Evaluation of disease, yield and economics associated with fungicide timing in Canadian Western Red Spring wheat

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Abstract: Protection from fungal plant pathogens is key for optimizing the yield and quality of wheat (*Triticum aestivum* L.). However, current grower practices and historical research do not always align with respect to optimum fungicide timing to maximize disease control, yield, quality, and profitability of Canadian Western Red Spring (CWRS) wheat. Six fungicide treatments were evaluated at eight site-years across Alberta in 2018 and 2019 to determine the optimum time for fungicide application. The treatments included early fungicide applications at BBCH 22–23 (herbicide timing), early- to mid-season application at BBCH 30–32 (plant growth regulator timing), 'traditional' timing at BBCH 39–45 (flag leaf), and head timing at BBCH 61–63 (Fusarium head blight timing) and were compared with a non-treated control. Yield responses to fungicide treatments occurred at 50% of the site-years when disease pressure was 32% higher than in non-responsive site-years. Responsive site-years were characterized by higher relative humidity (65.4–74.0%) and an average 273 mm of precipitation. At responsive site-years, McFadden leaf spot disease severity ratings were 50% greater in early August when fungicides were applied at BBCH 22–23 and 30–32 versus at BBCH 39–45. At responsive sites, yield and thousand-kernel weight were 9.3% and 5.2%, higher, respectively, for fungicide applications at BBCH 39–45 and BBCH 61–63 compared with fungicide applications at BBCH 22–23 and BBCH 30–32. The most economically beneficial practices were applications of propiconazole, benzovindiflupyr and azoxystrobin (Trivapro A+B) at BBCH 39–45 or prothioconazole and tebuconazole (Prosolan XTR) at BBCH 61–63 when environmental conditions were conducive for disease development.

Key words: *Triticum aestivum*, fungicide timing, economical analysis, foliar leaf spot.

Résumé : Pour optimiser le rendement et la qualité du blé (*Triticum aestivum* L.), il est capital de le protéger contre les champignons phytopathogènes. Malheureusement, les pratiques agricoles actuelles et les recherches dans le passé ne concordent pas toujours sur le moment où les fongicides devraient être appliqués pour obtenir les meilleurs résultats sur les plans de la lutte contre la maladie, du rendement, de la qualité et de la rentabilité avec le blé roux de printemps de l’Ouest canadien (CWRS). En 2018 et 2019, les auteurs ont évalué six fongicides à huit années-sites, en Alberta, en vue d’établir le moment idéal pour leur application. Les traitements étaient les suivants : application hâtive au stade BBCH 22–23 (en même temps que l’herbicide); application du début au milieu de la saison, au stade BBCH 30–32 (en même temps que le régulateur de croissance); application « classique », au stade BBCH 39–45 (feuille paniculaire); application à l’épiaison, au stade BBCH 61–63 (avec l’apparition de la brûlure de l’épi). Les résultats ont été comparés à ceux obtenus sur la parcelle témoign non traitée. Le fongicide a affecté le rendement la moitié des années-sites, quand la pression exercée par la maladie était de 32 % plus importante que les années-sites où le rendement n’avait pas été affecté. Les années-sites où une réaction a été notée, le taux d’humidité relative était plus élevé (65,4 à 74,0 %), avec des précipitations moyennes (273 mm de pluie). Les années-sites où les auteurs ont relevé une réaction, la gravité de la tache foliaire selon l’indice de McFadden était de 50 % plus importante au début d’août, quand on avait appliqué le fongicide aux stades BBCH 22–23 et 30–32 plutôt qu’au stade BBCH 39–45. Là où une réaction a été observée, le rendement et le poids de mille grains avaient augmenté respectivement de 9,3 % et de 5,2 % quand le fongicide avait été appliqué aux stades BBCH 39–45 et BBCH 61–63 when environmental conditions were conducive for disease development.
Introduction

Wheat (Triticum spp.) is the leading cereal grain produced, consumed, and traded globally. Canada was among the top 10 producers of wheat worldwide in 2018, growing approximately 32,011 metric tons, and was also one of the top three exporting countries in 2017 (FAOSTAT 2017; Statistics Canada 2019). Canadian Western Red Spring (CWRS) wheat (Triticum aestivum L.) has high protein levels and is valued for its superior milling and baking qualities (Canadian Grain Commission 2020).

In Canada, there are about 20 different fungal pathogens that can infect wheat (Aboukhaddour et al. 2020). Since the early 2000s, tan spot [Pyrenophora tritici-repentis (Died.) Drechsler], Fusarium head blight (FHB) [Fusarium spp.], and stripe rust [Puccinia striiformis Westend.] (Murray et al. 2015) have been a major concern throughout Canada, with different geographic areas being at risk of different diseases (Aboukhaddour et al. 2020).

Each pathogen can cause high levels of disease depending on the year and geographic area and are strongly influenced by weather conditions (Agrios 2004). Specifically, in Alberta, tan spot, stripe rust, septoria nodorum blotch (SNB) [Parastagonospora nodorum (Berk.) Quaedvlieg, Verkley, & Crous] and septoria tritici blotch (STB) [Zymoseptoria tritici (Roberge ex Desm.) Quaedvli. & Crous [syn. Mycosphaerella graminicola (Fuckel) J. Schröt.]] are diseases of concern. Alberta has seen an increase in FHB, but the disease is still limited mainly to southern Alberta with only a few cases in central and northern Alberta (Alberta Agriculture and Forestry 2020; Harding et al. 2018). Surveillance for FHB is a top priority as the risk of infection increases in the province (Pest Management Program 2019).

Previous research conducted in Saskatchewan found the optimal time to apply fungicide on spring wheat is between the flag leaf and medium milk growth stages (BBCH 41–72) (Meier 2018; Duczek and Jones-Flory 1994). Fungicide applications at BBCH 61–63 (start of flowering: first anthers visible to 30% of anthers mature) have been reported to reduce head and foliar disease levels, deoxynivalenol (DON) in the grains, and to protect yield and quality (MacLean et al. 2018; Wiersma and Motteberg 2005). However, there are many reports of farmers applying fungicides much earlier (i.e., tank-mixing fungicide with herbicides, at herbicide timing, or tank-mixing fungicide with plant growth regulators (PGRs) at early stem elongation), presumably in an attempt to manage cereal diseases proactively, reduce application costs, or for reasons of convenience or habit.

Traditional fungicide timing strategies may need to be re-evaluated as new cultivars are registered. In Canada, five fungal diseases [stem rust (Puccinia graminis subsp. graminis Pers.:Pers.), stripe rust, leaf rust [Puccinia triticina (Erikss.) Syd.], common bunt [Tilletia caries (DC.) Tul. & C. Tul], and FHB] (Murray et. al 2015) are ‘Priority 1’ diseases addressed in Canadian wheat breeding programs (Aboukhaddour et al. 2020). Wheat breeding in western Canada from 1885 onwards has led to improvements in several agronomic traits and disease resistance (Iqbal et al. 2016). Iqbal et al. (2016) reported older CWRS cultivars were more susceptible to leaf rust than new cultivars, suggesting that new cultivars may show less response to fungicide applications. However, there has been no research to identify the optimum fungicide timing on current CWRS spring wheat cultivars with improved disease resistance packages.

Currently, there are no studies evaluating the impact of leaf spot diseases (STB, SNB, tan spot) and FHB on the yield and quality of modern CWRS wheat cultivars with improved genetic resistance to plant disease. Therefore, the objective of this study was to determine the effects of single fungicide applications timings at Biologische Bundesanstalt, Bundessortenamt, and Chemical (BBCH) growth stage 22–23 [2–3 tillers (herbicide timing)] (Meier 2018), BBCH 30–32 [stem elongation (plant growth regulator (PGR) timing)], BBCH 39–45 (flag leaf timing), and BBCH 61–63 [10%–30% of anthers are mature (head timing)] on leaf spot disease severity, yield, quality, and economics. Two of the most commonly grown CWRS cultivars, AAC Brandon (Cuthbert et al. 2016) and AAC Viewfield (Cuthbert et al. 2018), were tested.

Materials and Methods

Field setup

Field experiments, designed as a split plot, were conducted in Alberta, Canada, over two growing seasons in 2018 and 2019 at three rain-fed sites (Barrhead, Bon Accord, and Red Deer) and one irrigated site (Lethbridge). Precipitation, temperature, relative humidity (RH), and FHB risk values were obtained from the nearest Alberta Climate Information System (ACIS) station from seeding date to physiological maturity based on days to maturity (DTM) (Table 1). For the Barrhead 2018 (54.1°N, −114.2°W) and 2019 (54.1°N, −114.3°W) field sites, the Barrhead CS weather station was used, which was approximately 20 km and 11 km away from each site, respectively. The St. Albert weather station was
Table 1. Observed precipitation, relative humidity, temperature, seeding dates, harvest dates, and soil types for 8 site-years over two growing seasons in 2018 and 2019. Barrhead 2018, Bon Accord 2018, Lethbridge 2018, and Lethbridge 2019 were considered non-responsive to fungicide treatments, while Barrhead 2019, Bon Accord 2019, Red Deer 2018, and Red Deer 2019 were considered responsive to fungicide treatments.

| Location       | Year  | Seeding date | Harvest date | Physiological maturity<sup>a</sup> | DTM (days) | Relative humidity (%)<sup>b</sup> | Air temperature (°C)<sup>b</sup> | May–June precipitation Observed<sup>b</sup> | Long-term<sup>b,c</sup> | Growing season precipitation (mm) Observed<sup>b</sup> | Long-term<sup>b,c</sup> | Soil type<sup>e</sup> |
|----------------|-------|--------------|--------------|-----------------------------------|-----------|----------------------------------|-----------------------------|---------------------------------------------|-----------------------|---------------------------------------------|-----------------------|---------------------|
| Non-responsive sites |       |              |              |                                   |           |                                  |                             |                                             |                       |                                             |                       |                     |
| Barrhead       | 2018  | May 2        | Oct. 1       | Aug. 12                            | 103       | 62.5                             | 16.0                        | 83                            | 89                    | 214                           | 247                   | Solonetzic Dark Gray Chernozem |
| Bon Accord     | 2018  | May 3        | Oct. 4       | Aug. 20                            | 110       | 63.7                             | 16.0                        | 75                            | 81                    | 207                           | 250                   | Eluviated Black Chernozem |
| Lethbridge     | 2018  | May 7        | Sep. 6       | Aug. 15                            | 104       | 57.7                             | 17.2                        | 69                            | 91                    | 121<sup>d</sup>             | 182                   | Dark Brown Chernozem        |
| Lethbridge     | 2019  | Apr. 15      | Sep. 4       | Aug. 12                            | 120       | 60.3                             | 14.2                        | 71                            | 91                    | 159<sup>d</sup>             | 207                   | Dark Brown Chernozem        |
| Average of non-responsive sites |       |              |              |                                   | 109       | 61.1                             | 15.8                        | 75                            | 88                    | 175                           | 222                   |                     |
| Responsive sites |       |              |              |                                   |           |                                  |                             |                                             |                       |                                             |                       |                     |
| Barrhead       | 2019  | May 6        | Sep. 30      | Aug. 27                            | 114       | 69.1                             | 14.2                        | 132                           | 89                    | 262                           | 269                   | Solonetzic Dark Gray Chernozem |
| Bon Accord     | 2019  | May 6        | Sep. 23      | Sep. 13                            | 131       | 72.3                             | 14.0                        | 161                           | 81                    | 364                           | 284                   | Eluviated Black Chernozem |
| Red Deer       | 2018  | May 21       | Oct. 16      | Sep. 5                             | 108       | 65.4                             | 15.3                        | 82<sup>f</sup>                | 98                    | 194<sup>f</sup>             | 275                   | Orthic Black Chernozem       |
| Red Deer       | 2019  | May 24       | Oct. 19      | Sep. 28                            | 128       | 74.0                             | 13.4                        | 71<sup>f</sup>                | 91                    | 272<sup>f</sup>             | 305                   | Orthic Black Chernozem       |
| Average of responsive sites |       |              |              |                                   | 120       | 70.2                             | 14.2                        | 112                           | 90                    | 273                           | 283                   |                     |

<sup>a</sup>Physiological maturity was calculated by adding the recorded DTM from seeding date (eg: May 6<sup>th</sup> + 114 days = Aug. 27<sup>th</sup>).<br>
<sup>b</sup>Data were collected from Alberta Climate Information System (ACIS) from each site’s respective seeding date to physiological maturity based on days to maturity (DTM).<br>
<sup>c</sup>Long-term precipitation obtained from interpolated data.<br>
<sup>d</sup>Growing season precipitation plus the average irrigation volume (29.5 mm) over 8 irrigation events in the growing season (May to August) at the Lethbridge site.<br>
<sup>e</sup>Soil descriptions from Alberta soil information viewer provided by Alberta Agriculture and Forestry (2015).<br>
<sup>f</sup>Observed rainfall data for Red Deer location obtained from Lacombe CDA station.
about 48 km away from the Bon Accord 2018 site (53.8°N, −113.3°W) and about 11 km away from the Bon Accord 2019 field site (53.7°N, −113.6°W). The Lethbridge Farm Irrigation Management Climate Information Network weather station was used for the Lethbridge field site in 2018 and 2019 (49.7°N, −112.7°W), which was located 400 m from the site. For the Red Deer 2018 site (52.2°N, −113.8°W) and Red Deer 2019 site (52.2°N, −113.9°W), the Red Deer regional station was used as the source of RH and temperature data. Both sites were between 12 and 16 km away from the station, respectively. However, this weather station did not have FHB risk values, or observed precipitation data, so the Lacombe CDA station was used to collect these data. The Lacombe CDA station was approximately 47 km away from the Red Deer sites.

Trials were seeded at a depth of 2–5 cm, in canola stubble, on fields with a history of short wheat rotations (wheat-canola-wheat-canola), to increase chances of cereal leaf disease and to mimic the typical rotations used by many farmers in this region of western Canada.

Certified seed was treated with tebuconazole (1-(4-chlorophenyl)-4,4-dimethyl-3-(1H-1,2,4-triazol-1-ylmethyl) pentan-3-ol), prothioconazole (2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1H-1,2,4-triazole-3-thione) and metalaxyl (Methyl N-(2,6-dimethylphenyl)-N-(methoxyacetyl)alaninate) formulated as Raxil PRO at a rate of 325 mL·100 kg⁻¹ of seed. Pre-seed or pre-emergence herbicide applications consisted of 900 g ai L⁻¹ ha⁻¹ of glyphosate (N-(phosphonomethyl) glycine) tank-mixed with Saflufenacil formulated as Heat LQ at a rate of 18 g ha⁻¹ rate. Two herbicide products were applied in-crop for weed control. The first included florasulam (N-(2,6-difluorophenyl)-8-fluoro-5-methoxy (1,2,4)-triazolo-(1,5c) pyrimidine-2-sulfonamide), fluroxypyr (1-methylheptyl(4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy) acetic acid) and MCPA formulated as Stellar XL at rate of 988 mL ha⁻¹. The second product was pinoxaden formulated as Axial BIA at a rate of 1.2 L ha⁻¹. These herbicides were not tank-mixed but were applied to coincide with early fungicide applications at BBCH 22–23. The PGR trinexapac-ethyl was applied at a rate of 100 gi ha⁻¹ to all plots at BBCH 30–32 (stem elongation) at 100 L ha⁻¹.

Fungicide treatments

Data reported herein are a sub-set of data collected as part of a larger study (Asif 2020). Five fungicide treatments and a non-treated control were compared (Table 2). The larger study was designed as a split-plot with four blocks. The main plot was the cultivar, and the sub-plot was fungicide treatment. Three fungicide products were applied at four growth stages to form the five fungicide treatments: (i) Tilt 250E (Syngenta 2019) and (ii) Trivapro A+B (Syngenta 2020) [both fungicide products are registered to control Septoria leaf spot (Septoria spp.) and tan spot (P. tritici-repentis)] at BBCH
Cultivars

In 2019, the top five CWRS cultivars grown on the Canadian Prairies included AAC Brandon, AAC Elie, CDC Landmark, AAC Viewfield, and CDC Plentiful (Canadian Grain Commission 2019a). The two cultivars used in this study were AAC Brandon and AAC Viewfield. In 2019, about 42% of CWRS hectares in western Canada were seeded to AAC Brandon, while 6% were seeded to AAC Viewfield. AAC Brandon is resistant to the prevalent races of leaf, stem, and stripe rust (Cuthbert et al. 2016). It is moderately resistant to loose smut and FHB. AAC Viewfield has intermediate resistance to FHB (Cuthbert et al. 2018). It is classified as resistant to yellow rust and stem rust and has moderate resistance to leaf rust and common bunt. Both cultivars are rated as having intermediate resistance to leaf spots (Alberta Seed Growers and Alberta Seed Processors 2020). AAC Brandon and AAC Viewfield represent genetic improvements in leaf spot resistance compared with other previously grown CWRS cultivars, Stettler and CDC Go, which have moderately susceptible and susceptible ratings, respectively.

AAC Brandon was registered with the Canadian Food Inspection Agency (CFIA) in 2013 (Cuthbert et al. 2016). It is a semi-dwarf variety with a low lodging score indicating strong straw. The cultivar’s yield, time to maturity, and test weight were within the range of the checks. AAC Viewfield was registered with the CFIA in 2016 and yielded significantly greater and matured later than the checks, Lillian and Katepwa (Cuthbert et al. 2018). Like AAC Brandon, AAC Viewfield is a semi-dwarf that was significantly shorter than all checks with a low lodging score. Both cultivars have a grain protein concentration within the range of the checks.

Data collection — agronomic traits, yield, and quality

Ten main stem heads were arbitrarily collected from each plot at 30% (thumbnail does not dent kernel) to 40% (moisture comes out of kernel) grain moisture to determine the DTM according to Karamanos et al. (2008). Grain was harvested using Wintersteiger Delta small plot combines (Wintersteiger Inc., Saskatoon, SK) equipped with a 2012 classic grain gauge automatic weigh system. Thousand-kernel weight (TKW) was measured on an individual plot basis by weighing 500 kernels and multiplying by two. Test weight was determined either automatically by the combine weigh system or measured with a GAC 2100 Dickey-john grain moisture tester (Churchill Industries, Minneapolis, MN). Grain protein concentrations were determined with a DS2500 near-infrared reflectance (NIR) spectrometer (FOSS, Eden Prairie, MN) and adjusted to standard grain moisture content and final protein levels were adjusted to 14.5% moisture. Plant heights were measured at BBCH 83 by taking the height of the main tiller from ground level to the top of the spike, not including the awns. Lodging was assessed at BBCH 89 on a 1–9 scale, where 1 = no lodging or ‘erect’ and 9 = severe lodging or ‘flat’.

Data collection — leaf spot disease

Leaf spot disease severity was rated using the assessment scale of McFadden (1991) which evaluates the severity of leaf spots on the lower, middle, and upper regions of a cereal plant. It is based on a 0–11 scale, with 0 indicating no disease and 11 indicating 26%–50% of the upper leaf area is covered with leaf spot disease lesions, and 50% of the middle and lower leaf area is covered with leaf spot disease lesions. McFadden leaf spot disease severity ratings were conducted immediately prior to each fungicide application (at growth stages BBCH 22–23, 30–32, 39–45, and 61–63) and two weeks after each fungicide application with the final assessment at approximately BBCH 83–85 in late July or early August. (Table 3). Only plots receiving a fungicide application were rated prior to fungicide applications.

To further quantify leaf spot disease levels, 10 representative flag leaves were collected two weeks after the fungicide applications at BBCH 61–63, which occurred in late July or early August (approximately at BBCH 83–85). These leaves were taped to plastic sheets, scanned, and assessed with Assess 2.0 Image Analysis Software for Disease Quantification (Lamari 2002). The calibration values were adjusted either manually or automatically according to picture quality and level of leaf disease.

At each time that a McFadden visual disease rating assessment was conducted, 10 representative, symptomatic young leaves were collected. For each symptomatic leaf, a small necrotic section or lesion (about 10 mm × 25 mm) was cut from the leaf and run under tap water for 1 h. Then, the leaf sections were surface-sterilized with 1% NaOCl for 1 min and plated on 1% water agar with 50 mg L⁻¹ Streptomycin. Plates were incubated at room temperature under 12/12 h light/dark for 2 d. Samples were then examined under a microscope to identify the leaf spot disease pathogens of concern: Z. tritici, causal agent of STB; S. nodorum, causal agent of SNB; and P. tritici-repentis, causal agent of tan spot, according to physical characteristics. To differentiate between Z. tritici and S. nodorum, the lesions and asexual fruiting bodies (pycnidia) were examined under a compound microscope. If pycnidia were present and rectangular lesions ran parallel to leaf veins, they were considered...
Z. tritici; if pycnidia were present and the lesions were lens shaped, they were considered S. nodorum (Bailey et al. 2003; Eyal et al. 1987). If the lesions ran along the veins but pycnidia were not present, the conidiophores were examined under a dissecting microscope to determine if a sample was P. tritici-repentis (Bailey et al. 2003). If the conidiophores were erect and simple with a swollen base, then the pathogen was considered P. tritici-repentis (Ellis and Waller 1976). If conidiophores were difficult to identify, then a slide was prepared to examine spores under a compound microscope to confirm whether it was P. tritici-repentis. If not, the samples were considered to be infected with an unknown pathogen.

Data collection — Fusarium head blight

Fusarium-damaged kernels (FDK) were hand-picked from a 500 g subsample of uncleaned harvested grain, straight from the combine, to ensure that FDK were properly represented in the subsample. Percent FDK was calculated by dividing the weight of FDK kernels by the total sample weight multiplied by 100. The FDK ratings were collected on three of the six fungicide treatments: the non-treated control, Trivapro A+B at BBCH 22-23, and Prosaro XTR at BBCH 61–63. These treatments were chosen to compare the ideal FHB target timing of Prosaro XTR fungicide application at BBCH 61–63 with the non-treated control and an early fungicide application at BBCH 22–23, where no FHB protection was expected.

The identification of the Fusarium spp. present on FDK seeds followed the method of Zuzak et al. (2018). The number of seeds infected with F. graminearum, F. avenaceum, F. culmorum or F. poae was recorded.

A second uncleaned sample of harvested grain, directly from the combine, was analysed for deoxynivalenol (DON) mycotoxins. Deoxynivalenol was analyzed via ELISA (enzyme-linked immunosorbent assay) using the Veratox® for DON5/5 kit according to the manufacturer’s recommendations (Neogen, Lansing, MI). The Veratox® kits detect DON for quantitative screening, but they cannot detect low DON concentrations and can sometimes have inadequate sensitivity to the antibodies used in the kits (Tangni et al. 2011). Therefore, liquid chromatography with tandem mass spectrometry (LC/MS/MS) was used as a reference method to detect lower DON concentrations. The LC/MS/MS analysis was performed with an Agilent series 1260 Infinity Quaternary High Performance Liquid Chromatography system (Agilent Technologies, Mississauga, ON, Canada) coupled to an AB Sciex API 4000 hybrid triple quadrupole linear ion trap (QTRAP®) mass spectrometer (AB Sciex, Concord, ON) equipped with a Turboionspray™ interface on 1 kg of uncleaned harvested grain.

Table 3. Average observed McFadden leaf spot disease severity ratings (0–11) and total number of pathogen isolates attributed to common leaf spot diseases from non-responsive (Barrhead 2018, Bon Accord 2018, Lethbridge 2018, and Lethbridge 2019) and responsive site–years (Red Deer 2018, Barrhead 2019, Bon Accord 2019, and Red Deer 2019).

| Growth stage of disease rating | McFadden leaf spot disease severity ratings in the absence of fungicide treatments | Total number of leaf spot lesions in the absence of fungicide treatments |
|-------------------------------|-------------------------------------------------|---------------------------------------------------------------|
|                               | Bon Accord 2018 | Barrhead 2018 | Lethbridge 2018 | Lethbridge 2019 | STB\(^a\) | SNB\(^b\) | Tan spot\(^c\) | Total |
| Non-responsive sites          |                  |               |               |                |             |             |                |       |
| BBCH 22–23                   | 0.60             | 0.14          | —              | 0.00           | 0           | 0           | 0               | 0     |
| BBCH 30–32                   | 0.00             | 1.97          | —              | 0.00           | 0           | 0           | 0               | 0     |
| BBCH 39–45                   | 0.33             | 2.16          | —              | 0.28           | 0           | 0           | 0               | 0     |
| BBCH 61–63                   | 0.93             | 2.64          | 1.13           | 0.51           | 0           | 0           | 0               | 0     |
| 2 wk after BBCH 61–63        | —                | —             | —              | —              | 1           | 0           | 10              | 11    |
|                               |                  |               |               |                |             |             |                |       |
| Red Deer 2018                 |                  |               |               |                |             |             |                |       |
| BBCH 22–23                   | —                | 0.09          | 0.01           | 0.00           | 0           | 0           | 0               | 0     |
| BBCH 30–32                   | —                | 0.01          | 0.00           | 0.13           | 0           | 0           | 0               | 0     |
| BBCH 39–45                   | 1.49             | 0.28          | 0.19           | 0.31           | 0           | 2           | 1               | 3     |
| BBCH 61–63                   | 1.96             | 1.41          | 1.58           | 1.30           | 0           | 0           | 6               | 6     |
| 2 wk after BBCH 61–63        | —                | —             | —              | —              | 6           | 12          | 2               | 21    |

\(^a\)STB, Septoria tritici blotch, caused by Zymoseptoria tritici.

\(^b\)SNB, Septoria nodorum blotch, caused by Parastagonospora nodorum.

\(^c\)Tan spot, caused by Phyrenophora tritici-repentis.
Economic analysis
The economic analysis compared yields achieved with fungicide applications at various crop growth stages. Fungicide costs were based on the fee structure of a typical agri-chemical retail company in northcentral Alberta. Yield required to break even was calculated as: (fungicide application cost + cost of fungicide)/(current wheat price) (Kleczewski 2019).

Statistical analysis
Data from the eight environments (site × year combinations) were analyzed using PROC GLIMMIX of SAS Studio v. 3.8 (SAS Institute Inc. 2018). The site-year, cultivar, fungicide treatments, and their interactions were treated as fixed effects. Blocks and their interactions with all fixed effects were considered random effects.

Yang (2010) states that location effects should be treated as ‘fixed’ as they usually represent a physical property (e.g., soil type of a location) or a long-term average (precipitation, temperature, RH, etc.). Both O’Donovan et al. (2011) and Yang (2010) state that if a factor has greater than 10 levels and there is no structure to these levels, then it is best to declare the factor ‘random’, but if it has less than 10 levels, the variance of the factor may be unreliable and it would be better to consider the factor ‘fixed’. Therefore, this study labels the site-year factor as ‘fixed’ since it has only eight levels. A mixed-effect model for combined split-plot experiments is as follows,

\[ Y_{ijkl} = \mu + E_i + B_{ijl} + A_k + AE_{ilk} + (AB)_{ijkl} + C_l + (AC)_{i kl} + (CE)_{i kl} + (ACE)_{ijkl} + \epsilon_{ijkl} \]

where \( \mu \) is the overall mean, \( E_i \) is the effect of ith environment (site-year), \( B_{ijl} \) is the effect of jth block within ith environment, \( A_k \) is the effect of the kth whole plot (cultivar), \( (AB)_{ijkl} \) is the interactions between the effects of the kth cultivar and jth block within ith environment, or the whole plot error, \( C_l \) is the effect of the lth split plot (fungicide treatment), \( (AC)_{i kl} \) is the interaction between the effects of kth cultivar and lth fungicide treatments, \( (CE)_{i kl} \) is the interaction between the effects of lth fungicide treatment and ith environment, and \( (ACE)_{ijkl} \) is the interaction between the effects of kth cultivar, lth fungicide treatment and ith environment, and \( \epsilon_{ijkl} \) is the split plot error.

The DON data set contained many zero values and followed a Poisson distribution. The DON data was multiplied by 100 and analyzed with PROC GLIMMIX specifying a Poisson distribution and the log link function. The inverse link option was used to transform the least-square means back to the original measurement scale.

Results and Discussion
Leaf spot disease
In the absence of fungicide applications, there were low levels (average McFadden ratings of 0.25) of early season leaf spot disease severity and no pathogens were identified at the early assessment times of BBCH 22–23 or BBCH 30–32 (Table 3). At the responsive sites, leaf spot disease severity ratings increased throughout the growing season. For instance, average McFadden disease severity ratings at BBCH 39–45 were 19 and 11 times higher than at BBCH 22–23 and BBCH 30–32, respectively (Table 3). Leaf spot disease severity continued to increase at responsive sites with average McFadden leaf spot disease severity being 2.7 times greater at BBCH 61–63 compared with leaf spot disease severity at BBCH 39–45.

Leaf spot diseases, SNB caused by P. nodorum and tan spot caused by P. tritici-repentis, were first observed at the responsive sites at BBCH 39–45 and BBCH 61–63 (Table 3). By comparison, no leaf spot disease causal agents were identified at the non-responsive sites at BBCH 39–45 or BBCH 61–63. In late July or early August, at the final disease assessment time (2 wk after BBCH 61–63), the non-responsive sites had a total of one STB leaf spot lesion, caused by Z. tritici, and a total of 10 tan spot lesions. By comparison, the responsive sites had nearly double the number of leaf spot lesions with a total of six STB, 12 SNB, and two tan spot lesions.

Two weeks after final fungicide application at BBCH 61–63, leaf spot disease severity (at approximately BBCH 83–85) was significantly different at individual responsive and non-responsive site-years, as measured by McFadden and Assess 2.0 (Tables 4 and 5). At the responsive sites, McFadden leaf spot disease severity was greatest at BA19 and BR19 (4.6 and 4.7, respectively) (Table 4). The lowest leaf spot disease severity was found at the non-responsive sites, BA18 and BR18 (1.2 and 1.9, respectively) (Table 5). On average, the non-responsive sites had 24% less McFadden leaf spot disease severity compared with the responsive sites. This may reflect the higher levels of precipitation and RH at the responsive sites compared with the non-responsive sites (Table 1). Most infections by plant pathogens appear and develop during wet, warm days and nights (Agrios 2004).

Image analysis with the Assess 2.0 disease quantification analysis software was an alternate method to quantify leaf spot diseases. The software provided a measure of the percent flag leaf disease, whereas the McFadden ratings provided a measure of leaf spot disease severity for the whole plant. These two methods of leaf spot disease ratings resulted in slightly different trends. The Assess 2.0 data indicated that the responsive site, BA19, had the highest percent flag leaf disease (5.3%), while the responsive site, RD19, had the lowest at 0.7% (Table 4). There was a lack of correlation \((r = 0.12)\) between the Assess 2.0 and McFadden disease severity rating systems, which may be explained by the fact that the latter is a more effective tool for evaluating disease levels in plots, because it evaluates a larger portion of the canopy, while the Assess 2.0 method is better suited to detect small differences on single flag leaves. Yields

\[ Y_{ijkl} = \mu + E_i + B_{ijl} + A_k + AE_{ilk} + (AB)_{ijkl} + C_l + (AC)_{i kl} + (CE)_{i kl} + (ACE)_{ijkl} + \epsilon_{ijkl} \]
| Effects                  | Leaf spot disease severity | Fusarium head blight disease severity |
|-------------------------|---------------------------|--------------------------------------|
|                         | McFadden (0–11) | Assess 2.0 (%) | DTM (d) | Yield (t·ha⁻¹) | Test weight (kg·L⁻¹) | TKW (g·1000 seeds⁻¹) | Protein (mg·g⁻¹) | DON – ELISA (mg·g⁻¹) | DON – LCMSMS (mg·g⁻¹) |
| Site–year               | 0.0001 | 0.0472 | <0.0001 | 0.0013 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0013 | 0.0001 | <0.0001 |
| Bon Accord 2019 (BA19) | 4.6a | 5.3a | 131a | 7.1a | 77.2a | 37.8b | 40.8a | 139b | 0.35b | 0.00126a | 0.00070 |
| Barrhead 2019 (BR19)   | 4.7a | 2.6ab | 114c | 7.0a | 76.3a | 40.8a | 139b | 0.35b | 0.00126a | 0.00070 |
| Red Deer 2018 (RD18)   | 2.0c | 3.0ab | 108d | 6.4b | 69.1c | 41.7a | 138b | 0.35b | 0.00126a | 0.00070 |
| Red Deer 2019 (RD19)   | 3.4b | 0.7b | 128b | 7.4a | 73.2b | 36.5b | 158a | 0.35b | 0.00126a | 0.00070 |
| Average                 | 3.7  | 2.9 | 120 | 7.0 | 74.0 | 39.2 | 144 | 0.71 | 0.00039 | 0.00026 |
| Cultivar                | 0.2554 | 0.1482 | 0.1310 | 0.1274 | 0.2459 | 0.0004 | 0.0414 | 0.3750 | 0.0239 | 0.6328 |
| Cultivar × Site–year    | 0.0071 | 0.0623 | 0.0004 | <0.0001 | <0.0001 | 0.0166 | 0.6584 | 0.4528 | 0.7700 | 0.8011 |
| BA19 AAC Brandon        | 4.8A | 5.9A | 130.8A | 6.8A | 76.4A | 39.5A | 145A | 1.16 | 0.00009A | 0.000044 |
| BA19 AAC Viewfield      | 4.4A | 4.8A | 131.2A | 7.4B | 78.1B | 36.2B | 136B | 1.11 | 0.00009A | 0.000051 |
| BR19 AAC Brandon        | 5.1A | 2.7A | 113.6A | 6.3A | 75.7A | 43.3A | 142A | 0.94 | 0.00011A | 0.000097 |
| BR19 AAC Viewfield      | 4.4B | 2.6A | 114.1A | 7.7B | 77.0B | 38.4B | 136B | 0.94 | 0.00011A | 0.000091 |
| RD18 AAC Brandon        | 1.8A | 3.9A | 107.2A | 6.2A | 69.9A | 43.3A | 141A | 0.33 | 0.00009A | 0.000018 |
| RD18 AAC Viewfield      | 2.1B | 2.1B | 109.6B | 6.4A | 68.3B | 40.1B | 136A | 0.46 | 0.00010A | 0.00014 |
| RD19 AAC Brandon        | 3.7A | 0.5A | 128.0A | 7.5A | 72.9A | 38.3A | 161A | 0.39 | 0.00013A | 0.00049 |
| RD19 AAC Viewfield      | 3.1B | 1.0A | 127.9A | 7.3A | 73.5A | 34.8B | 156A | 0.31 | 0.00012B | 0.00091 |
| Fungicide               | <0.0001 | 0.0219 | 0.0873 | 0.0013 | 0.9751 | <0.0001 | 0.3420 | 0.0063 | <0.0001 | 0.1854 |
| Fungicide × Site–year   | 0.2608 | 0.1547 | 0.2610 | 0.0896 | 0.2808 | 0.0180 | 0.2520 | 0.0011 | <0.0001 | 0.0659 |
| Fungicide × Cultivar × Site–year | 0.5411 | 0.6662 | 0.4641 | 0.6419 | 0.9758 | 0.0858 | 0.5470 | 0.9556 | <0.0001 | 1.0000 |
| Non-treated control     | 4.5a | 3.7a | 119.8 | 6.6c | 73.8 | 38.5b | 146 | 1.0a | 0.00041ab | 0.00019 |
| Tilt at BBCH 22-23      | 4.0ab | 3.4ab | 120.0 | 6.98abc | 74.0 | 38.4b | 143 | — | 0.00024c | 0.00013 |
| Trivapro at BBCH 22-23  | 4.0ab | 3.0ab | 120.5 | 6.77bc | 74.0 | 38.6b | 144 | 0.49b | 0.00036abc | 0.00014 |
| Trivapro at BBCH 30-32  | 3.7bc | 3.4ab | 120.1 | 6.54c | 74.0 | 38.7b | 146 | — | 0.00032bc | 0.000098 |
| Trivapro at BBCH 39-45  | 2.6d | 1.8b | 120.3 | 7.37ab | 74.0 | 40.7a | 144 | — | 0.00022c | 0.00012 |
| Prosaro XTR at BBCH 61-63 | 3.3dc | 2.2ab | 121.0 | 7.40a | 74.0 | 40.5a | 141 | 0.67b | 0.00073a | 0.00085 |
| Adjusted CV%            | 22.1 | 76.7 | 1.3 | 9.0 | 1.9 | 1.3 | 6.7 | 51.8 | 302.5 | 436.9 |

**Note:** Bolded P values indicate significance at P < 0.05. Lowercase letters indicate Tukey mean separations between site–years, uppercase letters indicate Tukey mean separations between AAC Brandon and AAC Viewfield within a site–year, lowercase italicized letters indicate Tukey mean separations between fungicide treatments, based on a Tukey test at P = 0.05.
Table 5. *P* values and least square means for McFadden leaf spot disease severity, Assess 2.0 leaf spot disease severity, days to maturity (DTM), yield, quality, Fusarium-damaged kernels (FDK), and deoxynivalenol (DON) levels as measured by enzyme-linked immunosorbent assay (ELISA) and liquid chromatography with tandem mass spectrometry (LCMSMS) responses of the Canadian Western Red Spring wheat cultivars AAC Brandon and AAC Viewfield following foliar fungicide treatments at the non-responsive site–years (Bon Accord 2018, Barrhead 2018, Lethbridge 2018, and Lethbridge 2019).

| Effects                     | Leaf spot disease severity | DTM (d) | Yield (t ha\(^{-1}\)) | Test weight (kg hL\(^{-1}\)) | TKW (g 1000 seeds\(^{-1}\)) | Protein (mg g\(^{-1}\)) | Fusarium head blight disease severity | DON – ELISA (mg g\(^{-1}\)) | DON – LCMSMS (mg g\(^{-1}\)) |
|-----------------------------|---------------------------|---------|------------------------|------------------------------|----------------------------|--------------------------|--------------------------------------|-------------------------------|-----------------------------|
|                             |                           |         |                        |                              |                            |                          | *P* value                           |                               |                             |
| Site-year                   |                           |         |                        |                              |                            |                          | Bon Accord 2018 (BA18)              | 1.2c                           | 2.2a                         |
|                             |                           |         |                        |                              |                            |                          | Assess 2.0 (%)                   | 109.7b                         | 6.6b                         |
|                             |                           |         |                        |                              |                            |                          | days to maturity (DTM)            | 76.1d                          | 41.4a                        |
|                             |                           |         |                        |                              |                            |                          | *P* value                          |                               |                             |
| Bon Accord 2018 (BA18)      | 1.2c                      | 2.2a    | 109.7b                 | 6.6b                         | 76.1d                     | 41.4a                     | 168a                               | 0.147                         | 0.9997                       |
| Barrhead 2018 (BR18)        | 1.9c                      | 2.4a    | 103.3c                 | 5.9c                         | 81.4b                     | 40.6a                     | 166a                               | 0.55a                         | 0.00009                      |
| Lethbridge 2018 (LB18)      | 3.2b                      | 2.5a    | 104.1c                 | 7.8a                         | 85.5a                     | 37.7c                     | 144b                               | 0.12b                         | 0.00009                      |
| Lethbridge 2019 (LB19)      | 4.8a                      | 1.0b    | 120.0a                 | 6.9b                         | 79.6c                     | 39.6b                     | 117c                               | 0.28ab                        | 0.00009                      |
|                             |                           |         |                        |                              |                            |                          | Lethbridge 2018 (LB18)            | 109.3                          | 6.8                          |
|                             |                           |         |                        |                              |                            |                          | *P* value                          |                               |                             |
| Bon Accord 2018 (BA18)      | 1.0A                      | 1.9A    | 109.7A                 | 6.5A                         | 76.4A                     | 42.9A                     | 171A                               | 0.60                          | 0.000090                     |
| Barrhead 2018 (BR18)        | 1.5A                      | 2.5A    | 109.8A                 | 6.7A                         | 75.7B                     | 40.0B                     | 164A                               | 0.50                          | 0.000090                     |
| Lethbridge 2018 (LB18)      | 2.0A                      | 3.3A    | 102.4A                 | 5.7A                         | 81.2A                     | 41.6A                     | 171A                               | 0.13                          | 0.000090                     |
| Lethbridge 2019 (LB19)      | 1.8A                      | 1.5B    | 104.0A                 | 8.0A                         | 85.9B                     | 36.4B                     | 144A                               | 0.23                          | 0.000090                     |
|                             |                           |         |                        |                              |                            |                          | Average                            | 2.8                           | 2.0                          |
|                             |                           |         |                        |                              |                            |                          | *P* value                          |                               |                             |
| Cultivar                    |                           |         |                        |                              |                            |                          | **0.0384**                         |                               |                             |
| Cultivar × Site–year        |                           |         |                        |                              |                            |                          | **<0.0001**                        |                               |                             |
| BA18 AAC Brandon            | 1.0A                      | 1.9A    | 109.7A                 | 6.5A                         | 76.4A                     | 42.9A                     | 171A                               | 0.60                          | 0.000090                     |
| BA18 AAC Viewfield          | 1.5A                      | 2.5A    | 109.8A                 | 6.7A                         | 75.7B                     | 40.0B                     | 164A                               | 0.50                          | 0.000090                     |
| BR18 AAC Brandon            | 2.0A                      | 3.3A    | 102.4A                 | 5.7A                         | 81.2A                     | 41.6A                     | 171A                               | 0.13                          | 0.000090                     |
| BR18 AAC Viewfield          | 1.8A                      | 1.5B    | 104.3B                 | 6.0A                         | 81.7A                     | 39.7B                     | 160B                               | 0.11                          | 0.000090                     |
| LB18 AAC Brandon            | 3.5A                      | 3.4A    | 104.2A                 | 7.6A                         | 85.1A                     | 38.9A                     | 143A                               | 0.33                          | 0.000090                     |
| LB18 AAC Viewfield          | 3.0A                      | 1.7B    | 104.0A                 | 8.0A                         | 85.9B                     | 36.4B                     | 144A                               | 0.23                          | 0.000090                     |
| LB19 AAC Brandon            | 2.0A                      | 1.5A    | 120.9A                 | 6.9A                         | 79.2A                     | 40.9A                     | 124A                               | 0.16                          | 0.000090                     |
| LB19 AAC Viewfield          | 4.0B                      | 0.5B    | 119.2B                 | 6.8A                         | 80.0B                     | 38.4B                     | 109B                               | 0.16                          | 0.000090                     |
|                             |                           |         |                        |                              |                            |                          | Adjusted CV%                        | 32.2                          | 58.9                         |
|                             |                           |         |                        |                              |                            |                          | *P* value                          |                               |                             |
| Fungicide                   |                           |         |                        |                              |                            |                          | Bon Accord 2018 (BA18)              | 0.6760                         | 0.8620                       |
| Fungicide × Site–year       |                           |         |                        |                              |                            |                          | Assess 2.0 (%)                     | 0.2320                         | 0.2410                       |
| Fungicide × Cultivar × Site–year | 0.5585       | 0.6729 | 0.1340                 | 0.5300                       | 0.4590                     | 0.9770                     | 0.7150                               | 0.0482                         | 1.0000                       |
| Non-treated control         | 3.5a                      | 2.3     | 109.0                   | 6.85                         | 80.8                      | 39.8                      | 152                                 | 0.29                          | 0.000090                     |
| Tilt at BBCH 22-23          | 3.4a                      | 2.0     | 109.1                   | 6.57                         | 80.3                      | 39.6                      | 148                                 | —                             | 0.000090                     |
| Trivapro at BBCH 22-23      | 3.2a                      | 2.0     | 109.4                   | 6.73                         | 80.6                      | 39.5                      | 150                                 | 0.28                          | 0.000090                     |
| Trivapro at BBCH 30-32      | 2.3b                      | 1.9     | 109.6                   | 6.88                         | 80.6                      | 39.5                      | 147                                 | —                             | 0.000091                     |
| Trivapro at BBCH 39-45      | 2.3b                      | 2.2     | 109.4                   | 6.78                         | 80.8                      | 40.2                      | 148                                 | —                             | 0.000090                     |
| Prosaro XTR at BBCH 61-63   | 2.0b                      | 1.8     | 109.4                   | 6.89                         | 80.7                      | 40.3                      | 147                                 | 0.26                          | 0.000090                     |
|                             |                           |         |                        |                              |                            |                          | Note: Bolded *P* values indicate significance at *P* < 0.05. Lowercase letters indicate Tukey mean separations between site–years, uppercase letters indicate Tukey mean separations between AAC Brandon and AAC Viewfield within a site–year, lowercase italicized letters indicate Tukey mean separations between fungicide treatments, based on a Tukey test at *P* = 0.05. |
were also poorly correlated with the Assess 2.0 values \((r = -0.13)\) and McFadden ratings \((r = 0.13)\).

**Effect of site-year**

Site-years were separated into those that showed a significant yield response to fungicide treatments based on the ANOVA, and hence are referred to as “responsive sites” (Table 4), and those that did not, referred to as “non-responsive sites” (Table 5). The responsive sites included Bon Accord 2019 (BA19), Barrhead 2019 (BR19), Red Deer 2018 (RD18), and Red Deer 2019 (RD19). The non-responsive sites included Lethbridge 2019 (LB19), Lethbridge 2018 (LB18), Bon Accord (BA18), and Barrhead 2018 (BR18).

Average observed precipitation from seeding to physiological maturity at the responsive sites was 273 mm (194–364 mm), which was approximately 96% of the long-term average (LTA) (71%–128% of the LTA) (Table 1). Of those sites with a significant yield response to fungicide treatments (responsive sites), the highest observed precipitation (364 mm) was recorded at BA19 and the lowest (194 mm) at RD18. The non-responsive sites received an average of 175 mm (121–214 mm) of observed precipitation, which was approximately 79% of the LTA (66%–87%). Of the non-responsive sites, Barrhead 2018 received the highest amount of precipitation (214 mm), with the lowest at LB18 (121 mm).

Relative humidity, on average, at the responsive sites was 70.2% (65.4%–74.0%) and the non-responsive saw an average of 61.1%, (57.7%–63.7%) (Table 1). The temperature difference between sites was minimal. The non-responsive sites had, on average, only 1.6 °C higher temperature versus the responsive sites.

On average, the responsive sites with higher observed precipitation and RH had 32% higher foliar disease levels compared with the non-responsive sites (Tables 4 and 5). The wetter environment at the responsive sites affected plant height. At these responsive sites, plants were approximately 17% taller \((P = 0.0008)\) than the plants at the non-responsive sites (data not shown). Lodging was also significantly greater (54%) \((P = 0.0004)\) at the responsive sites than at the non-responsive sites, but lodging and yield were not correlated \((r = 0.08)\), likely due to the PGR application (data not shown). Previous studies have indicated that lodging is often associated with wetter summers (Berry et al. 2004).

Yield varied between site-years (Tables 4 and 5). At the non-responsive sites, significantly higher yields \((P < 0.0001)\) were achieved at LB18 (7.8 t ha\(^{-1}\)), followed by LB19 (6.9 t ha\(^{-1}\)), BA18 (6.6 t ha\(^{-1}\)), and finally BR19 (5.9 t ha\(^{-1}\)) (Table 5). These sites had an average of 2.9% lower yields \((0.2 \text{ t ha}^{-1})\) than the responsive sites. Significant yield differences \((P = 0.0013)\) were also observed between the responsive sites (Table 4). Red Deer 2019 had the highest yield \((7.4 \text{ t ha}^{-1})\) followed by BA19 \((7.1 \text{ t ha}^{-1})\), BR19 \((7.0 \text{ t ha}^{-1})\), and RD18 \((6.4 \text{ t ha}^{-1})\).

Both the non-responsive sites and responsive sites showed significant differences in DTM \((P < 0.0001)\). At the responsive sites, DTM varied from 108 d at RD18 to 131 d at BA19 (average 120 d) (Table 4). At the non-responsive sites, DTM ranged from 103.3 d at BR18 to 120.0 d at LB19 (average 109.3) (Table 5). Averaged over all fungicide treatments, responsive sites took 11 d longer to mature because of the generally better growing conditions (i.e., higher precipitation levels).

The non-responsive sites showed significant \((P < 0.0001)\) test weight differences between sites (Table 5). LB18 had the highest test weights at 85.5 kg hL\(^{-1}\) with the lowest at BA18 with 76.1 kg hL\(^{-1}\). For a grade No. 1 CWRS, the test weight needs to be at least 75 kg hL\(^{-1}\), so test weights at the non-responsive sites met the minimum No. 1 grade requirement (Canadian Grain Commission 2019b). The responsive sites also saw significant \((P < 0.0001)\) test weight differences (Table 4). BA19 had the highest test weight at 77.2 kg hL\(^{-1}\) and RD18 had the lowest with 69.1 kg hL\(^{-1}\). Test weights at RD18 (69.1 kg hL\(^{-1}\)) and RD19 (73.2 kg hL\(^{-1}\)) would result in a No. 3 and No. 2 CWRS grade, respectively. On average, the responsive sites had 8.3% lower test weights than the non-responsive sites. Lower test weights are usually due to stresses such as disease, insects, unfavorable soil, or environment conditions that can disrupt grain filling (Isleib 2012). The additional disease at the responsive sites (average 3.7 McFadden leaf spot disease severity, Table 4) versus the reduced leaf spot disease severity at the non-responsive sites (average 2.8 McFadden leaf spot disease severity, Table 5) could have resulted in the lower test weights at these sites.

For the non-responsive sites, significant differences in TKW were observed \((P < 0.0001)\) (Table 5). LB18 had the lowest TKW at 37.7 g 1000 seeds\(^{-1}\) and BA18 had the highest at 41.4 g 1000 seeds\(^{-1}\). There were significant TKW effects attributed to the responsive sites \((P < 0.0001)\), with the highest TKW \((41.7 \text{ g 1000 seeds}^{-1})\) at RD18 and the lowest \((36.5 \text{ g 1000 seeds}^{-1})\) at RD19 (Table 4). On average, the non-responsive sites had about 1.5% greater TKW than the responsive sites. Similar to the test weight results, the moderate to high level of foliar disease at the responsive sites (Table 4) could have led to lower TKW.

For the non-responsive sites, protein levels were significantly different at the four sites \((P < 0.0001)\) (Table 5). BA18 had the highest protein levels at 168 mg g\(^{-1}\) and LB19 the lowest at 117 mg g\(^{-1}\). The responsive sites also had significant differences in protein levels at the four sites \((P < 0.0001)\) (Table 4). RD19 had the highest protein level at 158 mg g\(^{-1}\), while the lowest was 138 mg g\(^{-1}\) at RD18. On average, the responsive sites had about 3% lower protein than the non-responsive sites. This can be explained by the fact that initially, when there is a lot of available N, yield and protein increase simultaneously; however, when there is a lack of moisture (i.e., non-responsive sites), the yield increase...
halts but protein will continue to increase (Jones and Olson-Rutz 2020).

The ACIS Fusarium risk tool reports that the average risk score for the responsive sites was 13.6 (moderate FHB risk) and was 37% higher than the non-responsive sites risk score of 9.9 (low FHB risk) (Alberta Agriculture and Forestry 2019). The wetter environment in Bon Accord 2019 (BA19) and Barrhead 2019 (BR19) (Table 1) led to severe FHB risk values two weeks after fungicide application at BBCH 61–63. The ‘drier’ site-years, LB18 and LB19, saw very low FHB risk. FHB infection tends to be favored under conditions of high RH (>90%) and moderately warm temperatures (15 °C–30 °C), thus explaining, in part, why the ‘dry’ or non-responsive site-years (LB18 and LB19) had lower FHB risk and infection compared with the more ‘wet’ or responsive site-years (Schmale and Bergstrom 2010).

There was a significant difference between the site-years for FDK (Tables 4 and 5). The responsive sites, BA19 and BR19, had the highest percent FDK (1.07 % and 1.02% respectively) (Table 4), while the non-responsive sites, BR18 and LB19, had the lowest (0.12% and 0.16% respectively) (Table 5). This was expected as BA19 and BR19 received some of the highest observed precipitation (364 and 262 mm, respectively) and had the highest ACIS risk of FHB, while BR18 received lower levels of precipitation (214 mm) and had 38% lower FHB risk (Table 1). On average, the percent FDK was 0.28% at non-responsive sites (Table 5) and 0.71% at responsive sites (Table 4). However, these levels were still very low relative to other western Canadian provinces (Canadian Grain Commission 2019c).

At non-responsive sites, F. poae was the most common Fusarium species identified and represented 54% of the total number of FDK infections (Table 6). At responsive sites, F. avenaceum was the most common Fusarium spp. (63% of the total FDK infections). Fusarium graminearum was associated with a low proportion of FDK infections, representing 2.5% and 6.5% of the total FDK infections at non-responsive and responsive sites, respectively. This species produces the mycotoxin, DON, which is detrimental to animal and human health (Tittlemier et al. 2020), so while many Fusarium spp. were found, the low proportion of F. graminearum indicates less human and animal health risk and explains why the DON levels in the samples were so low (Edwards et al. 2001).

The ELISA DON data differed between responsive site-years due to the elevated DON at RD19 (0.00126 mg·g⁻¹) (Table 4). Unfortunately, the RD19 samples were not adequately dried after harvest, possibly resulting in post-harvest disease development and mycotoxin production, which may explain the elevated DON levels at this site. Harvested grain with high moisture content can lead to fungal growth and mycotoxin development in storage (Bolanos-Carriel et al. 2019). The maximum safe moisture level for wheat grain storage is 13.5% at 10 °C.

The LC/MS/MS method was used for the detection of DON at lower concentrations than possible by the ELISA. As suggested by the ELISA DON analysis, RD19 also had the highest LC/MS/MS DON levels, but these were not statistically significant compared with the other responsive sites (Table 4). At the non-responsive sites, LC/MS/MS DON levels were significantly lower at LB18 and LB19 compared with BA18 and BA19. Overall, it is important to put these finding into context. The DON values were 381% below the 0.001 mg·g⁻¹ DON limit for cereal grains, reflecting very low FHB pressure at all site-years.

In summary, the responsive sites had 2.9% greater yields, 11 d longer maturity, 8.3% lower test weights, 1.5% lower TKWs, 3.4% lower protein content, and 154% lower FDK than the non-responsive sites.

**Effect of cultivar**

Leaf plating to detect the foliar pathogens at the non-responsive sites indicated no Z. tritici (STB) or P. nodorum (SNB) infections on AAC Brandon, on which only P. tritici-repentis (tan spot) infections were found.

### Table 6. Number of Fusarium spp. isolated on Fusarium-damaged kernels at the responsive and non-responsive sites when subjected to two fungicide treatments at different growth stages and the non-treated control.

| Fungicide treatment                        | F. graminearum | F. culmorum | F. poae | F. avenaceum | Total |
|-------------------------------------------|----------------|-------------|---------|--------------|-------|
| **Non-responsive sites**                  |                |             |         |              |       |
| Non-treated control                       | 2              | 2           | 18      | 12           | 34    |
| Trivapro A + B at BBCH 22–23              | 0              | 0           | 10      | 9            | 19    |
| Prosaro XTR at BBCH 61–63                 | 0              | 2           | 15      | 9            | 26    |
| **Responsive sites**                       |                |             |         |              |       |
| Non-treated control                       | 5              | 3           | 7       | 34           | 49    |
| Trivapro A + B at BBCH 22–23              | 0              | 2           | 16      | 23           | 41    |
| Prosaro XTR at BBCH 61–63                 | 4              | 4           | 11      | 30           | 49    |
At three of eight sites, significant differences between cultivars were observed (Saskatchewan Seed Growers Association 2020). However, the BR18, LB18, LB19, and RD18 sites had more leaf spot disease than AAC Viewfield was supported by the image analysis data obtained with Assess 2.0 at the BR18, LB18, LB19, and RD18 site-years. The general trend was for AAC Brandon to have slightly more leaf spot disease than AAC Viewfield.

The small discrepancy between the seed guide disease ratings for each cultivar and the findings in our study may reflect variability in isolates or populations of fungi, disease pressure, and moisture and temperature conditions at each site-year. An ‘intermediate’ resistance rating covers a range of responses and it may be that both cultivars are considered ‘intermediate’, but AAC Viewfield is slightly more resistant than AAC Brandon. It should be noted that since these are not ‘Priority 1’ diseases, there is no mandatory requirement to breed for genetic resistance to the STB, SNB, or tan spot in Canadian wheat breeding programs.

At seven of the eight sites-years, there was no significant difference in the percent FDK, ELISA DON and LC/MS/MS DON between cultivars (Tables 4 and 5). Only at RD19 were there significant differences in ELISA DON between the two cultivars, and although the difference was statistically significant, it was very small in magnitude. It is important to note that this trend only occurred at RD19, where there may have been post-harvest DON development due to poor post-harvest sample management. AAC Brandon is rated as ‘moderately resistant’ to FHB versus an ‘intermediate’ resistance rating for AAC Viewfield. AAC Brandon is one of the five wheat cultivars in Canada related to Sumai 3, which is a highly resistant FHB cultivar due to the Fhb1 gene (Zhu et al. 2019). The lack of difference in FDK and DON levels between the cultivars in this study is likely attributable to the very low FHB pressure, and even lower presence of mycotoxin-producing species, in the study environments.

### Table 7. Number of pathogen isolates attributed to common leaf spot diseases and number of *Fusarium* spp. isolated on Fusarium-damaged kernels averaged over three fungicide treatments: the non-treated control, Trivapro A + B at BBCH 22–23, and Prosaro XTR at BBCH 61–63 for AAC Brandon and AAC Viewfield Canadian Western Red Spring wheat grown at the non-responsive and responsive sites.

| Cultivar          | Number of leaf spot lesions | Number of *Fusarium* spp. isolates |
|-------------------|-----------------------------|-----------------------------------|
|                   | STB<sup>a</sup> | SNB<sup>b</sup> | Tan spot<sup>c</sup> | Total | F. grae<sup>d</sup> | F. cul<sup>e</sup> | F. poae<sup>f</sup> | F. ave<sup>g</sup> | Total |
|-------------------|----------------|-|-|---|---|---|---|---|---|---|
| **Non-responsive sites** | | | | | | | | | | |
| AAC Brandon       | 0          | 0       | 4       | 4       | 1       | 2       | 18      | 11      | 32      |
| AAC Viewfield     | 1          | 4       | 0       | 5       | 1       | 2       | 25      | 19      | 46      |
| Total             | 1          | 4       | 4       | 9       | 2       | 4       | 43      | 30      | 78      |
| **Responsive sites** | | | | | | | | | | |
| AAC Brandon       | 1          | 6       | 7       | 14      | 8       | 4       | 22      | 43      | 77      |
| AAC Viewfield     | 6          | 8       | 2       | 16      | 1       | 5       | 12      | 44      | 62      |
| Total             | 7          | 14      | 9       | 30      | 9       | 9       | 34      | 87      | 139     |

<sup>a</sup>STB, Septoria tritici blotch, caused by *Zymoseptoria tritici.*
<sup>b</sup>SNB, Septoria nodorum blotch, caused by *Stagonospora nodorum.*
<sup>c</sup>Tan spot, caused by *Phyrenphora tritici-repentis.*
<sup>d</sup>*F. graminearum.*
<sup>e</sup>*F. culmorum.*
<sup>f</sup>*F. poae.*
<sup>g</sup>*F. avenaceum.*

(Table 7). In contrast, AAC Viewfield was infected with *Z. tritici* and *P. nodorum,* but not *P. tritici-repentis,* at non-responsive sites. At responsive sites, both cultivars were infected with all three pathogens. When compiling all site-years, both cultivars were infected at least once with all pathogens. This confirmed that at least some infection can occur and is consistent with the leaf spot resistance ratings of these cultivars as ‘intermediate’. The irregularity of pathogen presence is likely a reflection of different field histories (e.g., crop rotation, crop sequence, previous cultivars) and inoculum levels.

At both responsive and non-responsive sites, there was a significant cultivar × site-year interaction for the McFadden leaf spot disease severity ratings (Tables 4 and 5). At most site-years, AAC Viewfield and AAC Brandon had similar leaf spot disease levels, which was expected. In provincial seed guides, AAC Brandon and AAC Viewfield were both rated as ‘intermediate’ for resistance to the leaf spot complex (STB, SNB, and tan spot) (Alberta Seed Growers and Alberta Seed Processors 2020; Saskatchewan Seed Growers Association 2020). However, significant differences between cultivars were observed at three of eight site-years. At the responsive site-years, BR19 and RD19, AAC Brandon had an average leaf spot disease 17% higher than AAC Viewfield (Table 4), at the non-responsive site-year, LB19, McFadden disease ratings indicated that AAC Viewfield had more leaf spot disease than AAC Brandon (Table 5). The trend of AAC Brandon having more disease than AAC Viewfield was supported by the image analysis data obtained with Assess 2.0 at the BR18, LB18, LB19, and RD18 site-years. The general
**Fusarium** spp. plating of samples from non-responsive sites indicated that AAC Brandon was infected with *F. poae* 56% of the time and with *F. graminearum* only 3% of the time (Table 7). Similar trends were observed with AAC Viewfield having 54% of the infections attributed to *F. poae* and 2% to *F. graminearum*. At responsive sites, 56% of the infections on AAC Brandon were caused by *F. avenaceum*, while only 10% of the infections were caused by *F. graminearum*. As with AAC Brandon, *F. avenaceum* was the dominant species on AAC Viewfield, causing 71% of the infections; in contrast, only 2% of the infections on this host were attributed to *F. graminearum*. These results confirm that levels of FHB in many parts of Alberta remain much lower than levels in the eastern Prairies, and that *F. graminearum* is not the dominant *Fusarium* spp. across much of Alberta.

For the responsive sites, there was a significant cultivar × site interaction for yield (Table 4). This was attributed to yield differences between the two cultivars at two of four sites (BA19 and BR19), where AAC Viewfield averaged 15.5% higher yield than AAC Brandon. At BA19, AAC Viewfield yielded 0.6 t·ha⁻¹ more than AAC Brandon, and at BR19, AAC Viewfield yielded 1.4 t·ha⁻¹ more than AAC Brandon. There were no significant yield differences between cultivars at the non-responsive sites (Table 5).

At five of the eight site–years, there was no significant difference in maturity between AAC Brandon and AAC Viewfield (Tables 4 and 5). This was expected and matches the maturity ratings of the cultivars (Alberta Seed Growers and Alberta Seed Processors 2020). The slight differences in maturities at BR18, RD18, and LB19 may be attributed to a genotype × environment interaction.

All responsive and non-responsive sites showed significant differences in TKW between cultivars. Overall, AAC Brandon had 8.1% heavier seeds compared with AAC Viewfield (Tables 4 and 5). This was also expected, since AAC Brandon is rated as having a heavier seed (41 g·1000 seeds⁻¹) relative to AAC Viewfield (40 g·1000 seeds⁻¹) (Alberta Seed Growers and Alberta Seed Processors 2020). AAC Viewfield is reported to have a heavier test weight relative to AAC Brandon. Our data supported this trend at most site–years (Tables 4 and 5).

The cultivars showed significant differences in protein content in four of eight site–years, including at two responsive sites (BA19 and BR19) and two non-responsive sites (BR18 and LB19) (Tables 4 and 5). Specifically, AAC Brandon had a 5.5% and 9.7% higher protein than AAC Viewfield at the responsive and non-responsive sites, respectively. Again, this was expected, as AAC Viewfield is known to have lower protein levels compared with AAC Brandon (Alberta Seed Growers and Alberta Seed Processors 2020).

**Effect of fungicide treatment**

As described above, there were no significant yield responses to the fungicide treatments at non-responsive site–years (*P* = 0.2320) (Table 5). The responsive sites had significant yield differences between fungicide treatments (*P* = 0.0013), but no significant fungicide × site–year, or cultivar × fungicide × site–year interactions (Table 4). As such, fungicide responses will be discussed based on fungicide treatment means averaged over the four responsive sites and both cultivars.

The McFadden leaf spot disease severity ratings (*P* < 0.0001) and Assess 2.0 (*P* = 0.0219) both indicate significant differences between fungicide treatments (Table 4). The McFadden and Assess 2.0 data follow similar trends. The Tilt 250 E (propiconazole) and Trivapro A + B (azoxystrobin + propiconazole + benzoindiflupyr) treatments at BBCH 22–23 along with the non-treated control had the highest McFadden leaf spot disease severities of any fungicide treatments in early to mid-August (Table 4). The fungicide treatments at BBCH 22–23 and BBCH 30–32 had 54% and 42%, respectively, higher leaf spot disease severity compared with the fungicide treatment at BBCH 39–45 (flag leaf). These results are consistent with Duczek and Jones-Flory (1994) who found that a fungicide at BBCH 41–69 is far better at controlling leaf spots than earlier fungicide applications. The result also suggested that producers should avoid early fungicide applications at BBCH 22–23 and BBCH 30–32, as they do not result in significantly lower disease levels compared with the non-treated control. Unnecessary fungicide applications are economically unwise and may contribute to the development of fungicide resistance.

The lowest McFadden leaf spot disease severities were observed for Trivapro A + B applications at BBCH 39–45 (Table 4). The fungicide application of Prosaro XTR at BBCH 61–63 resulted in 27% more leaf disease than the application at BBCH 39–45, but these levels of leaf disease were not significantly different. Although the same fungicide product was not used at each of these growth stages, both fungicide products are registered to control the dominant leaf spot diseases [septoria leaf complex (STB, SNB) and tan spot] (Syngenta 2020; Bayer CropScience 2020). This suggests that a fungicide application at anthesis (BBCH 61–63) may also be helpful in controlling leaf spot diseases, giving producers a wider window for effective disease control from BBCH 39–45 to BBCH 61–63. Previous studies found that fungicide application at BBCH 61–63 can provide sufficient control against leaf spot disease without any reduction in grain yield while maintaining grain quality (Kutcher et al. 2018; MacLean et al. 2018; Wiersma and Motteberg 2005).

There were no significant yield differences between the non-treated control and fungicide applications at BBCH 22–23 or BBCH 30–32 (Table 4). This suggested
there was no yield advantage associated with early fungicide applications, and this practice provides no economic benefit to growers. The non-treated control and earlier fungicide treatments, applied at BBCH 22–23 and BBCH 30–32, had lower yields (but not always significantly less yield) relative to the later fungicide applications at BBCH 39–45 and BBCH 61–63. Fungicide applications at BBCH 39–45 and BBCH 61–63 yielded significantly more than the non-treated control. This suggests that under responsive environmental conditions, there may be an economic benefit associated with fungicide applications at BBCH 39–45 and BBCH 61–63.

On average, yield was a 0.63 t ha\(^{-1}\) lower in the earlier fungicide treatments versus the later ones (Table 4). This corresponds to the 32% higher foliar disease levels associated with fungicide applications at BBCH 22–23 and BBCH 30–32 compared with later fungicide applications at BBCH 39–45 and BBCH 61–63. This trend was consistent with previous studies that have found that applying fungicides as a protectant according to plant growth stage can be a more effective approach in limiting yield loss (Poole and Arnaudin 2014). This is based on the premise that protecting the upper canopy (flag leaf, flag leaf-1, flag leaf-2, flag leaf-3), which contributes the most to grain yield, from foliar diseases is key to protecting yield, whereas lower canopy leaves that contribute very little to grain yield do not require disease protection. Our results showed that flag leaf (BBCH 39–45) and head (BBCH 61–63) fungicide applications resulted in higher yields (on average an 9.3% increase) than any of the earlier applications. This was likely because the flag leaf had not yet emerged during the earlier application, whereas the later applications protected all of the upper leaves, thus preventing major yield loss from fungal leaf spots.

The TKW was significantly greater at the later fungicide application timings (BBCH 39–45 and BBCH 61–63) relative to the earlier fungicide treatments and the non-treated control (Table 4). The significant fungicide × sites interaction for TKW resulted from three sites (BA19, RD18, and RD19) showing significant responses to fungicide treatments, with later fungicide treatments (BBCH 39–45 and 61–63) having, on average, a 5% greater TKW relative to the earlier fungicide applications (BBCH 22–23 and 30–32) (data not shown).

There was a significant fungicide × site–year interaction for FDK at responsive sites (\(P = 0.0011\)) (Table 4) and a significant fungicide × cultivar × site–year interaction for FDK at non-responsive sites (\(P = 0.0482\)) (Table 5). This was attributed to trends at LB18, BA19, and BR19, where there were significant responses to fungicide treatments (data not shown). At LB18 site–year, both the non-treated control and Trivapro A + B at BBCH 30–32, had 21% higher FDK relative to the Prosaro XTR treatment at BBCH 61–63, which was expected since those two treatments are not targeting FHB. However, this trend was not observed for the other two site–years.

At BA19 and BR19, FDK for the Prosaro XTR (prothioconazole + tebuconazole) treatment at BBCH 61–63 had 31% and 42% higher FDK, respectively, than for the Trivapro (azoxystrobin + propiconazole + benzovindiflupyr) treatment at BBCH 22–23. We would have expected the treatments at BBCH 61–63 to have lower FDK than fungicide treatments at BBCH 22–23. Similar results were obtained in another study, where some fungicide treatments had higher, but not significantly different, levels of FHB and FDK than the unsprayed control in some site–years (Fernandez et al. 2014). This is unusual, but there have been cases where earlier fungicide treatments can reduce FDK and the risk of FHB, due to a reduction of Fusarium spp. debris on younger plants and leaf sheaths (Edwards and Godley 2010).

For ELISA DON at responsive site–years, there was a significant response attributed to fungicide treatment (\(P < 0.0001\)), fungicide × site–year (\(P < 0.0001\)), and fungicide × cultivar × site–year (\(P < 0.0001\)) (Table 4). Again, these trends were attributed to the RD19 ELISA DON data (data not shown). As mentioned above, the RD19 samples were not adequately dried after harvest, possibly resulting in post-harvest disease development, mycotoxin production, and unexpected data trends that are not attributed to fungicide treatments.

Days to maturity, test weight, protein, and LC/MS/MS DON were not affected by fungicide applications.

### Economic benefits of fungicide applications

The highest yield was achieved with the Prosaro XTR application at early anthesis (BBCH 61–63), which had a significant 10.8% yield increase (or 0.72 t ha\(^{-1}\)) over the non-treated control (Table 4). The next highest yield came from spraying at the flag leaf stage with Trivapro A + B, representing a significant 10.3% yield increase (equivalent to 0.69 t ha\(^{-1}\)) relative to the non-treated control. The lowest yielding treatment was fungicide application with Trivapro A+B at BBCH 30–32, which was not significantly different from the non-treated control or the BBCH 22–23 treatments. Fungicide applications at BBCH 22–23 were 0.2 t ha\(^{-1}\) higher yielding than the non-treated control, representing a non-significant yield difference of 2.9% relative to the non-treated control. It should be noted that some of the individual fungicide treatments at BBCH 22–23 and BBCH 30–32 were not always significantly different from the fungicide treatments at BBCH 39–45 and BBCH 61–63. Overall, the greatest yields occurred with late fungicide applications at BBCH 39–45 and BBCH 61–63.

If a fungicide application is to be profitable, the cost of fungicides and their application costs need to be offset by increased yields. Therefore, a grower applying Tilt 250 E in 2018 or 2019 needed to achieve an additional $32.46 ha\(^{-1}\) in revenue to break even, which was equivalent to an additional 0.12 to 0.14 t ha\(^{-1}\) of grain yield (Table 8). A grower applying Trivapro A + B in 2018 or 2019 needed to achieve an additional $58.62 ha\(^{-1}\) in
Decisions for effective fungicide use

There are several factors that should be considered prior to spraying a fungicide. First, is the field expected to be responsive? The field should be assessed for yield potential and disease potential. If yield potential is compromised due to severe weather, such as drought, hail, or flooding, then there is no need for a fungicide. If there is no or limited disease, then a fungicide is also not necessary.

Secondly, the relationship between the environment, pathogen, and host/cultivar (disease triangle) is critical in determining whether or not to use fungicides (Scholthof 2007). For example, if the host is resistant or moderately resistant to the target pathogens, then the risk of yield loss decreases, and a fungicide may not be needed. Despite AAC Brandon and AAC Viewfield having an intermediate rating for leaf spots (Alberta Seed Growers and Alberta Seed Processors 2020), the two CWRS cultivars were prone to foliar leaf spot diseases in this study as they both exhibited a response to fungicide application when disease pressure was high, as we observed at the responsive sites (Table 4). As such, AAC Brandon and AAC Viewfield were responsive to fungicide applications given the disease pressure present in the study conditions.

The environment also plays an important role in decision-making. Over the two growing seasons in this study, only half of the sites were responsive to fungicide application. The responsive site-years tended to have more overall precipitation, more precipitation in May and June, and higher RH (Table 1). Based on the present results, the best time to apply fungicides would be at growth stages BBCH 39–45 (flag leaf) and BBCH 61–63 (anthesis) to minimize yield and quality loss when observed season precipitation (194–364 mm) and RH (65.4% – 74.0%) are near the LTA. In this study, observed precipitation in May and June was 127% of the LTA across responsive site-years, suggesting the importance of early-season precipitation in determining fungicide response.

### Table 8. Estimated economic returns for a single application of Tilt 250 E, Trivapro A + B and Prosaro XTR to Canadian Western Red Spring wheat in Alberta, Canada, based on grain prices from 2018 and 2019.

| Year | Wheat price ($ t⁻¹)a | Application cost ($ ha⁻¹) | Fungicide costb,c ($ ha⁻¹) | Total application and fungicide cost ($ ha⁻¹) | Yield needed (t ha⁻¹) |
|------|----------------------|-------------------------|-------------------------|---------------------------------------------|---------------------|
|      | Single application of Tilt 250 E | | | | |
| 2018 | 259.78               | 17.50                   | 14.96                   | 32.46                                       | 0.12                |
| 2019 | 230.04               | 17.50                   | 14.96                   | 32.46                                       | 0.14                |
|      | Single application of Trivapro A + B | | | | |
| 2018 | 259.78               | 17.50                   | 41.12                   | 58.62                                       | 0.23                |
| 2019 | 230.04               | 17.50                   | 41.12                   | 58.62                                       | 0.25                |
|      | Single application of Prosaro XTR | | | | |
| 2018 | 259.78               | 17.50                   | 53.96                   | 71.46                                       | 0.28                |
| 2019 | 230.04               | 17.50                   | 53.96                   | 71.46                                       | 0.31                |

aAverage cost of wheat ($ t⁻¹) was collected from price and data quotes (PDQ) in 2018 and 2019 from September 3rd to October 31st. The data was averaged each year for southern and northern regions in Alberta.

bCalculated costs ($ ha⁻¹) from retail values of fungicide and recommended label rates.

cTilt 250 E retail price was $401.87 per 8L jug with recommended herbicide timing rate to be 0.25 L ha⁻¹. Trivapro A + B retail price was at $666.12 per case in a co-pack including two 8.1 L jugs of Trivapro A and two 2.43 L jugs of Trivapro B. Recommended rates were 1 L ha⁻¹ of A and 0.3 L ha⁻¹ of B. Prosaro XTR retail price was $433 per 6.5 L jug, with a recommended rate of 0.81 L ha⁻¹.
However, if disease incidence and severity are low throughout the growing season, such as we observed at the non-responsive sites (BR18, BA18, LB18, and LB19) with less growing season precipitation (121–214 mm), reduced May and June precipitation (85% of the LTA), and lower RH (57.7%–63.7%), there may not be a need to spray, since the financial benefits are non-existent given that yield loss due to disease is non-significant.

Conclusion

Overall, McFadden leaf spot disease severity levels were 32% higher at responsive sites compared with non-responsive sites. When fungicides were applied early, at BBCH 22–23 and BBCH 30–32, leaf spot disease severity in early August was 50% greater than if fungicide applications were delayed until BBCH 39–45. Fungicide applications at BBCH 61–63 reduced leaf spot disease severity compared with early season fungicide applications, but the reduction was not always statistically significant. This confirms that a fungicide application at the flag leaf stage (BBCH 39–45) represents the optimal timing for control of leaf spot diseases in AAC Brandon and AAC Viewfield. At responsive sites, percent FDK was 2.5 times greater than in non-responsive site-years. However, even in responsive years, these levels of FHB remain much lower than levels in the eastern Prairies. *F. graminearum* was identified only 2%–10% of the time, with *F. poae* and *F. avenaceum* being the dominant *Fusarium* spp. at the experimental sites.

When fungicide applications were made at BBCH 39–45 and 61–63, TKW was 5.2% greater and yields were 9.3% greater than when fungicide applications were made at BBCH 22–23 and 30–32. These data support earlier research showing that earlier fungicide applications provided no yield or quality benefits, even on new CWRS wheat varieties with improved genetic resistance to cereal diseases. Days to maturity, protein, test weight, and LC/MS/MS DON were not impacted by the fungicide treatments.

Our economic analysis indicated that applying propiconazole (Tilt 250 E) at BBCH 22–23 was less costly during the years of our study, but also did not provide the best return on investment since it did not protect yield and quality compared with later fungicide applications. Prothioconazole and tebuconazole (Prosaro XTR) applications at BBCH 61–63 resulted in an additional 0.72 t ha⁻¹ in yield compared with the non-treated control, when environmental conditions were conducive to disease development during the years of our study, and Trivapro A + B applications at BBCH 39–45 or Prosaro XTR at BBCH 61–63 were the most profitable choice for growers. Although this study found that later fungicide applications resulted in the greatest yield, it is important to note that yield responses occurred only at 50% of the site-years. Site-years where environmental conditions were not favorable for disease development, and thus fungicide applications were unnecessary, were characterized by low RH (57.7%–63.7%) and an average observed precipitation of 175 mm.

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