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Winter Wheat Grain Yield Response to Fungicide Application is Influenced by Cultivar and Rainfall

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Winter wheat is susceptible to several fungal pathogens throughout the growing season and foliar fungicide application is one of the strategies used in the management of fungal diseases in winter wheat. However, for fungicides to be profitable, weather conditions conducive to fungal disease development should be present. To determine if winter wheat yield response to fungicide application at the flowering growth stage (Feekes 10.5.1) was related to the growing season precipitation, grain yield from fungicide treated plots was compared to non-treated plots for 19 to 30 hard red winter wheat cultivars planted at 8 site years from 2011 through 2015. At all locations, Prothioconazole + Tebuconazole or Tebuconazole alone was applied at flowering timing for the fungicide treated plots. Grain yield response (difference between treated and non-treated) ranged from 66-696 kg/ha across years and locations. Grain yield response had a positive and significant linear relationship with cumulative rainfall in May through June for the mid and top grain yield ranked cultivars (R^2=54%, 78%, respectively) indicating that a higher amount of accumulated rainfall in this period increased chances of getting a higher yield response from fungicide application. Cultivars treated with a fungicide had slightly higher protein content (up to 0.5%) compared to non-treated. These results indicate that application of fungicides when there is sufficient moisture in May and June may increase chances of profitability from fungicide application.

Keywords **:** fungicide, weather, winter wheat, yield response

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Winter wheat (*Triticum aestivum* L.) is an important crop in the Great Plains region and is ranked third after corn and soybean in terms of revenue and acres planted (NASS, 2017). Winter wheat is grown for carbohydrate source domestically but also for export (USDA-ERS, 2017) and the Great Plains region accounts for one-third of US wheat production. This crop is currently being promoted as a rotational crop that allows a cover crop to be planted after wheat harvest in Midwestern U.S.A. before the killing frost sets in Bower (2018).

Winter wheat is susceptible to several fungal pathogens throughout the growing season that significantly reduce grain yield. Some of the most important fungal diseases include tan spot (*Pyrenophora tritici-repentis*), Stagonospora nodorum blotch (*Parastagonospora nodorum*), leaf rust (*Puccinia triticina*), stripe rust (*Puccinia stritiformis* f. sp. *tritici*), powdery mildew (*Blumeria graminis* f. sp. *tritici*) and Fusarium head blight (FHB, *Fusarium graminearum*) (Bockus et al., 2010). Fungal pathogens other than cereal rusts that infect wheat survive on the residue. Hence, inoculum is always present in wheat production areas. This is partly due to the agronomic practices such as no-till and

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planting in wheat fallow which promote survival of inoculum (Dill-Macky and Jones, 2000) as well as some areas of the Great Plains region having predominantly intermediate grass prairie type of vegetation that serves as a source of inoculum for some of the common fungal diseases (David, 2004).

One of the most common and effective fungal diseases management practice in winter wheat is the application of foliar fungicides (Lackermann et al., 2011; Wegulo et al., 2011). A recent survey in South Dakota indicated that wheat had a higher chance of receiving a fungicide treatment than corn or soybean (Byamukama et al., 2016). Fungicides provide protection against fungal pathogens, especially on the flag leaf, the main contributor to grain yield (Dimmock and Gooding, 2002). The majority of producers apply fungicides at flowering (Feekes 10.5.1) for the management of Fusarium head blight (FHB), however, applications at tillering (Feekes 2-5) and flag leaf (Feekes 8) growth stages are not uncommon (Byamukama E., unpublished data).

Several factors influence the profitability of fungicide application. These include the susceptibility of the cultivar, disease pressure, weather conditions, and grain prices. For instance, Wegulo et al. (2011) reported that fungicides reduced FHB and deoxynivalenol more in moderately resistant cultivars than in a susceptible cultivar. However, De Wolf et al. (2012) reported that susceptible varieties to leaf diseases had a higher likelihood of positive response to fungicide application than resistant varieties at low, moderate, or high levels of disease pressure.

Another factor that influences the yield response to fungicide application is the level of disease pressure driven by weather. Weather, specifically rainfall and temperature, drive fungal disease epidemic development (Hims and Cook, 1991; Te Beest et al., 2008; Wegulo et al., 2011; Wiik and Ewaldz, 2009). Although temperature influences fungal diseases development, rainfall by far is the most important factor for diseases to develop (Thompson et al., 2014). Rainfall influences the extent of disease development in two ways: leaf wetness period for infection initiation (Rowlandson et al., 2015) and in the pathogen dispersal through rain splashing (Madden, 1997). Rainfall can also decrease fungicide residual efficacy depending on the time of and frequency after fungicide application (Carroll et al., 2001; Fife and Nokes, 2002; Pigati et al., 2010).

Grain prices influence the profitability of fungicide application in wheat by influencing the minimum number of bushels required to offset the cost of purchase and application of the fungicide (Lopez et al., 2015; Wegulo et al., 2011; Weisz et al., 2011). At higher grain prices, only a few bushels are needed to break even, whereas at low prices, it would take several bushels to offset the cost of fungicide application and therefore may not be profitable (Ransom and McMullen, 2008; Thompson et al., 2014).

Although several studies on fungicides and yield response in wheat have been conducted, few have looked at paired studies to document response to fungicide application for several cultivars of hard red winter wheat as influenced by weather. Guy et al. (1989) analyzed the agronomic and economic responses of winter wheat to foliar fungicides but only two cultivars were evaluated. Similarly, Lackermann et al. (2011) analyzed the effect of location and cultivar on grain yield but this was for soft red winter wheat. Thompson et al. (2014) analyzed the economics of foliar fungicides for hard red winter wheat but the study was performed in the southern Great Plains, which has different weather conditions than northern Great Plains. Ransom and McMullen (2008) analyzed yield response to fungicides for several cultivars but relationship between yield response and weather variables was not reported. Similarly, very few studies have investigated the effect of fungicide application on protein content for several cultivars in paired studies. Herman et al. (1996) reported increase in protein content because of fungicide application but only one cultivar was considered. Jensen and Jorgensen (2016) reported varying protein content response to fungicide application across trial years but they evaluated three cultivars.

The objective of this study was to determine the response to fungicide application in terms of grain yield, test weight, and protein content as influenced by winter wheat cultivar and rainfall across different environments in South Dakota.

Materials and Methods

Trial locations and experiment set up. Between 21 and 30 hard red winter wheat cultivars per location were sown at Brookings (44.18 N 96.40 W) in 2011, 2013 and 2014; between September 5th and October 15th at Ideal (43.50 N, 99.89 W) in 2011, 2012, 2013 and 2015; and at Beresford (43.68 N, 97.48 W) in 2011 under the South Dakota State University Crop Performance Testing program. The cultivars came from public lines or private companies winter wheat breeding programs (Table 1). Some of the locations between 2011 and 2015 were not included in this study either because of winter-kill or a fungicide application was not done. For all locations, a split-plot design in randomized complete blocks was used, the main plot was the fungicide treated while the subplots were the cultivars. Plots measured 1.52 m wide by 4.27 m long and row spacing was 0.18 m. Seeding rate was 300 pure live seeds per

Table 1. Hard red winter wheat cultivars that were tested in the South Dakota Crop Performance Tests between 2011 and 2015

Cultivar	Source	Susceptibility to leaf spot diseases	Susceptibility to FHB
1863	Public, South Dakota	MS	-
Alice	Public, South Dakota	S	S
Antero	PlainGold	MR	S
Arapahoe	Public, Nebraska	S	MR
Art	Syngenta	MR	MR
Brawl CL Plus	Public, Colorado	-	-
Byrd	Public, Colorado	S	-
Camelot	Public, Nebraska	-	S
Darrell	Public, South Dakota	MS	MR
Decade	Public, Montana	MR	-
Denali	Public, Colorado	S	-
Emerson	Meridian Seeds	S	MR
Everest	Public, Kansas	S	MR
Expedition	Public, South Dakota	S	MR
Freeman	Public, Nebraska	S	MS
Fuller	Public, Kansas	MR	MR
Harding	Public, South Dakota	MR	S
Ideal	Public, South Dakota	MS	MS
Jagalene	Syngenta	MS	S
Jerry	Public, North Dakota	S	S
LCH08-80	Limagrain Cereal Seeds	MR	S
LCS Campus	Limagrain Cereal Seeds	MS	MR
LCS Mint	Limagrain Cereal Seeds	MS	-
Lyman	Public, South Dakota	MS	MR
McGill	Public, Nebraska	-	-
Millennium	Public, Nebraska	S	S
Overland	Public, Nebraska	S	MR
Redfield	Public, South Dakota	MS	MR
Robidoux	Public, Nebraska	S	S
Settler CL	Public, Nebraska	S	S
Smoky hill	Westbred	MR	S
SY Monument	Syngenta	MR	MR
SY-Wolf	Syngenta	MS	S
T158	Limagrain Cereal Seeds	S	S
WB Cedar	WestBred	S	-
WB Grainfield	WestBred	MR	-
WB Matlock	Westbred	MS	S
WB Matlock	Westbred	MS	-
WB Redhawk	Westbred	MS	-
Wesley	Public, Nebraska	S	S

FHB = Fusarium head blight, S = susceptible, MS = Moderately susceptible, MR = Moderately resistant; "-" Rating not available.

square meter or 2.7 million seeds per hectare. The previous crop at all locations was spring wheat and under no-till system. Standard agronomic practices for weed and fertilizer management (22.4 kg/ha urea at planting and 73 kg/ha urea at green-up in spring) were applied at all locations. At each location, for plots that received fungicide application, the fungicide Prothioconazole + Tebuconazole (Prosaro®; Bayer CropScience, Greensboro, NC; spray rate: 474.8 ml per ha) or Tebuconazole (Folicur®; Bayer CropScience, Greensboro, NC; spray rate: 292.2 ml per ha) was applied at flowering (Feekes 10.5.1) at recommended rates using a tractor mounted boom sprayer delivering 140 liters/ha at 45 psi.

Data collection and analysis. Plots were harvested using a small plot combine between July 2nd and July 28th and seed weight from each plot was recorded and converted to yield (kg/ha) after adjusting for moisture content at 13%. Test weight was determined for each plot for the four locations (Brookings, 2013, 2014; Ideal, 2013, 2015). Protein content was determined also for the four locations above using the near infrared spectroscopy grain analyzer (Infratec-1225, Eden Prairie, MN). Test weight and protein content data for other locations and years were not measured due to logistical challenges. Grain yield, test weight, and protein content for fungicide treated and non-treated plots were subjected to a paired t-test (PROCEDURE TTEST, version 9.3; SAS Institute Inc., Carey, NC). The paired t-test was preferred since the main objective of the study was to detect differences between fungicide treated and non-treated plots.

To determine if the yield response to fungicide application (fungicide treated grain yield – non-treated grain yield for each cultivar) was influenced by cultivar, cultivars at each location were classified as low-yielding (20% bottom yielding cultivars), average-yielding (60% medium yield) or high-yielding (20% top yielding) by arranging the cultivars in ascending order of yield for treated plots. Whereas classification by susceptibility would have been preferred, not all cultivars had disease rating available and only a few were classified as resistant or moderately resistant to FHB or leaf spots. The majority were rated as susceptible. Effect of cultivar class (top, average or bottom) was subjected to analysis of variance with locations as blocks. Yield difference between fungicide-treated and non-treated plots for each of the three yield classes was averaged across cultivars for each location and subjected to correlation to determine the variables that were highly correlated with yield response. The weather variables assembled were: i) total rainfall in May, ii) Rainfall in June, iii) Rainfall in May and June, iv) total rainfall June through July 15, v) Number of days rainfall was > 3 mm (Rainfall greater than 3 mm is considered sufficient to wet the wheat canopy for fungal infections to take place (Hooker et al., 2002)); vi) number of days with rainfall > 3 mm in June through July 15; vii) number of days with rainfall > 3 mm in May and June; viii) Rainfall May 15 through June; ix) number of consecutive days with rainfall in June through July 15; x) number of consecutive days with rain > 3 mm; xi) number of days with moving average rainfall > 0.05; and, xii) number of days with moving average rainfall > 0.05 mm in the June through July 15. Initial selection of variables related with yield response were identified by Pearson correlation. Variables that were correlated with yield were subjected to simple linear regression in R-program (version Ri386.3.3.2). The best independent weather variable relating yield response to fungicide application and weather variables was selected based on the largest coefficient of determination (R^2) and low predicted error sum of squares (Bowerman and O'Connell, 1990).

Results

Weather characteristics, grain yield, protein content, and test weight. The Brookings location in 2014 received the highest total rainfall (260 mm) compared to other locations in the two critical months of wheat growing season (May through June). Beresford in 2012 had the lowest rainfall (91 mm) in the same period (Table 2). Temperatures were comparable across all locations except Ideal and Beresford in 2012 which had slightly warmer temperatures (19.0 and 20.2°C, respectively) during the critical wheat growing period.

Average grain yield difference due to fungicide application across all cultivars varied among locations and years (Table 3). The Ideal location in 2011 had the highest yield response due to fungicide application (696 kg/ha) and Beresford had the lowest yield response (66 kg/ha). With the exception of Beresford in 2012, plots receiving fungicides yielded significantly higher than non-treated plots at the rest of the locations and years (Table 3).

Yield response as a result of fungicide application was not the same across cultivars. Low yielding cultivars (bottom 20% cultivars) generally had more than twice yield response than the top 20% cultivars (Table 4). Cultivars classified as average yielding (60% middle yield) had a moderate yield response from fungicide application. This was observed at all locations and years (Table 5).

Test weight difference (test weight response) between

Table 3. A paired t-test for grain yield for fungicide treated and non-treated plots for winter wheat cultivars planted at Brookings, Beresford or Ideal locations

Location	Year	df	Mean difference (kg/ha) (stderr)	*t*-value	*P*-value
Ideal	2015	23	398 (80.3)	-4.95	< 0.0001
Ideal	2013	30	86 (34.4)	2.50	0.0179
Ideal	2012	20	215 (73.8)	2.91	< 0.0001
Ideal	2011	22	696 (65.3)	10.66	< 0.0001
Beresford	2012	19	66 (71.1)	1.01	0.3261
Brookings	2014	26	496 (69.9)	7.09	< 0.0001
Brookings	2013	24	554 (51.7)	10.72	< 0.0001
Brookings	2011	22	523 (88.3)	5.93	< 0.0001

df = degrees of freedom; stderr = standard error

Table 4. Analysis of variance for location, cultivar classification on the yield response from applying a fungicide in winter wheat

Effect	df	*F*-value	*Pr* > *F*
location	8	13.72	< .0001
Class[a]	2	13.35	< .0001
location*class	16	1.15	0.3147

Class refers to the classification of a cultivar as either high yielding (top 20%, average yielding (middle 60%) or low yielding (bottom 20%) for each location and year, df = degrees of freedom.

Table 2. Weather conditions during the winter wheat growing season at various locations 2011-2015

Location	Year	Cumulative rainfall (mm) May through June	Growing season total rainfall (mm)	Average temperature (°C)	Yield (kg/ha)[a]	Yield range (kg/ha)
Ideal	2015	150	251	16.8	3828	1749-5313
Ideal	2013	190	256	16.7	3126	404-3968
Ideal	2012	163	194	19.0	5213	4170-5851
Ideal	2011	202	279	15.8	2710	1833-3430
Beresford	2012	91	97	20.4	4121	3295-4708
Brookings	2014	260	320	16.2	3609	2556-4506
Brookings	2013	191	272	15.6	3917	2421-5111
Brookings	2011	196	302	16.1	4658	3026-5985

[a]non-treated plots

Table 5. Yield response from fungicide application on winter wheat cultivars influenced by the cultivar class: bottom (20% lowest yielding), middle (60% average yield), and top (20% top yield)

Cultivar yield classification	Mean yield response (kg/ha)
Bottom 20%	615.96 A
Middle 60%	426.21 B
Top 20%	249.32 C

Table 6. A paired t-test for test weight between fungicide treated and non-treated plots for winter wheat cultivars planted at Brookings, Beresford or Ideal locations

Location	Year	df	Mean difference (kg/m^3) (stderr)	*t*-value	*P*-value
Ideal	2015	23	14.7 (2.30)	-6.40	< 0.0001
Ideal	2013	30	9.7 (1.78)	-5.45	< 0.0001
Brookings	2014	26	22.64 (3.96)	5.72	< 0.0001
Brookings	2013	24	15.75 (3.8)	4.09	< 0.0001

Table 7. A paired t-test for protein content between fungicide treated and non-treated plots for winter wheat cultivars planted at Brookings and Ideal locations

Location	Year	df	Mean difference (%)	*t*-value	*P*-value
Ideal	2015	23	0.50	5.37	< 0.0001
Ideal	2013	30	0.48	9.73	< 0.0001
Brookings	2014	26	-0.10	-1.18	0.2471
Brookings	2013	24	0.35	3.76	0.001

fungicide-treated and non-treated plots also varied across all locations and years (Table 6). The Brookings location in 2014 had the highest test weight response (22.64 kg/m^3) while Ideal in 2013 had the lowest test weight response (9.7 kg/m^3). A paired t-test revealed significant difference between fungicide-treated and non-treated plots for test weight at all the locations. Similarly, the application of fungicide significantly increased average protein content (%) across cultivars at the three locations out of four locations ($P < 0.001$) (Table 7).

Relationship between yield response and weather variables. Total rainfall in May through June had a significant positive linear relationship with yield response to fungicide application ($P < 0.05$) for the middle and top ranked cultivars. Total rainfall from May through June explained 54 and 76% of the variation in yield response for the middle and top ranked cultivars (Fig. 1).

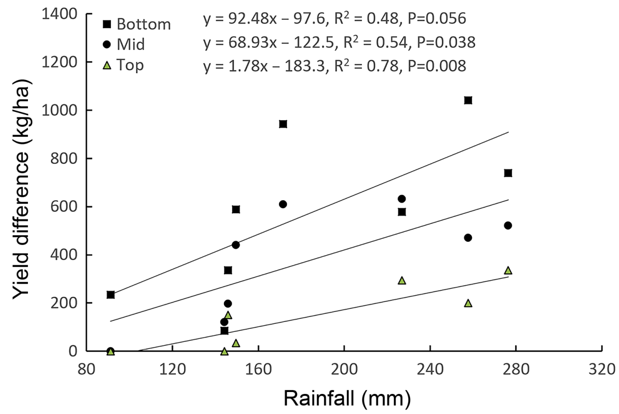

Fig. 1. Relationship between yield response as a result of fungicide application with total rainfall May through June for the bottom 20% yielding cultivars, 60% middle yielding cultivars, and top 20% yielding cultivars from three locations in 2011, 2012, 2013 and 2015.

Discussion

This study investigated grain yield response among winter wheat cultivars treated with a fungicide for three locations and five years. The location and cultivar influenced the yield response to fungicide application. This is consistent with previous reports in which location and cultivar were the main factors that influenced grain yield (Lackermann et al., 2011; Ransom and McMullen, 2008). The locations differed in the amount of rainfall received. The greatest yield response to fungicide application occurred at Ideal in 2011 and the least yield response occurred in Beresford in 2012. The Ideal location in 2011 had weather conditions that favored disease development (FHB and tan spot, Shaukat Ali, personal communication) compared to the Beresford location in 2012 which was an extremely dry year at this location. Similar findings of weather influencing fungicide yield response in wheat were reported by Wegulo et al. (2011) where they found that profitability of fungicide application was more likely with conducive weather for disease development in winter wheat.

Response of cultivars to fungicide application was not the same across all locations. The top yielding cultivars had limited yield response as a result of fungicide application whereas low yielding cultivars had almost twice yield response to fungicide application. This indicates that whereas a fungicide may help protect against yield loss from susceptible cultivars, depending on disease pressure, yield loss can still occur. This may be the case in this study given that a fungicide was applied at the flowering timing. This timing was aimed at controlling FHB and protecting the flag leaf. The limited yield response from high yielding cultivars may be attributed to the inherent good disease resistance/tolerance of the high yielding cultivars. These cultivars may have had less disease developing and hence yield loss prevented by fungicide application was limited. These findings are in agreements with Gomes et al. (2016) findings where they reported that resistant cultivars did not benefit from fungicide application. De Wolf et al. (2012) and Thompson et al. (2014) also reported similar findings where susceptible cultivars had a larger response to fungicides than resistant cultivars. Similarly, Ranson and McMullen (2008) reported that susceptible cultivars had a great response to fungicide compared to resistant cultivars. On the contrary, for other pathosystems such as FHB, response to fungicide is higher in moderately resistant cultivars because for the susceptible cultivars to *Fusarium graminearum*, even with a fungicide application, FHB can still develop (Willyerd et al., 2012). Although disease severity data was not recorded for this study, paired data analysis demonstrated that the only treatment difference was fungicide application. Therefore, yield difference may be attributed to disease control in environments that had higher rainfall. It can be noted that the yield benefit from fungicide application not only depended on the amount of rainfall received in the critical wheat-growing period but also frequency of the rainfall. For instance, rainfall for Ideal 2011 was more frequent than in 2013 (29 rain days) hence the yield difference between fungicide treated and non-fungicide treated was greatest in 2011 at this location. Frequent rains provide conditions for continued disease pressure buildup hence the higher benefits of fungicide application.

In all locations, winter wheat was sown under no-tillage system and in wheat following wheat fields (non-rotated). These conditions tend to increase foliar and wheat head diseases, especially where sufficient moisture is available for infection to take place, hence the reason why fungicide treated plots yielded better than non-treated. Jorgensen and Olsen (2007) also found higher yield from fungicide treated plots in “non-inversion tillage”. Other than biotroph pathogens, the rest of the fungal pathogens that infect wheat survive on wheat residue. These pathogens infect wheat early under no-till conditions can lead to significant yield losses. Therefore fungicides applied to protect the flag leaf and the leaf below flag leaf protect against yield losses.

Although average yield difference between fungicide treated an non-treated plots across cultivars and locations was significant, the Beresford 2012 and Ideal 2013 locations had yield difference below breakeven point for Prothioconazole + Tebuconazole ($44.6 fungicide plus application cost per ha) or Tebuconazole ($16.7 fungicide plus applications cost per ha) programs (based on revenue for each location determined from past six years wheat average price of $0.184/kg and yield difference between fungicide and non-fungicide treated plots for each location). This means that it did not pay to apply a fungicide in wheat for these locations in these years. This may be attributed to low moisture especially around wheat heading when wheat is more vulnerable to disease development.

Fungicide treated plots had higher test weights than non-treated plots across all cultivars and locations in this study. The fact that the Brookings location in 2014 had the highest test weight difference between fungicide treated and non-treated plots and yet this location had also the highest total rainfall for May and June, indicate that fungicides kept leaf tissues healthy and hence prolonged accumulation of assimilates compared to non-treated. Paul et al. (2010) also reported increases in test weight relative to a non-treated check in their meta-analysis study across several locations and years in the United States. Similarly, Milus (1994) reported that fungicide application increased test weight in the three cultivars evaluated. In wheat, test weight is one attribute that can influence the selling price. Low test weight grain may be priced lower than higher test weight grain (Hossain et al., 2003).

Protein content was slightly higher (up to 0.5%) in fungicide-treated plots versus non-treated plots combined across cultivars at all locations except for the Brookings 2014 location. This is in contrast to previous report where fungicides were found to reduce protein content (Jensen and Jorgensen, 2016). The difference with our results may be comparison across several cultivars whereas in other studies only two or three cultivars have been considered. Puppala et al. (1998) also reported varying levels of response in protein content across cultivars. The prolonging of flag leaf photosynthesis was reported to be closely correlated with accumulation of protein in grain (Pepler et al., 2005) and this may be the reason for slight increase in protein content in our study. The flowering timing is considered the best timing because a fungicide applied at this growth stage can control FHB as well as protect against diseases developing on flag leaf, which is the biggest contributor to yield (Wiersma and Motteberg, 2005).

This study examined the yield response as a result of fungicide application across several winter wheat cultivars under varying weather conditions. The results indicate that rainfall in the later part of the winter wheat growing season and the yield potential of the cultivar grown influence the yield response from fungicide application.

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