for an effective and reliable forecasting system (Fabre et al., 2007). Although various disease forecast systems exist, the precise control time or economic injury threshold is not always clearly available (Shtienberg, 2013). In our study, we emphasized the grain yield gain and the financial return of a single fungicide treatment scheduled on the basis of a DSS. This analysis was achieved by a comparison with a control and with both a two and three fungicide spray approach (as usually applied by farmers in the GDL). The results showed that the DSS satisfactorily recommended none or a single fungicide treatment at each study site, regardless of geographical location or possible variability among the fungal diseases involved.

The single fungicide treatment recommended using the DSS most often resulted in efficient control of the major fungal diseases that was equal to that of the double or triple fungicide treatments. Treating once but timely with an appropriate fungicide mix appears thus to be a judicious strategy to safeguard yield while minimising environmental damages. However, it may be speculated that the general success of the DSS-based single treatment observed during the studied period might be attributed to the predominance in this study of SLB which can be easily controlled by a timely single treatment (El Jarroudi et al., 2012b). In years with severe outbreaks of other important diseases such as WLR, FHB, a second fungicide application might be required to achieve an adequate crop protection.

When the weather conditions were not conducive to fungal infection or disease progress, no fungicide spray was recommended on the basis of the DSS, thus reducing further the use of chemical products that might be detrimental to the environment or human health. Multiple fungicide applications (two or three sprays) in such years did not provide significant gain in grain yields and often resulted in financial losses (Fig. 3). Several factors can affect the efficacy of wheat disease control (and thus profitability) using fungicides, in addition to the prevailing environmental conditions. The factors affecting profitability include cultural practices, cultivar resistance, other pest damage, key fungicide-related aspects (application timing and costs, effectiveness in controlling the diseases, type of fungicides), and the price of wheat (Ordish and Dufour, 1969; Carlson and Main, 1976). Plant physiological responses to fungicide exposure may also impact the profitability (Nason et al., 2007; Berdugo et al., 2012; Dias, 2012). Furthermore, fungicides might affect naturally occurring microflora (especially yeasts) on the phylloplane which might provide protection against pathogens, thus increasing the susceptibility of the plant to the pathogens (Bashi and Fokkema, 1977; Magan and Lacey, 1986; Mukerji et al., 1999; Rodgers-Gray and Shaw, 2001; Wachowska, 2005). In our analysis, the gain in yield in 2T and 3T treated plots did not necessarily result in a financial gain (see Fig. 3). In general, when factors that significantly reduce disease intensity, such as unfavourable environmental conditions, and when resistant cultivars prevail, the probability of a positive net return due to fungicide application is reduced. In our study, the probability of a positive net return was greatest when environmental conditions during the growing season favoured development of moderate to severe levels of fungal diseases. These conclusions support those of Guy et al. (1989) and Wegulo et al. (2011). In this respect, our results might provide useful information for operational fungal disease warning systems which will help reducing synthetic chemical fungicide sprays in winter wheat. Future studies may also test the DSS described herein for use in other cereal crops such as barley.

In the GDL, three types of farmers have been identified based on their method for making crop protection decisions (Guy Reiland, Personal comm.): (i) system-orientated farmers, (ii) experience-based farmers and (iii) advisory-orientated farmers. System-orientated farmers generally apply treatments following a partially fixed strategic plan (which is also used as a list for planning purchases of chemicals). They tend to manage big farms with specialised production and demand high levels of disease control. Experience-based farmers use a close, personal knowledge of each individual field (farm size low to medium) to base individual field-specific management choices, substituting detailed disease assessments with continuous more general observations of their fields. Advisory-orientated farmers contract their decision-making out to an advisor, and give higher priority to operations other than growing crops (generally livestock management). None of these groups of farmers have been prepared to perform detailed field-specific assessments in order to adjust the inputs according to the need in specific fields (Langvad and Noe, 2006). Thus, despite DSS systems based on in-season fungal diseases monitoring being a potentially useful, valuable and practical option, significant fractions of growers are not using them. Since 2004, warning bulletins (based on the DSS involved in this study) have been issued weekly throughout the growing season in the GDL so as to provide information to growers on the need for fungicide sprays and fungal diseases control. These bulletins are available in the GDL through various websites (http://www.centralpaysanne.lu, http://www.agrimeteo.lu, http://www.lwk.lu). The results presented in this study demonstrate the potential advantages to disease management and profitability of using this sort of DSS based approach. They also emphasize the need for a continued awareness of the wheat production sector on the actual requirement for crop protection through chemical fungicides.

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