Economics of foliar fungicides for hard red winter wheat in the USA southern Great Plains

Nathanael M. Thompson a,1, Francis M. Epplin a,*, Jeffrey T. Edwards b,2, Robert M. Hunger c,3

a Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078-6026, USA
b Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078-6028, USA
c Department of Entomology & Plant Pathology, Oklahoma State University, Stillwater, OK 74078, USA

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A B S T R A C T
Grain yields of winter wheat (Triticum aestivum L.) in the southern Great Plains are often reduced by the presence of foliar diseases. This study was conducted to determine whether the application of foliar fungicides is an economically optimal management strategy. The effects of fungicide treatment on commercially available hard red winter wheat varieties with differing levels of genetic resistance (i.e., resistant, intermediate, and susceptible) to foliar diseases were investigated at two locations, Apache and Lahoma, OK, USA, for the harvest years 2005–2012. Two fungicides were rotated between the two locations and applied at approximately Feekes growth stage 9–10.5. When averaged across years, plots to which fungicide was applied generated greater average net returns than plots that did not receive fungicide for susceptible varieties at Apache, and for resistant, intermediate, and susceptible varieties at Lahoma. However, foliar fungicide application was not economical in every year at either location suggesting fungicide use should be reassessed each year given that profitability depends on year specific yield potential, prices, and foliar disease conditions. At both locations high disease incidence occurred in all but one site-year when the average March through May relative humidity exceeded 65%. Additional research would be required to determine the relationship between weather, including relative humidity, and disease incidence, and to develop an economic threshold for treatment decision aid.

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1. Introduction
Foliar diseases such as leaf rust (Puccinia triticina Erikkss.), stripe rust (Puccinia striiformis Westend. f. sp. tritici Erikkss.), and powdery mildew [Blumeria graminis (DC.) Speer f. sp. tritici emend. É.J. Marchal] often reduce the grain yield of winter wheat in the USA southern Great Plains. Yield losses from leaf rust alone have averaged over 3% per year from 1980 to 2011 in Oklahoma, with some individual year losses in excess of 10% (USDA ARS, 2012). Historically, control of these diseases through foliar fungicide applications has not been economical for U.S. producers (Milus, 1994). As a result, management of foliar diseases has largely relied on genetic resistance and other cultural practices such as crop rotations (Roelfs et al., 1992). However, in recent years there has been a growing interest in reevaluating fungicide treatments as part of an economically optimal foliar disease management plan.

Fungicides may be applied to protect yield potential that is present at the time of application by increasing the activity of plant antioxidants and slowing chlorophyll and leaf protein degradation (Zhang et al., 2010; Hunger and Edwards, 2012). By delaying leaf senescence, fungicides allow plants to keep their leaves longer, and thus use more nutrients during late developmental stages (Morris et al., 1989; Dimmock and Gooding, 2002). Nevertheless, De Wolf et al. (2012) describe the yield response of winter wheat to foliar fungicides as “highly variable.” This is primarily due to the large number of factors influencing this response, including the incidence and severity of specific foliar diseases, cultivar disease resistance, yield potential, timing of fungicide application, and environmental conditions (Kelley, 2001; De Wolf et al., 2012).

Some researchers have found that the potential for positive economic returns to fungicide treatment exists for winter wheat grown in Europe (Mercer and Ruddock, 2005; Wiik and Rosenqvist, 2005) and other parts of the world (Petersen et al., 2008; Zhou et al., 2008; Vahter and New, 2009). Therefore, this study was conducted to determine whether the application of foliar fungicides is an economically optimal management strategy.
Returns to fungicide treatment are also influenced by treatment cost and wheat price. If wheat price is high relative to fungicide treatment cost, positive returns are more likely. However, a high cost to benefit ratio (either from high cost of treatment or low wheat price or both) may negate the profitability of fungicide applications. In years when disease pressure is high (Wilk and Rosenqvist, 2010; Wegulo et al., 2011; Edwards et al., 2012a), Ransom and McMullen (2008) suggest that foliar fungicides always be applied to susceptible winter wheat varieties. However, varieties with genetic resistance to common foliar diseases have also been shown to generate positive economic returns to fungicide treatment in years of high disease severity (Ransom and McMullen, 2008; Edwards et al., 2012a).

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2. Materials and methods

2.1. Wheat grain yield

Hard red winter wheat grain yield data were produced in field experiments conducted during harvest years 2005–2012 at two locations, the Oklahoma State University North Central Research Station near Lahoma, OK, USA (36.38, –98.10) and an on-farm research site near Apache, OK (34.89, –98.39). Plots were lost at Apache in 2009 due to drought, and at Apache and Lahoma in 2007 due to excessive rainfall during harvest. Soil series was a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustoll) at Lahoma and a Port silt loam (fine-silty, mixed, superactive, thermic Cumulic Haplustolls) at Apache. Experimental design was a randomized complete block, split-plot with four replications. Whole plots were wheat cultivar and sub-plots were fungicide treatment.

Plots were sown in mid-October at a seeding rate of 67 kg ha\(^{-1}\). Plots were prepared using conventional tillage methods in all years except for 2010 at the Apache location, where plots were planted using no-tillage practices following full season soybean [Glycine max (L.) Merr.]. Conventional till plows were fifteen 15-cm rows wide by 6.7 m long and were sown using a Hege 500 small-plot, conventional drill (Wintersteiger, Salt Lake City, UT). No-till plots were seven 19-cm rows wide by 6.7 m long and were sown using a Great Plains no-till drill modified for small plot research (Kincad Manufacturing, Haven, KS). Conventional and no-till plots received in-furrow applications of 56 kg ha\(^{-1}\) diammonium polyphosphate (18-46-0) and 65 kg ha\(^{-1}\) of ammonium polyphosphate (10-34-0) at planting, respectively. Additional nitrogen application rates and timing varied by location and year, but were sufficient at Feekes growth stage 6 (Large, 1954) to produce at least 3360 kg ha\(^{-1}\) grain yield according to Oklahoma State University Extension recommendations (Zhang et al., 2009). Weeds and insects were controlled using commercially available pesticides as needed.

Cultivars tested varied by location and year with 15–24 commercially released cultivars per year. Varietal resistance for each wheat cultivar was determined based on average disease resistance rating to leaf rust, stripe rust, and powdery mildew using variety resistance ratings published in the previous year’s Oklahoma State University Extension variety comparison (Edwards et al., 2012b). These publications rate varieties on a scale of one to four, where one indicates high genetic resistance and four indicates high susceptibility to a particular disease. Varieties with average disease resistance ratings between 1.0 and 1.9 were considered resistant, 2.0–2.9 were intermediate, and greater than or equal to 3.0 were classified as susceptible to common foliar diseases. One-half of each plot was randomly selected to be treated with fungicide at approximately Feekes growth stage 9–10.5 using 140 L ha\(^{-1}\) of water carrier delivered through a bicycle-wheel, small-plot sprayer set 0.38 m above the plant canopy. Two foliar fungicides, Quilt (0.12 kg L\(^{-1}\) propiconazole and 0.75 kg L\(^{-1}\) azoxytrobin) and Stratego (0.12 kg L\(^{-1}\) propiconazole and 0.12 kg L\(^{-1}\) trifloxystrobin), were rotated between the two locations each year. Fungicides were applied at recommended rates of 1.02 kg ha\(^{-1}\) for Quilt and 0.73 kg ha\(^{-1}\) for Stratego, and were assumed to provide similar disease control based on the results of previous Oklahoma State University research studies (Hunger and Edwards, 2012).

Plots were harvested using a small plot combine (Hege 140, Wintersteiger, Salt Lake City, UT) when grain moisture content of all varieties was less than 12%. Wheel tracks between plots were included in the plot area for grain yield calculations, resulting in an overall plot width of 1.5 m. A 1.5 m alley was cut between fungicide treated and not treated sub-plots resulting in a final plot length of 5.2 m.
Analysis of variance (ANOVA) was performed using Proc Mixed in SAS (SAS Institute, 2012). Wheat grain yield was the dependent variable and fungicide treatment and varietal resistance and their interactions were treated as fixed effects with year treated as a random effect. Given significant differences in location, results for Apache and Lahoma sites were investigated separately. Least-squares mean grain yields were estimated using the LS means option in the Mixed procedure. Least-squares means were then compared for differences in fungicide treated and nontreated yields using the diff option with a Tukey–Kramer adjustment.

2.2. Partial budget analysis

A partial budgeting approach was used to estimate expected net returns for each evaluated foliar disease management strategy at both locations. Revenues were the product of mean grain yields and a 2013 USA wheat grain price of $0.275 kg$^{-1}$ (USDA AMS, 2013). Wheat yields were adjusted to account for yield losses associated with ground application for scenarios where fungicide was applied. Assuming a commercial-scale sprayer would make two 0.38 m tire tracks at the center of each spray swath, a sprayer with a 27.4 m boom width would result in a 2.8% ha$^{-1}$ yield reduction (Weisz et al., 2011). However, the potential exists for some of these wheat plants to recover and produce yield; so sensitivity analysis was done to determine the impact of yield loss on optimal disease management strategy. Average fungicide treatment cost was $38.47$ ha$^{-1}$; $25.00$ ha$^{-1}$ for materials and $13.47$ ha$^{-1}$ for ground application (Doye and Sahs, 2012). Fungicide treatment cost is also subject to variability given the availability of generic fungicides with comparable efficacy (De Wolf, 2013; Hunger and Edwards, 2012). Therefore, additional fungicide treatment cost scenarios of $28.47$ and $48.47$ ha$^{-1}$ were also evaluated.

Seed costs for wheat varieties with differing levels of resistance to foliar diseases were explored, but notable differences were unable to be quantified. Seed prices varied by many factors other than disease resistance traits such as insect resistance, test weight, and most importantly yield potential (Conley and Gaska, 2012). Therefore, seed cost and all other costs associated with wheat production were assumed constant and not included as part of the partial budgeting analysis.

2.3. Risk analysis

Depending on risk preferences, decision makers may not always prefer the alternative that generates the greatest expected net returns. Instead, they may be interested in both the expected returns and the variability or distribution of net returns. Stochastic dominance analysis allows for the simultaneous comparison of cumulative distribution functions (CDF) of net returns to alternative production strategies (Chavas, 2004). For this analysis, each season is assumed to be equally likely, and the years of the study are assumed to represent the entire distribution. Both first degree stochastic dominance (FSD) and SSD were performed.

The sole restriction placed on FSD is that the decision maker prefers more wealth to less. Therefore, an alternative with CDF $F$ dominates another alternative with CDF $G$ by FSD if $F(x) \leq G(x) \forall x$, where $x$ is some measure of wealth (e.g., mean returns minus fungicide treatment cost) (Chavas, 2004; Hardaker et al., 2004). This assumption is not very restrictive, and therefore tends to find few, if any, strategies that are unambiguously better than any of the alternatives. In other words, FSD often cannot successfully differentiate among the alternatives. Second degree stochastic dominance maintains the assumption that the decision maker prefers more wealth to less and adds the restriction that the decision maker is risk-averse. A sufficient condition for SSD is $\int G(x)dx \leq \int F(x)dx$ (Chavas, 2004; Hardaker et al., 2004). By adding this additional restriction, SSD is more discriminatory, and therefore has a greater chance of finding a strategy that would be economically preferable for a risk-averse producer. SSD and SSD analyses were conducted using Simetar (Richardson et al., 2005).

3. Results and discussion

Across the years of the study, yields from fungicide treated plots were significantly greater at the 0.1% level at Lahoma for all three wheat variety categories and at the 5% level for susceptible varieties at Apache (Table 1, Fig. 1). Similar to findings reported in previous literature, wheat grain yield response to foliar fungicide in this study varied by year and location (Kelley, 2001; Ransom and McMullen, 2008; Wiik and Rosengvist, 2010; Wenguo et al., 2011; De Wolf et al., 2012; Edwards et al., 2012a). Many of the individual year yield responses to fungicide treatment can be associated with observed disease incidence and severity (Table 2). For example, yield benefits from fungicide application were realized in resistant and intermediate varieties at Apache and Lahoma in 2012 when stripe rust severity was high at both locations. Relatively large yield benefits occurred at Lahoma in 2008, a year with high leaf rust incidence at that location.

Given similar soil qualities, the greater average yield benefits from fungicide treatment at Lahoma over Apache were likely the result of relatively greater incidence and severity of foliar diseases (Table 2). The study was not designed to determine why disease incidence may differ across the locations (Williams and Littlefield, 2004). The Lahoma location is approximately 170 km north of the Apache location. Average temperature, average relative humidity, and total precipitation for March through May at both locations for the years of the study are reported in Table 3. The average relative humidity at Apache was greater in 2010 (68%) and 2012 (71%) than in the other four seasons which averaged 61%. Stripe rust incidence was reported as high at Apache in both 2010 and 2012. Leaf rust incidence was also high in 2010 at Apache (Table 2). The average yield gain from using fungicides at Apache for susceptible varieties was greatest in these two years (560 kg ha$^{-1}$ in 2010 and 574 kg ha$^{-1}$ in 2012).

At Lahoma, incidence of either leaf rust or stripe rust or both was rated high in every year except for 2006 and 2011. The average relative humidity was lowest for these two years (57% in 2006 and 63% in 2011). For the other four seasons for which incidence of either leaf rust or stripe rust or both was rated high, the relative humidity averaged 69%. Averaged across the two years with lower average relative humidity and no high incidence of disease (2006 and 2011) the average estimated difference in mean yields between the treated and untreated plots at Lahoma across the three categories of varieties was a nearly negligible 65 kg ha$^{-1}$.

As noted, the study was not designed to determine why disease incidence may differ across the locations. However, these findings suggest that further research may be warranted to determine the relationship between weather, including relative humidity, and disease incidence. If disease incidence could be predicted based on weather events prior to Feekes growth stage 9–10.5, it could be combined with other information including cost to treat and expected wheat price, to determine an economic threshold for treatment. Armed with this information, growers could treat in years with a high probability of economic benefit and avoid treatment in other years.

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4 For a more detailed discussion of first and second degree stochastic dominance see Chavas (2004) or Hardaker et al. (2004).
and Lahoma (expected, the greatest average increase in expected net returns was 17.32, df = 1, 1106). Individual wheat cultivars were categorized as either resistant, intermediate, or susceptible based on average rating for resistance to leaf rust, stripe rust, and powdery mildew. Plots were lost at both locations in 2007 due to excessive rainfall at harvest and at Apache in 2009 due to drought. Realized for susceptible varieties at both locations (Mercer and Ruddock, 2005; Ransom and McMullen, 2008; Edwards et al., 2012a). Holding wheat price and yield loss from wheel tracking constant, sensitivity analysis for fungicide treatment cost ($\pm 10$ ha$^{-1}$) did not change the expected net returns maximizing disease management strategy at Apache or Lahoma. In addition, decreasing the yield loss from wheel tracking during fungicide application to 1.8 to reflect the potential for some plants to recover and produce yield also did not change the optimal disease management strategy at either location.

Breakeven wheat prices were estimated for three fungicide treatment cost scenarios at each location (Table 5). As expected, resistant and intermediate varieties command higher breakeven wheat prices than susceptible varieties at both locations. Breakeven prices at Apache were higher than Lahoma due to the differences in average yield response to fungicide treatment. At Apache, break-even prices ranged from $0.18 to $1.23 \text{ kg}^{-1}$. For the budgeted wheat price, of $0.275 \text{ kg}^{-1}$, conditions that prevailed at Apache during the course of the experiment did not warrant fungicide treatment for resistant or intermediate varieties. Estimated break-even wheat prices at Lahoma were all below the budgeted wheat price of $0.275 \text{ kg}^{-1}$ and ranged from $0.05 to $0.18 \text{ kg}^{-1}$.

Although fungicide treatment increased expected net returns in some cases, it also increased standard deviations of net returns, meaning higher variability or risk. For this reason, CDFs of net returns were evaluated using stochastic dominance. As expected, FSD yielded large efficient sets at both locations (Table 6). None of the fungicide treatments significantly increased grain yields of resistant, intermediate, or susceptible varieties at Apache and Lahoma.

Average differences across years in expected net returns between fungicide treated and nontreated plots for resistant, intermediate, and susceptible varieties were $-28.5, -19.5,$ and $61.5 \text{ ha}^{-1}$ at Apache, and $36.5, 36.5$, and $116 \text{ ha}^{-1}$ at Lahoma (Table 4). As expected, the greatest average increase in expected net returns was realized for susceptible varieties at both locations (Mercer and Ruddock, 2005; Ransom and McMullen, 2008; Edwards et al., 2012a). Holding wheat price and yield loss from wheel tracking constant, sensitivity analysis for fungicide treatment cost ($\pm 10$ ha$^{-1}$) did not change the expected net returns maximizing disease management strategy at Apache or Lahoma. In addition, decreasing the yield loss from wheel tracking during fungicide application to 1.8 to reflect the potential for some plants to recover and produce yield also did not change the optimal disease management strategy at either location.

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regardless of specific year factors. Lower observed disease incidence and severity did not justify a strategy to apply fungicide every year at this location. Dominance of intermediate varieties was likely the result of higher yield potential of some varieties classified as intermediately resistant to common foliar diseases. As described by Brown (2002), plant breeders’ most effective strategy may not be to select for excellent disease resistance if that means sacrificing yield, but rather select for moderate resistance and maintain yield potential.

At Lahoma, planting resistant wheat varieties and use of fungicide was identified by SSD as the appropriate foliar disease management strategy for risk-averse producers who plan to use the same strategy year-after-year regardless of specific year factors. In other words, based on the data produced in the field experiments, the foliar disease management strategy with the highest level of protection would be recommended for risk-averse producers at a location with relatively high levels of disease incidence and severity.

4. Conclusions

The objective of this research was to determine the expected net returns to fungicide treatment on hard red winter wheat cultivars with differing levels of foliar disease resistance in the USA southern Great Plains, and to determine if fungicide treatment is part of an economically optimal risk management strategy. Previous literature has focused on the agronomic and economic benefits of fungicide treatment, but ignored the risk associated with foliar disease management decisions. When averaged across the years, yields from fungicide treated plots were significantly greater at the 0.1% level at Lahoma for all three wheat variety categories and at the 5% level for susceptible varieties at Apache. However, yield response was not the same at both locations and yields from treated plots were not greater in every year.

To the extent that the years included in the study include the entire distribution of weather and other yield impacting events, and under the assumption that each season is equally likely, second degree stochastic dominance analysis can provide recommended strategies for a risk-averse producer who plans to use the same strategy year-after-year regardless of specific year factors. For risk-averse producers whose production conditions are similar to those encountered at the Apache location, stochastic dominance identified planting wheat varieties with intermediate resistance to foliar diseases and not using fungicide as the preferred strategy. Lower observed disease incidence and severity would not have justified a strategy to apply fungicide in every year at Apache. Dominance of intermediate varieties was likely the result of higher yield potential of some varieties classified as intermediately resistant to considered diseases.

Second degree stochastic dominance also identified a single strategy for risk-averse producers whose production conditions are similar to those encountered at the Lahoma location and who plan to use the same strategy year-after-year regardless of specific year factors. For these producers given the conditions that prevailed during the course of the study, stochastic dominance identified planting wheat varieties classified as resistant and treating with fungicide as the preferred strategy.

A recommendation for risk-averse producers who farm at one location to apply fungicide every year and for risk-averse farmers

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### Table 4

Descriptive statistics for expected returns minus fungicide treatment costs by foliar disease management strategy and location.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Mean $ ha$⁻¹</th>
<th>Standard deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apache</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Fungicide</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistant</td>
<td>786</td>
<td>308</td>
<td>351</td>
<td>1103</td>
</tr>
<tr>
<td>Intermediate</td>
<td>802</td>
<td>275</td>
<td>391</td>
<td>1098</td>
</tr>
<tr>
<td>Susceptible</td>
<td>784</td>
<td>279</td>
<td>368</td>
<td>1154</td>
</tr>
<tr>
<td>Fungicide</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistant</td>
<td>758</td>
<td>292</td>
<td>324</td>
<td>1006</td>
</tr>
<tr>
<td>Intermediate</td>
<td>783</td>
<td>280</td>
<td>349</td>
<td>1020</td>
</tr>
<tr>
<td>Susceptible</td>
<td>790</td>
<td>297</td>
<td>335</td>
<td>1068</td>
</tr>
<tr>
<td>Lahoma</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Fungicide</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistant</td>
<td>947</td>
<td>254</td>
<td>507</td>
<td>1315</td>
</tr>
<tr>
<td>Intermediate</td>
<td>930</td>
<td>277</td>
<td>433</td>
<td>1296</td>
</tr>
<tr>
<td>Susceptible</td>
<td>855</td>
<td>261</td>
<td>365</td>
<td>1256</td>
</tr>
<tr>
<td>Fungicide</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Resistant</td>
<td>983</td>
<td>271</td>
<td>518</td>
<td>1392</td>
</tr>
<tr>
<td>Intermediate</td>
<td>966</td>
<td>289</td>
<td>469</td>
<td>1324</td>
</tr>
<tr>
<td>Susceptible</td>
<td>971</td>
<td>287</td>
<td>459</td>
<td>1276</td>
</tr>
</tbody>
</table>

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### Table 5

Breakeven wheat grain prices by location and varietal resistance for three fungicide treatment cost scenarios.

<table>
<thead>
<tr>
<th>Location</th>
<th>Varietal resistance</th>
<th>Fungicide treatment cost ($ ha⁻¹)</th>
<th>$ $28.47</th>
<th>$ $38.47</th>
<th>$ $48.47</th>
<th>$ $kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apache</td>
<td>Resistant</td>
<td>$0.72b</td>
<td>$0.98</td>
<td>$1.23</td>
<td>$1.50</td>
<td>$0.004</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>$0.41</td>
<td>$0.56</td>
<td>$0.71</td>
<td>$0.86</td>
<td>$0.002</td>
</tr>
<tr>
<td></td>
<td>Susceptible</td>
<td>$0.18</td>
<td>$0.24</td>
<td>$0.30</td>
<td>$0.36</td>
<td>$0.001</td>
</tr>
<tr>
<td>Lahoma</td>
<td>Resistant</td>
<td>$0.11</td>
<td>$0.14</td>
<td>$0.18</td>
<td>$0.22</td>
<td>$0.001</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>$0.05</td>
<td>$0.07</td>
<td>$0.09</td>
<td>$0.10</td>
<td>$0.001</td>
</tr>
</tbody>
</table>

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### Table 6

Stochastic dominance results by location.

<table>
<thead>
<tr>
<th>Efficient set</th>
<th>Apache</th>
<th>Lahoma</th>
</tr>
</thead>
<tbody>
<tr>
<td>First degree stochastic dominance (FSD)</td>
<td>R-F</td>
<td>R-F</td>
</tr>
<tr>
<td></td>
<td>R-NF</td>
<td>R-NF</td>
</tr>
<tr>
<td></td>
<td>I-F</td>
<td>I-F</td>
</tr>
<tr>
<td></td>
<td>I-NF</td>
<td>I-NF</td>
</tr>
<tr>
<td></td>
<td>S-F</td>
<td>S-F</td>
</tr>
<tr>
<td></td>
<td>S-NF</td>
<td>S-NF</td>
</tr>
<tr>
<td>Second degree stochastic dominance (SSD)</td>
<td>I-NF</td>
<td>R-F</td>
</tr>
</tbody>
</table>

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Notes:

- R-F = resistant, fungicide treated, R-NF = resistant, not fungicide treated, I-F = intermediate, fungicide treated, I-NF = intermediate, not fungicide treated, S-F = susceptible, fungicide treated, S-NF = susceptible, not fungicide treated.

- a Mean returns minus fungicide treatment costs were estimated using mean grain yields reported in Table 1, wheat price of $0.275 kg⁻¹ fungicide treatment cost of $38.47 ha⁻¹, and a 2.8% yield loss from wheel tracking during fungicide application.

- b Individual wheat cultivars were categorized as either resistant, intermediate, or susceptible based on average rating for resistance to leaf rust, stripe rust, and powdery mildew.

- c Breakeven prices were estimated assuming a 2.8% yield loss from wheel tracking during fungicide treatment. Lower yield losses would result in lower breakeven prices.
who farm under similar soil and climate conditions only 170 km distant, to not apply fungicide is not very satisfying. Indeed, what would the recommendation be for a risk-averse grower whose farm was equidistant between the two study sites? Clearly, the findings suggest a need for additional research to try to determine factors that cause, or are associated with, greater disease incidence. If disease incidence could be predicted based on parameter values revealed prior to Feekes growth stage 9–10.5, the prediction of incidence could be combined with estimated treatment cost and expected wheat price, to determine an economic threshold for treatment. Extension personnel could then provide a recommendation for growers to apply fungicide in regions and years with a high probability of economic benefit and avoid treatment in regions and years with a low probability of economic benefit.

At both locations incidence of either leaf rust or stripe rust or both was rated high in years with relatively greater average relative humidity during the March through May period. At Apache, in years when the average relative humidity during the March through May period was 68% or greater, stripe rust disease was rated as high and the average yield gain from using fungicides for susceptible varieties was greatest in these years (567 kg ha$^{-1}$). At Lahoma, in years when the average relative humidity during the March through May period was 68% or greater, either stripe rust or leaf rust or both were rated as high, and the yield gain from use of fungicides was greatest in these years. And, in years during which the average relative humidity was less than 64% average yields of treated and untreated plots across the three variety classifications differed by only 65 kg ha$^{-1}$.

Additional research would be required to test the relationship between relative humidity and other environmental factors and disease incidence. The ultimate goal would be to develop an economic threshold decision aid that could be used to provide a timely recommendation to farmers based on conditions for specific locations for the specific growing season enabling growers to apply fungicide in regions and years with a high probability of economic benefit and avoid treatment in regions and years with a low probability of economic benefit.

Results of this analysis suggest that fungicide treatment on hard red winter wheat in the southern Great Plains can be an economically sound management strategy under some conditions. Despite the variable response, fungicide treatment did tend to protect producers from the downside risk of large yield losses in years of high disease incidence and severity, especially when growing wheat varieties susceptible to common foliar diseases.

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