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The economics of foliar fungicide applications in winter wheat in Northeast Texas

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ABSTRACT

Among plant pathogenic organisms, fungi are a major reason for crop losses around the world and have a significant impact on yield and quality. Previous studies suggest that up to 42% yield loss caused by fungal diseases can be prevented by applying foliar fungicides to winter wheat. Local wheat production data on fungicide application, yield, and disease severity for four soft-red winter wheat cultivars (Magnolia, Terral LA841, Pioneer 25R47, Coker 9553) for two years (2011 and 2012) in three locations in Northeast Texas (Royse City, Howe, and Leonard) were analyzed to study the economics of one foliar fungicide (TebuStar® 3.6L). A preventive application of the fungicide resulted in a relatively conservative 9.41% overall yield gain and a net return (from investing in tebuconazole) of $107.7/ha in 2012, which lead to an overall positive (two-year average) net returns of $52.09/ha. A probability analysis indicated that positive overall net returns are likely and that most of the cultivars considered have the potential to produce a yield gain necessary to at least break even with or exceed the cost of applying tebuconazole.

1. Introduction

The U.S. is the world's largest wheat producing and exporting country. World wheat trade is expected to increase as the population grows in Egypt, Algeria, Iraq, Brazil, Mexico, Indonesia, Nigeria, and other developing countries (USDA ERS, 2012). Wheat is the third largest crop planted in the U.S., behind corn and soybean, and is expected to remain an important agricultural commodity for years to come. It generates about 198,000 jobs and accounts for $20.6 billion to the U.S. economy (Richardson et al., 2006). In 2007, Texas ranked as the 4th largest wheat producing state with about 3.84 million acres in production (Census of Agriculture, 2007). Wheat is the third most planted crop behind forages and cotton in Texas. In 2005, the wheat industry generated 11,273 jobs and contributed with $658.8 million to the Texas economy (Richardson et al., 2006).

Among plant pathogenic (disease-causing) organisms, fungi are the number one reason for crop losses around the world and have a significant impact on yield and quality in wheat production (McGrath, 2004). According to Wegulo et al. (2012), the most prevailing foliar diseases in winter wheat in the Great Plains of the U.S. are leaf rust (*Puccinia triticina*), powdery mildew (*Blumeria graminis* f. sp. *graminis*), tan spot (*Pyrenophora tritici-repentis*) (anamorph: *Drechslera tritici-repentis*), Septoria tritici blotch (*Mycosphaerella graminicola*) (anamorph: *Septoria tritici*), spot blotch (*Cochliobolus sativus*) (anamorph: *Bipolaris sorokiniana*), and Stagonospora nodorum blotch (*Phaeosphaeria nodorum*) (anamorph: *Stagonospora nodorum*). Stripe rust (*Puccinia striiformis* f. sp. *tritici*) and stem rust (*Puccinia graminis* f. sp. *tritici*) are sometimes considered less common (Wegulo et al., 2012), and sometimes considered the most frequent in the wheat producing regions of the U.S. (Kolmer, 2007).

In the U.S., foliar fungicides used in wheat are usually grouped in two categories: strobilurins and triazoles. Strobilurins are highly effective when applied preventively (Wegulo et al., 2012) while triazoles are highly effective and reliable against early fungal infections (Hewitt, 1998). Examples of strobilurin fungicides include azoxystrobin, pyraclostrobin and trifloxystrobin; while examples of triazoles include metconazole, propiconazole, prothioconazole, and tebuconazole.

Fungicide costs and wheat prices influence the decision of spraying or not spraying. To be effective, most fungicides need to be applied before the disease occurs or at the appearance of the first symptoms. When the fungicide is applied to wheat before the flag leaf emergences, it generally results in less disease control on the upper leaves during grain development and smaller yield benefits (De Wolf et al., 2012). In general, fungicides primarily protect plants

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from getting infected and just few fungicides are effective in plants that have already been infected (McGrath, 2004). The benefits from fungicide applications in crop production are reflected in returns of up to three times the cost involved (McGrath, 2004). However, Hershman (2012) and McGrath (2004) explained that when the disease severity is low and there is minimal yield loss, applying a fungicide will not result in either a yield or an economic advantage.

Northeast Texas has traditionally being a region of moderate to high disease pressure. Leaf rust infection levels of susceptible cultivars are typically moderate or high, frequently reaching above 16% and every so often above 50% (Personal Communication, Texas A&M AgriLife Extension Representative in Commerce, TX). According to several wheat trials conducted by Texas A&M AgriLife Extension Representative in Commerce, TX in six locations in Northeast Texas (Leonard, Fairlie, Royse City, Greenville, Celeste, and Bailey) during 2005–2013, leaf rust infection levels for three common susceptible varieties (Pioneer 25R49, Pioneer 25R54, and Syngenta Jackpot) averaged 1% for plots treated with tebuconazole at 280 g/ha and 63% for untreated plots (with a median of 70%).

Several regional studies (Reid and Swart, 2004; and frequent technical reports by Swart, 2014) report yield increases greater than 30% of the treated plots over untreated plots. Studies in neighbor states (i.e., Thompson et al., 2014) have also reported yield increases close to 20% in recent years (i.e., 2012). Chen (2012) explained that yield losses of up to 60% due to stripe rust have been documented in experimental fields. Wegulo et al. (2009) showed that up to 42% yield loss was prevented by applying foliar fungicides to winter wheat. O'Brien (2007) showed that potential average wheat yield losses of 30% are common in Kansas when leaf rust is not controlled at flowering. From 1991 to 2002, the U.S. Department of Agriculture, Agricultural Research Service (USDA ARS, 2013) reports winter wheat yield losses in Texas from stem rust, leaf rust, and stripe rust averaging approximately 0.02%, 2.4%, and 0.4% per year respectively; while in the U.S. they average 0.14%, 2.1%, and 0.5% per year respectively. Clearly, fungal diseases have a significant economic impact on wheat yield and quality. Higher net returns may be obtained by carefully managing fungal diseases. “The formula for success in growing wheat in Northeast Texas is quite simple. Plant several high yielding resistant varieties in a timely manner, manage for optimum yet realistic yields, and use an inexpensive foliar fungicide [TebuStar® 3.6L] to protect yourself against a leaf rust race change or late season glume blotch infection” (Swart, 2014).

Unlike previous studies, this study conducts an analysis of four soft-red winter wheat cultivars (Magnolia, Terral LA841, Pioneer 25R47, Coker 9553) for two years (2011 and 2012) in three locations in Northeast Texas (Royse City, Howe, and Leonard). The general objective of the study is to analyze the effect of foliar fungicides on wheat yields and net returns, and to assist wheat growers in Northeast Texas with economic tools that may allow them to assess the economic benefits from foliar fungicide applications. The specific objective is to evaluate yield and net return from using the foliar fungicide tebuconazole (TebuStar® 3.6L) in Northeast Texas wheat production. The hypothesis examined is whether a preventive application of a relatively inexpensive foliar fungicide (TebuStar® 3.6L) to winter wheat in Northeast Texas is likely to result in a yield gain necessary to at least break even with or exceed the fungicide application cost.

2. Materials and methods

2.1. Wheat field trials, prices, and costs

Winter wheat (*Triticum aestivum* L.) data on fungicide treatment, location, yield, and disease severity for four soft-red winter wheat cultivars (Magnolia, Terral LA841, Pioneer 25R47, Coker 9553) was obtained from the Texas A&M AgriLife Extension Representative in Commerce, TX. Those are common cultivars in Northeast Texas and are considered to be moderately resistant to fungal diseases according to the agency's wheat trials over the last several years. Table 1 also summarizes the responses of these four cultivars to some common diseases and pests according to the agronomic assessments made by the companies that produce them. Specific environmental conditions, plant development stages, other disease and pest pressures, and disease resistance over time, among others, influence each cultivar's disease and pest response.

Wheat field trials for the four cultivars were conducted in 2011 and 2012 in three locations in Northeast Texas: a location in Royse City (32°58′27″N, 96°19′58″W), a location in Howe (33°30′18″N, 96°36′51″W), and a location in Leonard (33°22′59″N, 96°14′43″W). The corresponding elevations at each of these locations are 167 m, 256 m, and 219 m. The soil types in all three locations are either Houston Black Clay (calcareous clays and marls) or Leson Clay (alkaline shale and clays). Both soil types are very deep, moderately well drained, and very slowly permeable soils. Those are typical soils characteristics where wheat is grown in Northeast Texas.

Each wheat trial was replicated six times in a randomized complete block design. Each plot was 1.22 m wide and 6.06 m long and 15.24 cm row spacing. The treated plots were sprayed with the foliar fungicide TebuStar® 3.6L at 280 g/ha (diluted in 93 L of water per hectare) when the plants were approximately at Feekes Growth stage 10 (Large, 1954). The CO_2 powered backpack sprayer was equipped with a three-nozzle boom with 8002VS stainless steel tips 48 cm apart and flat-fan nozzles at 2.11 kg/cm^2.

Each experimental unit was evaluated one month after the foliar fungicide was applied. Ten plants per plot (subsamples) were randomly selected. Flag leaves on each plant were visually assessed for the presence of Septoria, barley yellow dwarf (BYD), leaf rust, and strip rust.

The harvest was done with a research Kincaid combine (Kincaid Manufacturing, Haven, Kansas). After weighing the grain and correcting to 13% moisture, grain yield in bushels per acre was recorded. Table 2 summarizes the three locations where the trials were conducted, their soil types, the weather conditions, and the planting, spraying, and harvesting dates.

Wheat prices per bushel were obtained from Texas A&M AgriLife Extension–Extension Agricultural Economics (2011, 2012). The average wheat price regardless of variety and location over the two years analyzed was $0.25/kg. The tebuconazole cost ($12.36/ha) and its application cost ($4.94/ha) were obtained from fungicide companies in Northeast Texas. When wheat prices are high relative to fungicide treatment costs, positive net returns are more likely (Thompson et al., 2014; Wegulo et al., 2011; Wiik and Rosenqvist, 2010).

Table 1
Disease and pest response.

	Disease and pest ratings			
	Magnolia[a]	Coker 9553[a]	Terral LA841[b]	Pioneer 25R40[c]
Stripe rust	3	2	9	7
Leaf rust	6	4	8	7
Septoria leaf blotch	5	5	7	n.a.
Powdery mildew	8	4	7	4

[a] Ratings according to AgriPro (2014a,b) numeric scale from 1 (good/resistant) to 9 (poor/susceptible).
[b] Ratings according to Terral Seed (2014) disease resistance numeric scale from 1 to 9, where 1–3 (below average), 4–6 (average), and 7–9 (above average).
[c] Ratings according to DuPont Pioneer (2014) numeric scale from 1 (poor) to 9 (excellent). The abbreviation n.a. stands for not available, which means that the authors were unable to find a rating.

Table 2
Locations, soil types, dates, and weather.

Year	Location	Soil		Date planted	Date sprayed	Date harvested	Weather during spraying date			Winter season
		Type	Elev. (m)				Wind (km/h)	Temp (°C)	Relative humidity (%)	Rainfall[a] (mm)
2011	Howe	Houston Black or Leson Clays	256	10/29/10	4/1/11	06/07/11	6.4	18.3	61.6	361
2011	Leonard	Houston Black or Leson Clays	219	11/10/10	3/8/11	06/02/11	8.0	12.1	61.6	314
2011	Royse City	Houston Black or Leson Clays	167	11/19/10	3/27/11	05/31/11	6.4	18.3	61.6	369
2012	Howe	Houston Black or Leson Clays	256	11/02/11	3/29/12	05/22/12	4.8	27.5	51.8	537
2012	Leonard	Houston Black or Leson Clays	219	10/31/11	3/28/12	06/06/12	6.4	24.4	61.0	556
2012	Royse City	Houston Black or Leson Clays	167	11/01/11	3/28/12	05/17/12	8.0	20.0	87.0	537

[a] The amount of rainfall during the winter season was obtained from the National Weather Service Forecast Office (2013).
Source: Texas A&M AgriLife Extension Representative in Commerce, TX.

2.2. Analysis of variance

The effects of TebuStar® 3.6L applications on net returns and wheat yields were analyzed using the GLM and REG procedures in SAS version 9.3 (SAS Institute Inc., 2011a,b). Several linear regression models were estimated using Ordinary Least Squares (OLS) to evaluate if wheat yields were statistically different across years, locations, and cultivars; and to determine if tebuconazole had a statistical effect on wheat yields. The general form of the linear regression models is

$$Y = \beta_1 + \beta_2\text{Yr} + \beta_3\text{Leonard} + \beta_4\text{Royse} + \beta_5\text{Coker} + \beta_6\text{Magnolia} + \beta_7\text{Pioneer} + \beta_8\text{Trt} + \varepsilon, \tag{1}$$

where Y is wheat yield; Yr is a dummy variable (a zero-one binary variable) for year; Leonard and Royse are dummy variables for locations; Coker, Magnolia, and Pioneer are dummy variables for the cultivars; Trt is a dummy variable for treatment; $\beta_1, \beta_2, \ldots, \beta_8$ are the regression parameters that will be estimated; and ε is a random error. The dummy variables corresponding to the Howe location and the cultivar Terral AL841 have been omitted from equation (1) to avoid the problem of perfect multicollinearity.

In addition, several linear models are also estimated to conduct several pairwise comparisons using Tukey's (1953) honestly significant difference tests (Tukey's studentized range tests). The general form of these linear models is:

$$Y_{ijklmn} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \lambda_m + \alpha\gamma_{ik} + \varepsilon_{ijklmn}, \tag{2}$$

where μ is the overall yield mean from the treated group, α_i is the effect due to the ith treatment, β_j represents the effect from the jth block, γ_k is the effect from the kth cultivar, δ_l is the effect from the lth location, λ_m is the effect from the mth year, $\alpha\gamma_{ik}$ represents the interaction effect of the ith level of treatment depending on the kth level of cultivar, and ε_{ij} is the error term. The errors are assumed to be independently normally distributed with a zero mean and constant variance.

2.3. Economic analysis

Similar to Bestor (2011), De Bruin et al. (2010), Esker and Conley (2012), and Munkvold et al. (2001), a profitability analysis is conducted based on Bayesian inference. Net returns ($/kg) from investing in tebuconazole are calculated as

$$R_n = P^*(Y_t - Y_c) - \left(C_f + C_a\right), \tag{3}$$

where P is wheat price ($/kg), Y_t is the observed yield from tebuconazole treatment (kg/ha), Y_c is the observed yield from the untreated plots (kg/ha), C_f is the fungicide cost ($/ha), and C_a is the cost of fungicide applications ($/ha). Net return in this economic analysis is not the same as net return inclusive of all expenses faced by the producer when growing a specific wheat cultivar. Net return from investing in tebuconazole, equation (3), includes the costs associated with the spraying decision, which are the fungicide and its application costs. The net return from growing wheat depends on each farmer's management practices, and generally includes direct costs (wheat seed cost, wheat crop insurance, fertilizers, herbicides, custom harvest, operator labor for tractors, diesel fuel for tractors, gasoline or diesel for pickup trucks, repair and maintenance, interest expense, etc.) and fixed costs (implements, tractors, pickup trucks, land lease, etc.).

Following Bestor (2011) and Munkvold et al. (2001), the probability of tebuconazole treatments resulting in a yield difference larger than the estimated yield difference needed to offset the cost of tebuconazole was calculated from the observed yield difference between the treated and untreated plots and their observed standard deviation which was calculated from a pooled variance. That is, the probability that net returns from a tebuconazole treatment will at least break even, PT[$R_n > (1+0)^* (C_f + C_a)$]; be at least 25% greater than the investment on tebuconazole, PT [$R_n > (1 + 0.25)^* (C_f + C_a)$]; and be at least 50% larger than the investment on tebuconazole PT[$R_n > (1 + 0.50)^* (C_f + C_a)$] are estimated as

$$\text{PT} = 1 - \text{Prob}\ t\left[\frac{\beta_0 - \left(Y_f - Y_c\right)}{S_p\left(\frac{1}{n_t} + \frac{1}{n_c}\right)^{1/2}}, \text{df}_e\right], \tag{4}$$

where β_0 is the yield difference needed to offset the cost of tebuconazole application (kg/ha), $S_p^2 = ((n_t - 1)S_1^2 + (n_c - 1)S_2^2) / ((n_t - 1) + (n_c - 1))$ is a pool variance (Box and Tiao, 1973), S_1^2 is the variance of the observed yield from the treated plot, S_2^2 is the variance of the observed yield from the untreated plot, n_t is the number of observations in the treated plot, n_c is the number of observations in the control plot, and df_e is the number of degrees of freedom which is calculated using n_t and n_c.

The yield difference needed to offset the cost of tebuconazole application is computed as

$$\beta_0 = \frac{(1 + \text{ER}_n)\left(C_f + C_a\right)}{P}, \tag{5}$$

where $\text{ER}_n = 0$, 0.25, or 0.50, when breaking even, achieving net returns 25% greater, or achieving net returns 50% greater than the tebuconazole investment respectively.

Equations (3)–(5) are used to conduct a probability analysis based on Bayesian inference. Bayesian inference approaches have

Table 3
Linear regression coefficients for wheat yield response to fungicide applications.

	Independent variables								Goodness of fit	
	Intercept	Yr	Leonard	Royse	Coker	Magnolia	Pioneer	trt	Pr > *F*	*R*-Sq
2011	5238.66*	–	−1009.84*	−695.72*	276.48*	−93.46	−447.68*	56.26	<0.0001	0.6324
2012	5507.95*	–	−592.56*	−497.22*	812.04*	216.46	360.92*	516.63*	<0.0001	0.3973
Overall	4814.18*	1118.25*	−801.20*	−596.47*	544.26*	61.50*	−43.38*	286.45*	<0.0001	0.6406

*Significant at the 0.05 probability level.

Table 4
Yield and barley yellow dwarf (BYD) disease infection per cultivar at Howe in 2011.

Cultivar	Plots at Howe in 2011					
	Untreated		Treated		Overall	
	Yield[a] (kg/ha)	BYD (%)	Yield[a] (kg/ha)	BYD (%)	Yield[a] (kg/ha)	BYD (%)
Coker 9553	5590a	1.00	5703a	1.08	5646a	1.04
Magnolia	4913b	1.50	5115ab	1.58	5014b	1.54
Pioneer 25R47	4596b	2.00	4672b	1.58	4634b	1.79
Terral AL841	5478a	1.17	5540a	1.00	5509a	1.08
Overall	5144	1.42	5257	1.31	5201	1.37

[a] Within columns, means followed by the same letter are not significantly different according to Tukey's (1953) honestly significant difference test at the 0.05 probability level. Means represent averages across locations.

been used in the management of fungal diseases (Esker and Conley, 2012; Bestor, 2011; De Bruin et al., 2010; Wiik and Rosenqvist, 2010; Munkvold et al., 2001; Tari, 1996), in the management of insects (Foster et al., 1986), ecological studies (Cullinan et al., 1997), genetics (George et al., 2000; Zhivitovsky, 1999), and in human and veterinary epidemiology (Knorr and Rasser, 2000; Richardson and Gilks, 1993).

3. Results and discussion

Table 3 reports the OLS regression coefficients from equation (1). Overall average wheat yields in 2011 and 2012 were statistically different at the 5% significance level. In fact, at the 5% probability level, wheat yields in 2012 were typically 1118.25 kg/ha greater than in 2011, regardless of the location, cultivar, and treatment. This statistical difference in yield may be attributed to the presence of a disease in the Howe location in 2011 as discussed below, but it could also be partially attributed to the 56.13% increase in precipitation from 2011 to 2012 and other differences in uncontrollable factors between 2011 and 2012 (Table 2). Although the difference in overall average yield between 2011 and 2012 cannot be attributed to the fungicide application (since plots were sprayed both years), it is worth noting that fungicide application had a statistical significant effect on overall yield (Table 3). Overall, at the 5% probability level, the treated plots were typically 286.45 kg/ha greater than the untreated plots, regardless of the location and year.

The fungal diseases Septoria, leaf rust, and stripe rust were not detected in both the treated and untreated plots during the two years analyzed. This may be because 2011 and 2012 were years of moderate and low disease pressure respectively, but also the cultivars considered in the study are moderately resistant to fungi. Unlike these fungal diseases, barley yellow dwarf (BYD) infected both the treated and untreated plots only at the Howe location in 2011. Overall, the BYD infection levels at the Howe location in 2011 averaged 1.31% in the treated plots and 1.42% in the untreated plots (Table 4). Coker 9553 had the lowest infection level (1.04% on average) and the highest overall yield (5646 kg/ha on average) in the presence of BYD (Table 4).

In 2011, wheat yield from the treated plots was not statistically different from the untreated plots at the 5% probability level (Table 3). Several studies report statistical differences in yield between fungicide treated and untreated plots (Reid and Swart, 2004; Wiik and Rosenqvist, 2010). Although the emergence of BYD at Howe after the fungicide was applied may have affected yield in 2011, BYD is not likely to have been the reason for this statistical insignificance, since it affected both the treated and untreated plots at about the same rate (Table 4). The statistical insignificance may be attributed to the fact that 2011 was a year of moderate disease pressure, which means there probably was minimal potential yield loss between the treated and untreated groups at the time the fungicide was applied.

Unlike 2011 and even when 2012 was a year of low disease pressure, there was statistical difference on overall yield between the treated and untreated plots in 2012 (Table 3). Regardless of the location and cultivar, in 2012, wheat yield from the treated plots was on average 517 kg/ha greater than the wheat yield from the untreated plots (Table 3). On average in 2012, Coker 9553, Terral LA841, Magnolia, and Pioneer 25R47 yields from the treated plots were 6.40%, 4.26%, 16.01%, and 11.92% greater than their respective untreated plots (Table 7). In 2004, Reid and Swart (2004) reported yield increases of treated plots over untreated plots that ranged from 34% to 41% for a variety that was highly susceptible to stripe rust but resistant to leaf rust (Agripro Patton) in Royse City, TX. Thompson et al. (2014) also reported higher yield responses in 2012 than 2011 in two locations in Oklahoma (Apache and Lahoma) regardless of varietal resistance. For instance, in 2011, Thompson et al. (2014) reported resistant, intermediate, and susceptible wheat cultivars treated with Quilt or Stratego producing yields 4.09%, −0.46%, and 1.41% greater than the respective untreated plots.[1] In 2012, these yield increases were 19.86%, 19.76%, and 15.67% respectively. Although our finding in 2012 could be attributed to differences in uncontrollable factors between the treated and untreated groups, it is possible that the disease severity in the untreated plots could have increased since the day it was last measured (i.e., an undetected late disease infection in the untreated plots). On the other hand, Zhang et al. (2010) and Hunger and Edwards (2012) explain that fungicides protect the yield potential by increasing the activity of the plant antioxidants and by slowing chlorophyll and leaf protein degradation, which allows plants to keep their leaves longer and use more nutrients during late developmental stages (Morris et al., 1989; Dimmock and Gooding, 2002).

Several results, although expected, were also important to confirm. For example, similar to Orum et al. (2006), there were statistical differences in yields (Table 5) and net returns (Table 6) among locations during each year. Statistical differences in locations are usually attributed to agronomic practices such as crop rotation, soil quality, and disease severity (Orum et al., 2006), or

[1] Yield responses represent averages across the two locations and were computed in this study.

Table 5
Yield response to fungicide applications per location.

Location	Yield (kg/ha)[a]					
	2011		2012		Overall	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
Howe	5144a	5257a	5649a	6578a	5397a	5918a
Royse City	4501b	4509b	5434b	5799b	4968b	5154b
Leonard	4167c	4215c	5393b	5650b	4780c	4932c
Overall	4604	4660	5492	6009	5048	5335

[a] Within columns, means followed by the same letter are not significantly different according to Tukey's (1953) honestly significant difference test at the 0.05 probability level. Means represent averages across four cultivars.

Table 7
Yield response to fungicide applications per cultivar.

Cultivar	Yield (kg/ha)[a]					
	2011		2012		Overall	
	Untrt.	Treated	Untrt.	Treated	Untrt.	Treated
Coker 9553	4908a	5042a	6022a	6408a	5465a	5725a
Terral LA841	4666ab	4731b	5644b	5884bc	4882b	5219bc
Magnolia	4572b	4638b	5203c	6036b	4887b	5337b
Pioneer 25R47	4271c	4230c	5099c	5707c	4957b	5057c
Overall	4604	4660	5492	6009	5048	5335

[a] Within columns, means followed by the same letter are not significantly different according to Tukey's (1953) honestly significant difference test at the 0.05 probability level. Means represent averages across locations.

attributed to different fungicides and temperature conditions (Tadesse et al., 2010). Statistical differences among locations in this study may be attributed to small differences in the two soil types, rainfall, elevations over the sea level, and/or several other uncontrollable factors such as temperature and wind (Table 2).

There were also statistical differences in yield (Table 7) and net returns (Table 8) among the cultivars during each year. Thompson et al. (2014), Edwards et al. (2012), Ransom and McMullen (2008), and Mercer and Ruddock (2005) explain that wheat cultivars that are susceptible to common foliar diseases are more likely to generate positive returns when treated with fungicide. Among the four cultivars considered in this study, Coker 9553 was the most susceptible cultivar to common foliar diseases, followed by Magnolia (Table 1). Among the untreated plots, Coker 9553 had the highest yield and it was statistically different from Magnolia and Pioneer 25R47 in 2011; and statistically different from the other three cultivars in 2012 (Table 7). Among the treated plots, Coker 9553 also had the highest yield and it was statistically different from the other three cultivars in both 2011 and 2012 (Table 7). Although Coker 9553 provided the highest average yield in each of the two years (Table 7), it did not necessarily provide the highest average net return from treatment in both years (Table 8). In fact, in 2011, none of the cultivars produced a net return from treatment that was statistically different from the other three cultivars. Only in 2012, the net return from treatment from Magnolia was statistically different from the net returns from treatments from Coker 9553 and Pioneer 25R47. However, during the same year Magnolia net return from treatment was not statistically different from Terral LA841.

Overall, net returns from investing in tebuconazole in 2011 were estimated at −$3.53/ha (Tables 6 and 8). The negative net return in 2011 is likely the result of the statistical insignificance in yields from the treated and untreated plots. On the contrary, in 2012, net returns from investing in tebuconazole were $107.70/ha (Tables 6 and 8); and as discussed earlier, yields from the treated plots were statistically different from the untreated plots. More importantly, our conservative 9.41% overall wheat yield increase of the treated over the untreated plot in 2012 results in a positive return from investing in tebuconazole. In fact, the positive net return in 2012 offset the relatively small negative net return in 2011, and it results in an overall (two-year average) positive net return of $52.09/ha (Tables 6 and 8).

Table 8 cannot be used to analyze which variety is most likely to produce a positive net return on the tebuconazole investment. As explained by Munkvold et al. (2001, p. 482), mean separation results only indicate whether there is statistical evidence that a treatment mean is different from another; they do not indicate whether the probability that the yield increase is sufficient to offset the cost of the fungicide treatment (i.e., the probability of a profitable fungicide application). Consequently, a probability analysis based on Bayesian inference was also conducted to further assess whether a preventive application of a relatively inexpensive foliar

Table 6
Net return from treatment per location.

Location	Net return ($/ha)[a]		
	2011	2012	Overall
Howe	11.77a	204.46a	108.12a
Leonard	−5.45a	73.25b	28.18b
Royse City	−16.90a	45.39b	19.97b
Overall	−3.53	107.70	52.09

[a] Within columns, means followed by the same letter are not significantly different according to Tukey's (1953) honestly significant difference test at the 0.05 probability level. Means represent averages across four cultivars. Net return from treatment is computed using equation (3).

Table 8
Net return from treatment per cultivar.

Cultivar	Net return ($/ha)[a]		
	2011 ($n = 72$)	2012 ($n = 72$)	Overall ($n = 144$)
Magnolia	−0.32a	182.80a	91.24a
Terral LA841	−1.55a	133.43ab	65.94a
Coker 9553	16.83a	73.92b	45.37a
Pioneer 25R47	−29.06a	40.66b	5.80a
Overall	−3.53	107.70	52.09

[a] Within columns, means followed by the same letter are not significantly different according to Tukey's (1953) honestly significant difference test at the 0.05 probability level. Means represent averages across three locations. Net return from treatment is computed using equation (3).

Table 9
Probability that net returns from treatment (per location) will break even, be at least 25% greater than the tebuconazole investment, and be at least 50% greater than the tebuconazole investment.

Year	Location	$PT[R_n > (1 + ER)^* (C_f + C_a)]$		
		ER = 0%	ER = 25%	ER = 50%
2011	Leonard	0.4470	0.3981	0.3508
	Royse City	0.3209	0.2755	0.2335
	Howe	0.6162	0.5757	0.5343
2012	Leonard	0.8561	0.8323	0.8061
	Royse City	0.9362	0.9248	0.9118
	Howe	0.9999	0.9999	0.9999
Overall	Leonard	0.6850	0.6500	0.6135
	Royse City	0.7680	0.7355	0.7008
	Howe	0.9963	0.9950	0.9934
Overall		0.9817	0.9731	0.9614

Note: $(C_f + C_a)$ = $17.29/ha and P = $0.25/kg.

Table 10
Probability that net returns from treatment (per cultivar) will break even, be at least 25% greater than the tebuconazole investment, and be at least 50% greater than the tebuconazole investment.

Year	Cultivar	$PT[R_n > (1+ER)^*(C_f + C_a)]$		
		ER = 0%	ER = 25%	ER = 50%
2011	Coker 9553	0.6308	0.5976	0.5635
	Magnolia	0.4990	0.4620	0.4254
	Pioneer 25R47	0.2589	0.2285	0.2002
	Terral LA841	0.4994	0.4738	0.4484
2012	Coker 9553	0.9419	0.9308	0.9181
	Magnolia	0.9999	0.9999	0.9998
	Pioneer 25R47	0.7078	0.6887	0.6690
	Terral LA841	0.9987	0.9983	0.9978
Overall	Coker 9553	0.8240	0.8007	0.8007
	Magnolia	0.9805	0.9757	0.9701
	Pioneer 25R47	0.5543	0.5284	0.5024
	Terral LA841	0.9371	0.9244	0.9102
Overall		0.9817	0.9731	0.9614

Note: $(C_f + C_a)$ = $17.29/ha and P = $0.25/kg.

fungicide to winter wheat in Northeast Texas is likely to result in a yield gain necessary to cover or exceed fungicide application costs.

Tables 9 and 10 report the probabilities that net returns from treatment (per location and per cultivar respectively) will break even, be at least 25% greater than the tebuconazole investment, and be at least 50% greater than the tebuconazole investment. Table 10 shows that most of the cultivars have the potential to produce a yield gain that would break even on the tebuconazole spraying decision. Overall, the probability analysis indicates positive overall net returns are likely. In fact, the probability of a positive net return on a single application exceeded 0.50 in 12 out of 12 scenarios over the two years analyzed (i.e., overall). Unlike Tables 6 and 8, Tables 9 and 10 incorporate the uncertainty that is associated with treatment means. One shortcoming of looking simply at differences in mean returns is that "[m]ean separation results do not quantitatively describe the uncertainty associated with treatment means and can lead to misinterpretations" (Munkvold et al., 2001, p. 482).

4. Summary and conclusion

This study found positive (two-year average) net returns from treatment when a foliar fungicide (TebuStar® 3.6L) was applied as a preventive measure. During the first year (2011) the net return was estimated to be negative, −$3.53/ha, but wheat yield from the treated plots were not statistically different from the untreated plots at the 5% significance level. Although the emergence of a disease in one of the locations after the fungicide was applied may have affected yield in 2011, this new disease is not likely to have been the reason for the statistical insignificance, since this new disease affected both the treated and untreated plots at about the same rate. The statistical insignificance between the treated and untreated plots in 2011 may be attributed to the fact that 2011 was a year of moderate disease pressure, which means there probably was minimal potential yield loss between the treated and untreated plots at the time the fungicide was applied. Unlike 2011 and even when 2012 was a year of low disease pressure, wheat yield from the treated plots were statistically different from the untreated plots in 2012, and the net return from spraying tebuconazole in 2012 was estimated to be $107.70/ha.

Several studies have found statistical differences in yield between fungicide treated and untreated plots (Reid and Swart, 2004; Wiik and Rosenqvist, 2010). Fungicides increase the activity of the plant antioxidants and slow chlorophyll and leaf protein degradation (Zhang et al., 2010; Hunger and Edwards, 2012) allowing plants to keep their leaves longer, and consequently, using more nutrients during late developmental stages (Morris et al., 1989; Dimmock and Gooding, 2002). Although the statistical significance in 2012 could also be attributed to differences in uncontrollable factors between the treated and untreated plots, it is also possible that there could have been a late disease infection in the untreated plots (i.e., the emergence of a fungal disease in the untreated plots since it was last measured). Our findings in 2012, although relatively conservative (an overall 9.41% increase of the treated over the untreated plots), are consistent with previous studies. Reid and Swart (2004) reported yield increases of 34–41% of treated plots over untreated plots. Our relative conservative 9.41% overall yield gain in 2012 resulted in a positive return from investing in tebuconazole. In fact, the positive net return of $107.7/ha in 2012 offset the relatively small negative net return of −$3.53/ha in 2011, resulting in an overall positive net return of $52.09/ha.

Similar to Orum et al. (2006), there were statistical differences in yields and net returns among locations during each year. These differences may be attributed to small differences in soil types and their elevation above the sea level, and/or differences in several other uncontrollable factors such as rainfall, temperature, and wind. There were also statistical differences in yield and net returns among cultivars. Coker 9553, the most susceptible cultivar to common foliar diseases considered in the study, was generally statistically different from the other cultivars and it also provided the highest average. However, it did not provide the highest average net return from treatment. In fact, overall, none of the cultivars produced a net return from treatment that was statistically different from the other three cultivars considered.

A probability analysis based on Bayesian inference was also conducted to further assess whether a preventive application of a relatively inexpensive foliar fungicide to winter wheat in Northeast Texas is likely to result in a yield gain necessary to cover or exceed fungicide application costs. A Bayesian probability analysis has the advantage of incorporating some of the uncertainty that is associated with the treatment means. However, it should be emphasized that the cultivar's susceptibility, the timing of the fungicide applications, grain prices, and fungicide costs can influence the probability of a profitable fungicide application. When the plants were sprayed at approximately Feekes Growth stage 10, wheat price was $0.25/kg, and tebuconazole and its application cost were $17.29, our probability analysis indicated that positive overall net returns for the cultivars analyzed are likely, and that most of them have the potential to produce a yield gain that would break even on the tebuconazole spraying decision. Based on these probability results, it is recommended to apply a preventive application of tebuconazole. Foliar fungicides could be a particularly valuable tool managing winter wheat in regions of moderate to high disease pressure.

Our study also made several contributions to the current literature review on the economics of fungicide applications in wheat production. First, the study contributes with additional findings related to the economic effect of fungicide applications to prevent fungal diseases on wheat production. Second, the study illustrates the applicability of a Bayesian inference approach in evaluating net returns from fungicide applications. Finally, our study assists wheat farmers in Northeast Texas with economic tools that can be used in formulating educated expectations about their spaying decision and future net returns.

The study analyzed four red winter wheat cultivars (Magnolia, Terral LA841, Pioneer 25R47, Coker 9553), but due to data availability it was limited to two years (2011 and 2012). There were additional cultivars that were excluded from the analysis because they were not planted during 2011 and 2012. However, additional years can be analyzed when cultivars are grouped into categories.

For instance, Thompson et al. (2014) were able to analyze data from 2005 to 2012 by grouping cultivars into three categories (resistant, intermediate, and susceptible cultivars) and by assuming that two different fungicides provide similar disease control. On the contrary, our study has the advantage that it considers only one foliar fungicide (TebuStar® 3.6L). Similar to Hunger and Edwards (2012), an analysis can be conducted to explore whether different fungicides can be assumed to provide similar disease control. Furthermore, additional insight may be gained by studying the effects of TebuStar® 3.6L on the plant antioxidants, the plant chlorophyll, and the leaf protein degradation. Finally, it may also be relevant to further investigate the effect of weather (temperature humidity and precipitation) on fungal disease incidences as well as the timing of fungicide applications in Northeast Texas.

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