Published May 6, 2016

Winter Wheat Yields Are Increased by Seed Treatment and Fall-Applied Fungicide

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ABSTRACT

Poor stand establishment resulting in lower yield is a major constraint to expanding winter wheat (*Triticum aestivum* L.) land area across the semiarid temperate regions of the northern Great Plains. We conducted a direct-seeded study at nine sites across western Canada totaling 26 environments (site-years) over three growing seasons (2011–2013) to observe the responses of the winter wheat cultivar CDC Buteo to five levels of seed treatment (i) Check–no seed treatment, (ii) tebuconozole [(*RS*)- 1-(4-Chlorophenyl)-4,4-dimethyl-3-(1*H*, 1,2,4-triazol-1-ylmethyl)pentan- 3-ol], (iii) metalxyl {2-[(2,6-dimethylphenyl)-(2-methoxy-1-oxoethyl) amino} propanoic acid methyl ester], (iv) imidacloprid (*N*-{1-[(6-Chloro-3-pyridyl) methyl]-4,5-dihydroimidazol-2-yl}nitramide), and (v) dual fungicide/insecticidal seed treatment: tebuconozole, + metalxyl + imidacloprid; and two levels of fall-applied fungicide (i) Check–no application or (ii) foliar-applied prothioconazole {2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1H-1,2,4-triazole-3-thione} performed in mid-October. The check and the fungicide seed treatment, metalaxyl, produced similarly low grain yield resulting in lower net returns, whereas the dual fungicide/insecticide seed treatment provided the highest yield and net returns (CAN+$13 ha^{-1}). Fall-applied fungicide improved yield (0.06 Mg ha^{-1}), but decreased net returns (–$12 ha^{-1}). Plant density increased slightly (13 plants m^{-2}) when seed treatments included the insecticide component, imidacloprid. Fall foliar fungicides generally improved spring plant density; however, no benefit was observed in seed treatments containing imidacloprid. Greater yield and plant stand stability was observed with fall-applied foliar fungicide applications; however, fall foliar would be cost prohibitive. The benefits of a fall foliar fungicide application requires further exploration in the context of an added input or as an alternative to a spring application as the net returns of a fall foliar compared to no application in the system render the input cost-prohibitive.

Core Ideas

- Seed treatment increases winter wheat yield.
- Fall-applied fungicide increases winter wheat yield.
- Seed treatment increases winter wheat net returns.

Published in Agron. J. 108:1379–1389 (2016)
doi:10.2134/agronj2015.0573
Received 30 Nov. 2015
Accepted 1 Mar. 2016
Available freely online through the author-supported open access option

Winter wheat provides an alternative for spring wheat producers in the northern Great Plains due to high yield potential, weed competitiveness, less pest pressure, and unique seeding/harvest dates that spread out operational work load, which can also reduce capital costs (Anonymous, 2013, 2014). Given the potential advantages of winter wheat, adoption and integration into regions of the northern Great Plains including Canadian Prairie cropping systems remain modest. Although winter wheat production on the prairies peaked at more than 300,000 ha from 2007 to 2009, and at 600,000 ha in 2012 to 2014, spring wheat production was much higher during this period and typically ranged from 5.9 to 7.9 million ha from 2000 to 2015 (Anonymous, 2015a). A major impediment to the expansion of winter wheat production relates to perceptions around crop establishment in fall and subsequent winter survival.

Reduced adoption of winter wheat may reflect a lack of familiarity with the crop and the need to continually evolve winter wheat production systems with sound agronomic practices. Best management practices for winter wheat requires direct seeding in late summer into standing stubble to catch snow, which provides sufficient insulation to moderate soil temperatures and enhance winter survival (Anonymous, 2013, 2016; Loeppky et al., 1989). For example, canola (*Brassica* spp.), silage barley (*Hordeum vulgare* L.), and field pea (*Pisum sativum* L.), are considered the best stubble to seed winter wheat into (Irvine et al., 2013), while the optimum seeding dates for many areas in the Canadian Prairies range from 27 August in more northern latitudes to 9 September in more southern regions (Anonymous, 2013, 2016). Further refinement of seeding management to maintain adequate plant stands has been identified as one of the key areas for successful winter wheat production (Anonymous, 2014).

In addition to stubble type, early seeding, healthy seed, shallow seeding, and increased seeding rates have been identified as important factors contributing to an adequate winter wheat

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stand and good winter survival (Anonymous, 2013, 2016). Seed treatment with a registered fungicide can be an important strategy to ensure optimal stand establishment and lessen early-season disease (Menzies and Gilbert, 2003; Wiese, 1987). Given the potential role of seed treatments, there have been relatively few studies on seed treatment and its impact on stand establishment, winter survival and crop yield, especially in western Canada. In Ontario, Schaafsma and Tamburic-Ilincic (2005) reported that a fungicide seed treatment increased fall seedling emergence and the number of tillers the following spring. Most products also increased yield in the presence of Fusarium head blight caused by *Fusarium graminearum*, but seed and soil-borne disease levels and causal agents were not assessed. The authors reported that the impact of seed treatments on fusarium head blight (FHB) was likely via increased canopy density, which may have favored FHB development, while most products increased yield, but had no impact on deoxynivalenol concentrations in harvested grain. In general, the focus of applying a seed treatment is typically to target either seed-borne or soil-borne plant pathogens (Hewett and Griffiths, 1986; Mathre et al., 2001). May et al. (2010) evaluated a range of seed treatments in both *F. graminearum*-infected barley and wheat seed. They reported increased emergence and yield with seed treatment when levels of seed infection in wheat were high (>50%). However, with low levels of seed infection (≤10%), seed treatments did not improve emergence and grain yield. With moderate levels of infection (25–35%) emergence increased with seed treatment, but grain yield was unaffected. In Georgia, Buck et al. (2009) demonstrated that seed treatments with insecticides improved winter wheat yield when the risk of barley yellow dwarf virus (BYDV) was high as a consequence of elevated aphid populations. Although not in winter wheat, Gaspar et al. (2014) demonstrated that soybean yield increased when seed treatments contained a combination of fungicide and insecticide vs. fungicide alone. Also in soybean, Cox and Cherney (2014) compared seed treatments with either fungicide alone or fungicide and insecticide vs. untreated seed. When averaged over both years, stand establishment was increased vs. the untreated control at all four study sites with the combination treatment, while the fungicide only treatment increased establishment vs. the untreated control at two of four sites. Cox and Cherney (2014) reported that grain yield was not affected by seed treatments at two of four sites, while only the combination seed treatment increased yield at the remaining two sites. In both studies, seed and soil-borne disease or insect damage levels and associated causal agents were not reported.

Crop responses to seed treatments can extend beyond mitigation of pathogens or insect pests. Studies of winter wheat report improved plant stands, yield components, and grain yield where only a fungicide seed treatment such as tebuconazole was applied (Schaafsma and Tamburic-Ilincic, 2005). A Canadian study on canola reported improved seedling emergence and grain yield with dual fungicide/insecticide seed treatments (Hwang et al., 2015). Fungicide treatments with the active ingredient prothioconazole are purported to improve frost tolerance in wheat by modulating morphological changes to the mesocotyl, and tebuconazole purportedly causes physiological changes that improves root development (Anonymous, 2009). Vernon et al. (2009) reported improved plant stands with imidicloprid and hypothesized this was likely due to wireworm (Coleoptera: Elateridae) control, but noted that toxic effects were temporary and not lethal; however, the improved plant stand may have been unrelated to biotic stress. Ford et al. (2010) established that neonicotinoids such as imidacloprid and clothianinidin induce salicylic acid-associated responses, which elicits plant protection to pathogens such as powdery mildew concomitant with abiotic stress tolerance. Given the longer growth duration of winter wheat vs. spring wheat, there may be greater opportunity for fungicide or insecticide seed treatments to elicit abiotic stress tolerance. As an alternative, or in addition to a seed-applied strategy, applications of foliar fungicides containing the active ingredient prothioconazole may further enhance this response.

A study was therefore designed to identify alternative seeding and crop management practices that may impact winter wheat stands and grain yield. In particular, we wanted to know if fungicide/insecticide seed treatments influence fall stand establishment, winter survival, and grain yield. There have been no winter wheat research studies in the frigid environments of the northern Great Plains including the Canadian Prairie region and the northern United States that report the interactive effects of seed treatment and foliar fungicide application in the fall. Thus, a knowledge gap exists around whether fall application of foliar fungicide may enhance or modulate winter wheat responses to seed treatment. The following objectives were established: (i) to determine if seed treatments can improve crop competitiveness of winter wheat, and if crop responses differ between active ingredients; and (ii) to assess if fall application of foliar fungicide improves crop health, vigor, and competitiveness, and yield alone or in concert with particular seed treatments. To study the integrated role of seed treatments combined with fall-applied foliar fungicides, the following hypothesis was established: seed treatments can improve winter wheat establishment and productivity, and fall-applied foliar fungicides may further improve crop health, yield components, and competitiveness. A companion paper addresses how the integration of seed treatment, seed lot vigor (seed size), and sowing density can be manipulated to enhance winter wheat production systems (Beres et al., 2016).

MATERIALS AND METHODS

Site Description and Experiment Design

The experiment was conducted with the Canada Western Red Winter wheat cultivar CDC Buteo (Fowler 2010) at 26 sites (location × year combinations) across western Canada from the fall of 2010 to the summer of 2013 with individual field trials established on a new study area each year. A summary of the characteristics for each environment is presented in Tables 1 and 2. The treatment design consisted of a four replicate factorial combination of seed treatments and fall-applied foliar fungicides. The seed treatments were commercial liquid formulations obtained from the manufacturer (Bayer CropScience Inc., Calgary, AB) and applied at the registered label rates as follows: (i) Check–no seed treatment; (ii) Raxil 250 FL (tebuconazole, 6 g.a.i. L^{-1}) at 300 mL 100 kg^{-1} seed; (iii) Allegiance FL (metalaxyl, 300 g.a.i. L^{-1}) at 6.3 mL 100 kg^{-1} seed; (iv) Stress Shield (imidacloprid, 480 g.a.i. L^{-1}) at 62.5 mL 100 kg^{-1} seed; and (v) dual fungicide/insecticidal seed treatment, Raxil MD (tebuconazole, 5.0 g.a.i. L^{-1} + metalaxyl 6.6 g.a.i. L^{-1}) + Stress Shield (imidacloprid, 480 g.a.i. L^{-1}) at 300 mL 100 kg^{-1} seed and 62.5 mL 100 kg^{-1} seed, respectively (Fig. 1).

The two levels of fall-applied fungicide were: (i) Check–no application or (ii) foliar-applied Proline 480 SC (prothioconazole, 480 g L^{-1}, Bayer CropScience Inc., Calgary, AB). Treatment combinations were allocated to experimental units (plots) in a randomized complete block experiment design. Plot size generally was 3.7 m wide by 15.2 m long.

Seeding Operations and Plot Maintenance

Plots were direct-seeded into barley (*Hordeum vulgare* L.) silage, pea (*Pisum sativum*, L.), canola (*Brassica napus* L.), or chem-fallow stubble using a commercial zero tillage Conserva Pak air drill (Model CP 129A, Conserva Pak, Indian Head, SK, Canada) equipped with a Valmar air delivery system (Valmar Airflo Inc., Elie, MB, Canada) and knife openers spaced 23 cm apart, or a comparably configured plot seeder. Soil characteristics and planting dates for each site are summarized in Tables 1 and 2. Nitrogen and P_2O_5 fertilizer was side-banded at time of seeding according to soil test recommendations. Weed control was typically achieved by applying herbicides according to label recommendations to manage important weeds at each site (Anonymous 2015c). The winter wheat cultivar, CDC Buteo (Fowler 2010), was sown at a rate of 450 seeds m^{-2}. The foliar application of the fungicide Proline 480 SC (fall foliar fungicide treatment) was made at the three to four leaf stage at a rate of 315 mL ha^{-1} (150 g a.i. ha^{-1}) with a non-ionic surfactant, Agral 90 or Surf 92 at 0.125% v/v using a motorized sprayer calibrated to deliver a carrier volume of 100 L ha^{-1} at 275 kPa pressure. Dates of application are indicated in Table 1.

Data Collection

Winter wheat plant counts were performed first in the fall (late-October to mid-November) by staking and counting two paired 1-m sections of crop row in each plot. Spring (early May) plant counts were done destructively from 1 m sections of rows at two spots in each plot to assess winter survival. Plots were harvested at maturity using a plot combine equipped with a straight-cut header, pickup reel and crop lifters (Wintersteiger AG, Salt Lake City, UT). A 2-kg subsample was retained post-harvest to characterize seed weight (g 1000 $kernels^{-1}$), test weight (kg hL^{-1}), and dockage (defined as extraneous plant, insect, or other material in the harvested seed) as per industry standards (Canadian Grain Commission, 2011). Whole grain protein concentration was determined from a subsample using near infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc., Eden Prairie, MN).

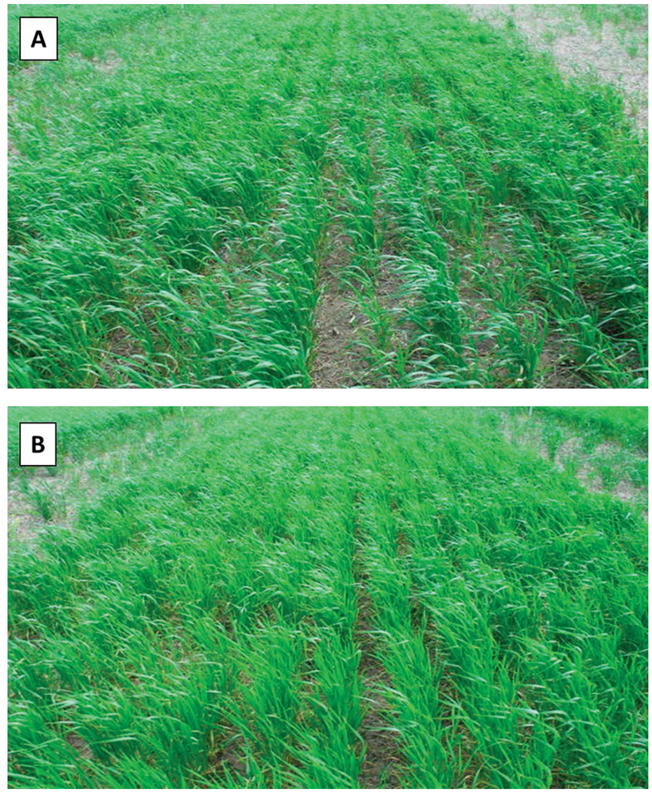

Fig. 1. Seeding system treatment examples showing (A) control treatment of winter wheat (Cultivar CDC Buteo)- no seed treatments applied (Lethbridge, AB, Canada, 2011); and (B) showing winter wheat (Cultivar CDC Buteo) treated with dual fungicide/insecticide tebuconozole + metalaxyl + imidacloprid ('Raxil WW').

At the early dough stage, GS 83 (Zadoks et al., 1974), 20 flag leaves were randomly collected from each plot, dried at room temperature and then stored at approximately 4°C. Total leaf disease severity was rated for each leaf as the total percentage leaf area diseased (TPLAD) by a combination of the leaf spot complex [Septoria blotch, *Septoria tritici* Roberge in Desmaz.; Stagonospora blotch, *Phaeosphaeria avenaria* (G.F. Weber) O. Eriksson f. sp. *triticea* T. Johnson; Tan spot, *Pyrenophora*

Table 1. Location characteristics for a direct-seeded winter wheat experiment conducted at sites in Alberta (AB), Saskatchewan (SK), and Manitoba (MB), Canada, from the fall of 2010 to the summer of 2013.

Site and province	Latitude and longitude	Soil type	Soil classification	Soil organic matter	pH
				g kg^{-1}	
Beaverlodge, AB	55°12′ N, 119°24′ W	Grey Wooded	Boralfs and Udalfs	72	5.7
Lacombe, AB	52°28′ N, 113°44′ W	Black	Udic Boroll	83	6.4
Lethbridge, AB†	49°41′ N, 112°45′ W	Dark Brown	Typic Boroll	30	8.0
Medicine Hat, AB	50°03′ N, –110°55′ W	Brown	Aridic Boroll	22	7.6
Scott, SK	52°17′ N, 108°57′ W	Dark Brown	Typic Boroll	40	5.9
Melfort, SK	52°54′ N, 104°42′ W	Black	Udic Boroll	110	6.6
Canora, SK	51°37′ N, 102°26′ W	Black	Udic Boroll	75	7.9
Indian Head, SK	50°32′ N, 103°39′ W	Black	Udic Boroll	45	7.7
Brandon, MB	49°49′ N, 99°57′ W	Black	Udic Boroll	50	8.1

† Includes dry, irrigated, and Farming Smarter sites.

tritici-repentis (Died.) Drechs.] and powdery mildew (*Erysiphe graminis* DC. f. sp. *tritici* Em. Marchal). Although little or no stripe rust (*Puccinia striiformis* Westend.) was generally observed at most sites at GS 83, a notable level of stripe rust was observed at Scott and Melfort, SK, and Lethbridge, AB, in 2010.

Statistical Analysis

All data were analyzed with GLIMMIX procedures of SAS (Littell et al., 2006; SAS Institute, 2013) with the effects of replicate, site (location × year combinations; environments), and site × treatment interaction as random, and the effect of seed treatment and foliar fungicide as fixed (Table 3). Exploratory analyses revealed that residual variances were heterogeneous among environments (sites) for all data (results not presented). The AICc (corrected Akaike's information) model fit criterion confirmed that the preceding model parameterization was better than a model not modeling residual variance heterogeneity. Variance heterogeneity was modeled for all analyses using the random statement for PROC GLIMMIX with group option set to site. Random site and site × treatment variance estimates were assessed to determine if they were different from zero with P values derived from a Wald test using critical Z values (Table 3). Also, the relative size of the

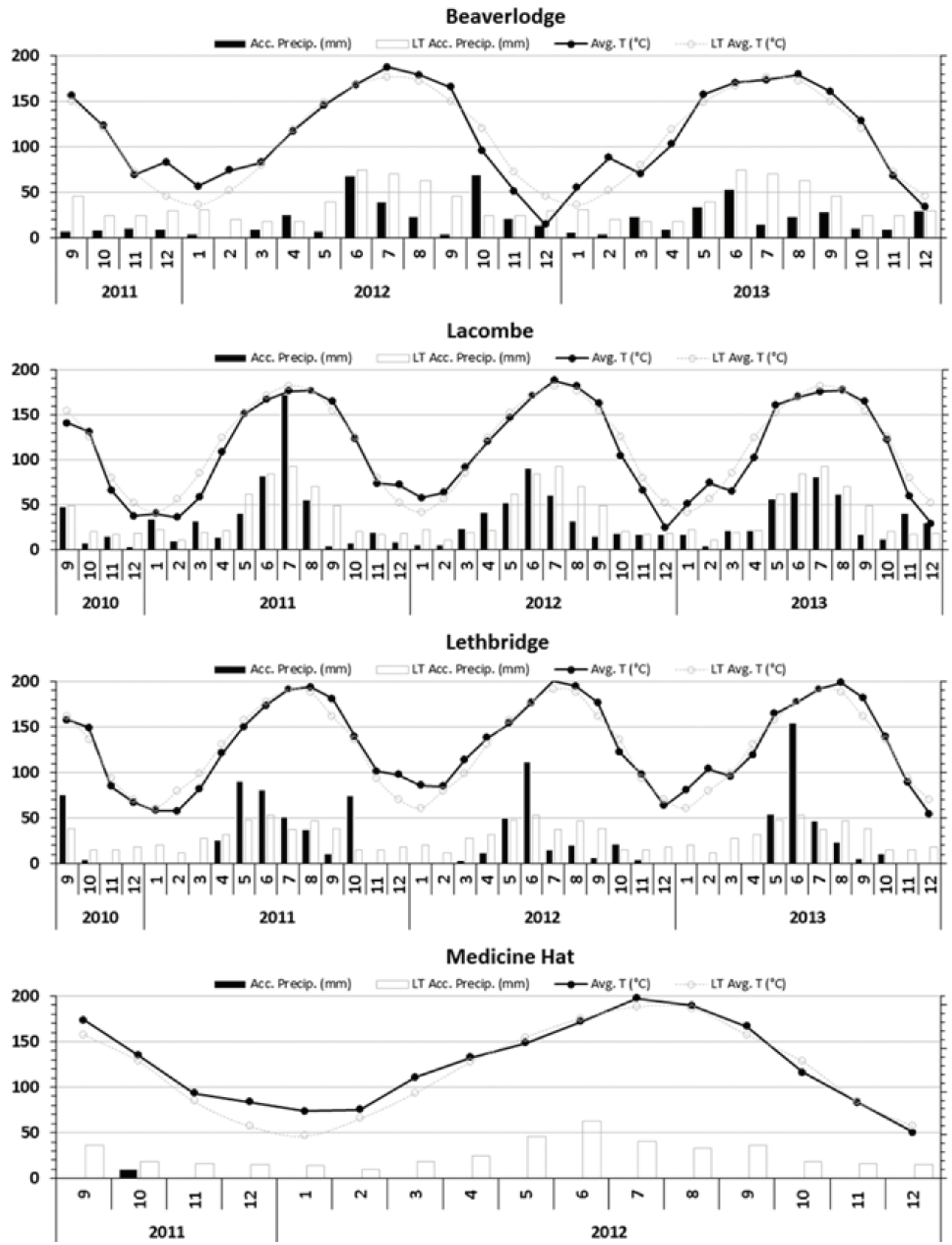

Fig. 2. Monthly accumulated precipitation and mean temperature at 26 sites in Manitoba, Saskatchewan, and Alberta over the course of the study. (Fig. 2 is continued on the next page.)

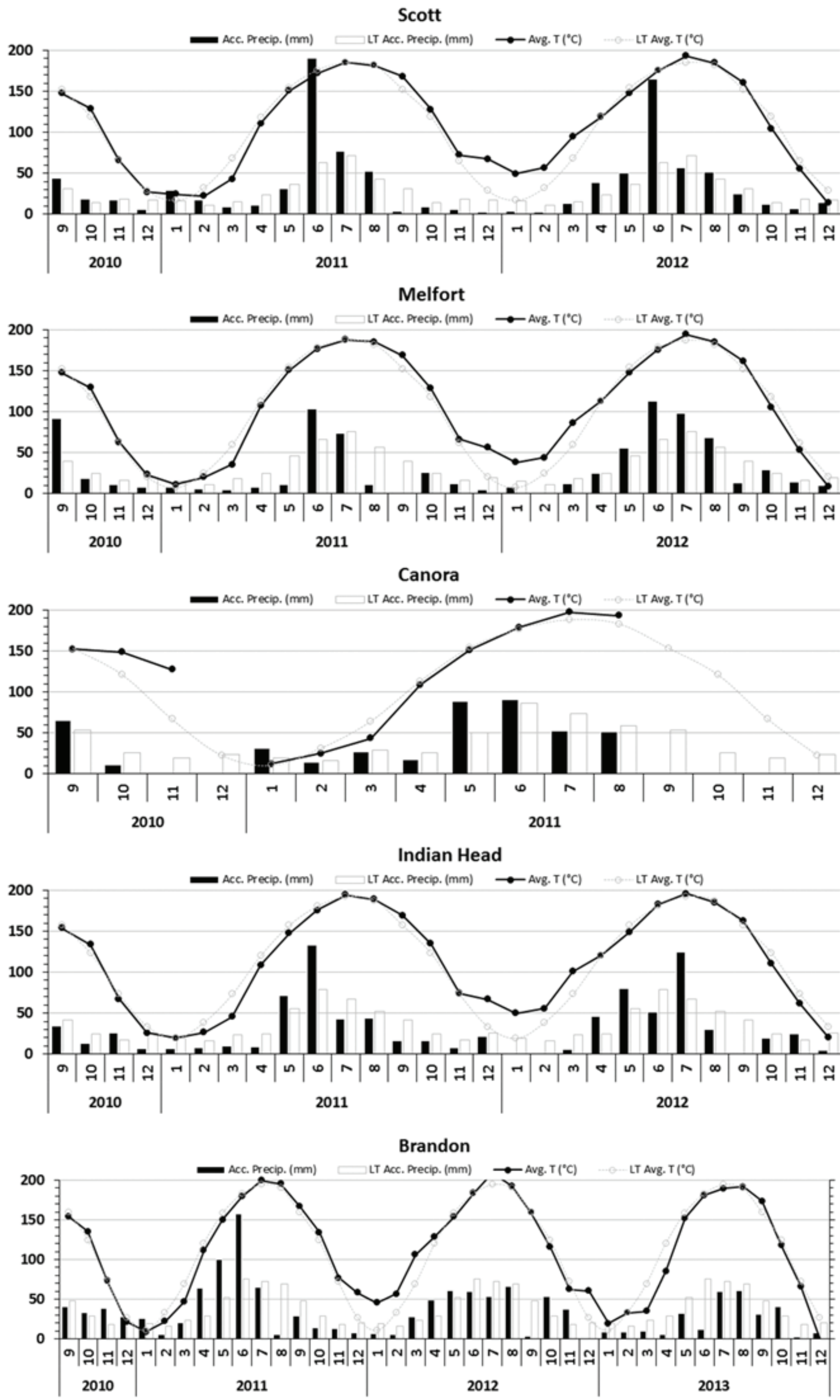

Fig. 2. continued.

site × treatment variance estimates were compared to the sum of site and site × treatment interactions.

Specifically, for the agronomic data, a preliminary PROC MIXED analysis was conducted before GLIMMIX analysis to estimate covariance parameter estimates. These estimates were "passed" into a final PROC GLIMMIX analysis using the parms statement (Table 3, SAS Institute, 2013). Using a two-stage analysis to provide starting covariance estimates improved computational efficiency and model convergence.

Leaf disease severity data were assessed on a proportion (percentage) scale. To properly account for the binomial nature of this type of data (Stroup, 2015), the GLIMMIX procedure of SAS (Littell et al., 2006; SAS Institute, 2013) along with a b error distribution and default logit link function was used to analyze these data (Table 3). The effects of replicate, environment (location × year combinations), and environment × treatment were treated as random, and the effect of seed treatment and foliar fungicide application as fixed (Table 3). The parms statement was used to seed all covariance parameters to 1, which ensured proper convergence and stable solutions. Means and standard errors were back-transformed from logit scale to original percentage scale using an inverse link function.

A grouping methodology, as previously described by Francis and Kannenberg (1978), was used to explore system responses and variability. The mean and coefficient of variation (CV) were estimated for each treatment combination across sites and replicates. Means were plotted against CV for each system, and the overall means and CVs were included in the plot

Table 2. Site (location × year combinations) characteristics for a direct-seeded winter wheat experiment conducted at sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013.

Location/Year	Previous crop	Seeding date	Fungicide applicationdate	Harvest date	Spring plant density	Yield
					no. m^{-2}	Mg ha^{-1}
Beaverlodge						
2012	Oats	11 Sept. 2011	25 Oct. 2012	28 Aug. 2012	317	4.01
2013	Chem–Fallow	7 Sept. 2012	15 Oct. 2012	15 Oct. 2013	136	1.19
Lacombe						
2011	Canola	2 Sept. 2010	6 Oct. 2010	29 Aug. 2011	379	6.14
2012	Canola	9 Sept. 2011	24 Oct. 2011	21 Aug. 2012	297	5.46
2013	Canola	7 Sept. 2012	19 Oct. 2012	23 Aug. 2013	314	3.56
Lethbridge						
Dry						
2011	Canola	14 Sept. 2010	20 Oct. 2010	23 Aug. 2011	164	2.89
2012	Peas	10 Sept. 2011	31 Oct. 2011	19 Aug. 2012	119	4.91
2012 (Crighton)	Canola	15 Sept. 2011	1 Nov. 2011	14 Aug. 2012	211	8.26
2013	Fallow	20 Sept. 2012	5 Dec. 2012	27 Aug. 2013	95	4.10
Farming Smarter†						
2011	Barley silage	13 Sept. 2010	20 Oct. 2010	‡	276	‡
2012	Barley silage	13 Sept. 2011	1 Nov. 2011	8 Aug. 2012	226	5.53
2013	Barley silage	24 Sept. 2012	6 Nov. 2012	21 Aug. 2013	360	4.24
Irrigated						
2011	Canola	15 Sept. 2010	20 Oct. 2010	20 Aug. 2011	189	5.81
2012	Canola	9 Sept. 2011	10 Nov. 2011	18 Aug. 2012	178	4.84
2013	Canola	19 Sept. 2012	5 Dec. 2012	20 Aug. 2013	146	3.35
Medicine Hat 2012†	Chem fallow	21 Sept. 2011	2 Nov. 2011	2 Aug. 2012	226	3.83
Scott						
2011	Chem–Fallow	13 Sept. 2010	20 Oct. 2010	17 Aug. 2011	297	4.02
2012	Chem– Fallow	9 Sept. 2011	17 Oct. 2011	23 Aug. 2012	313	3.82
Melfort						
2011	Barley silage	25 Aug. 2010	1 Oct. 2010	15 Aug. 2011	97	3.76
2012	Barley silage	25 Aug. 2011	25 Oct. 2011	24 Aug. 2012	‡	2.13
Canora 2011	‡	‡	‡	‡	‡	3.80
Indian Head						
2011	Canola	6 Oct. 2010	‡	18 Aug. 2011	310	4.45
2012	Canola	6 Sept. 2011	‡	18 Aug. 2012	301	4.33
Brandon						
2011	Canola	8 Sept. 2010	‡	23 Aug. 2011	180	3.55
2012	Flax	6 Sept. 2011	‡	13 Aug. 2012	184	4.56
2013	Barley Silage	11 Sept. 2012	‡	26 Aug. 2013	64	3.19

† Farming Smarter is a not for profit organization representing agricultural producers in southern Alberta. Farming Smarter conducted the experiment at sites at Lethbridge and Medicine Hat, AB.

‡ Data are not available for these sites.

to categorize the data into four categories: Group I: High mean, low variability; Group II: High mean, high variability; Group III: Low mean, high variability; and Group IV: Low mean, low variability.

Economic Analysis

An economic analysis was conducted to determine the gross and net returns for the seed treatment and foliar fungicide treatments. The variable costs, fixed costs, and estimated crop value based on historical prices in Canadian dollars were sourced from the Saskatchewan Ministry of Agriculture's Crop Planning Guide 2015 (Anonymous, 2015b). The seed input costs were increased slightly to reflect the average selling price of CDC Buteo during the period of the study as it was a newly released cultivar (\$10/bushel = \$368 T^{-1}; Wes Woods, personal communication, 2015). The net return was calculated as:

$$N = (YP) - (V + F)$$

where N is the net return in \$ ha^{-1}, Y is crop yield (Mg ha^{-1}), P is crop price in \$ T^{-1} [\$5.25 $bushel^{-1}$ × 36.77 (bushels T^{-1}) = \$193 T^{-1}], V is variable costs ha^{-1}, and F is fixed costs ha^{-1}. The preceding calculation was conducted for individual data points. Economic data were analyzed with the same mixed model analysis used for the agronomic data.

RESULTS AND DISCUSSION

Production Variability and Environmental Conditions

A wide range of environmental conditions were encountered over the course of this study (Table 1 and Fig. 2), which is typical for crop production in the Prairies. Trends are summarized in the companion paper to this study (Beres et al., 2016). Briefly, eastern Prairie locations tended to be cooler during the winter months than more westerly locations. Perhaps as a result, Brandon in 2013 had notably thinner stands and slightly lesser yields than the other years at the same location (Table 2). Additionally, poor snow cover may have compromised winter wheat survival at Brandon in 2012–2013. Across all locations, except Beaverlodge and Brandon, June/July precipitation was often above average (Fig. 2), which usually resulted in average to above-average grain yield (Table 1).

Environment by Agronomic Factor Variability

The analysis of variance indicated that the overall effect of site (location × year combinations) was the largest source of variation (Table 3). Of greater interest was the amount of variance associated with the site by treatment interaction. For most responses, the variance estimates for these interactions were not significant and always less than or equal to 2% of the total variance associated with the effect of site (Table 3). However, for fall and spring plant density the site × treatment interaction was significant, but the variance estimates represented only 1% of the total variance associated with the overall effect of site. Therefore, the treatment effects were generally consistent among the sites (environments) for the winter wheat response variables measured.

Treatment Effects

Treatment effects were detected for all winter wheat responses except for fall plant density, winter survival, and kernel wt. (Table 3); however, weaker responses were noted for spring plant density and grain protein concentration ($P < 0.10$). The main effects of seed treatment and fall-applied foliar fungicide caused strong responses for grain yield and net revenue (Table 3). The check and the fungicide seed treatment, metalaxyl, produced similarly low grain yield resulting in lower net returns, whereas the dual fungicide/insecticide seed treatment (combination) provided the highest yield and net returns (Table 4). The neonicotinoid seed treatment, imidicloprid, and the fungicide seed treatment, tebuconazole, generally provided intermediate grain yields and net returns. Grain yield also improved with the application of foliar fungicides in fall, but there was no apparent synergistic or antagonistic relationship noted with seed treatments (Tables 3–5). Fungicide seed treatments have been effective in improving winter wheat stand establishment and yield when seed infection with *Fusarium graminearum* is a concern (Schaafsma and

Table 3. Analysis of variance and variance components for winter wheat data collected at 26 sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013.

Effect/Seed treatment	Plant density: Fall	Plant density: Spring	Winter survival	Yield	Kernel wt.	Test wt.	Percent area of the flag leaf diseased	Protein concentration	Net revenue
	– no. plants m^{-2} –		%	Mg ha^{-1}	mg	kg hL^{-1}	%	g kg^{-1}	\$ ha^{-1}
Fixed effects									
					ANOVA (*P* value)				
Seed treatment (ST)	0.366	0.223	0.808	0.001	0.491	0.109	0.413	0.279	0.024
Foliar fungicide (F)	0.814	0.180	0.329	0.024	0.104	0.366	0.017	0.078	0.050
T × F	0.594	0.094	0.162	0.887	0.303	0.040	0.536	0.667	0.850
Random effects									
					Variance estimate†				
Site (S)	8684**	8108**	1171**	2**	28**	8**	0.705**	2**	13**
S × ST × F	61**	71*	6	<0.01	0	0	0.011**	0	0
Percent variance S × ST × F	1	1	1	<1	<1	0	2	<1	0

* Statistical significance of variance estimates is represented as follows: 0.05 > *P* value > 0.01.

** Statistical significance of variance estimates is represented as follows: *P* value < 0.01.

† The percent variance S × ST × F is estimated by dividing the site by seed treatment by foliar fungicide variance estimate by the sum of the variance estimates associated with the effect of site multiplied by 100.

Table 4. Mean winter wheat grain yield and net revenue responses to seed treatment for data collected at 26 sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013.

Variable	Check	Tebuconazole	Metalaxyl	Imidacloprid	Combination	LSD 0.05
Yield, Mg ha^{-1}	4.17	4.24	4.18	4.25	4.33	0.05
Net revenue, \$ ha^{-1}	90	97	86	99	104	12

Table 5. Mean winter wheat yield, leaf disease severity and net revenue responses to foliar fungicide (Prothioconazole) for data collected at 26 sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013.

Variable	Check	Foliar fungicide
Yield, Mg ha^{-1}	4.20	4.26
Percentage flag leaf area diseased, %	14.8	13.9
Protein concentration, g kg^{-1}	110.3	109.8
Net revenue, \$ ha^{-1}	107	83

Table 6. Mean winter wheat spring plant density and test wt. responses to seed treatment and foliar fungicide for data collected at 26 sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013.

	Fungicide treatment		
Variable/Seed treatment	Check	Foliar fungicide	LSD 0.05
Spring plant density, no. m^{-2}			
Check	217	221	11
Tebuconzole	218	227	
Metalxyl	218	231	
Imidicloprid	229	226	
Combination	230	223	
Test wt., kg hL^{-1}			
Check	79.7	79.6	0.2
Tebuconzole	79.6	79.6	
Metalxyl	79.5	79.6	
Imidicloprid	79.8	79.6	
Combination	79.6	79.6	

Tamburic-Ilincic, 2005). More recently, May et al. (2010) evaluated a range of seed treatments in both *F. graminearum*-infected barley and wheat seed and reported an increase in emergence and yield with seed treatment when levels of seed infection in wheat were high (>50%), but not when infection levels were ≤10%. In the current study, only certified seed with germination levels of >90%, and little or no infection with *F. graminearum* was used. In a companion study by Beres et al. (2016) the same dual fungicide/insecticidal seed treatment, as used in the current study, increased winter wheat fall and spring plant density as well as winter survival. They also reported that the same combination seed treatment, increased grain yield and net returns, especially when a lower seeding rate was used (Beres et al., 2016).

Fall-applied foliar fungicide (prothioconazole) reduced leaf disease severity at GS 83 and improved grain yield, and weakly affected grain protein concentration ($P < 0.10$), and net returns (Table 5). Generally, the winter wheat responses were modest with a reduction of 0.8% in leaf disease severity and a 0.06 Mg ha^{-1} increase for yield (Tables 3 and 5). Foliar fungicide application can significantly increase wheat yields and increase net returns when the risk of leaf disease is high (Fernandez et al., 2014; Wegulo et al., 2011; Weisz et al., 2011). In the current study, foliar fungicides were applied in the fall at a relatively early crop growth stage to determine if mitigation of disease pests in the fall would improve crop productivity, or if the systemic activity of prothioconazole in the plant would provide any benefit. Although foliar fungicide increased grain yield in the current study, the increase was small and resulted in a reduction in net revenue. Yield gains were more apparent at sites (Lethbridge, AB; Scott and Melfort, SK, 2010) that had confirmed stripe rust in the fall, but net revenues compared to not applying any foliar fungicide were still cost-prohibitive (data not shown). From a disease management perspective, these results are consistent with Fernandez et al. (2014), Turkington et al. (2004; 2015), and Poole and Arnaudin (2014), who reported that direct protection of the key upper canopy leaves from cereal leaf disease is critical for maintaining seed yield. Fungicide applications at early crop growth stages, like that used in the current study, will not provide direct protection of upper canopy leaf tissue (Poole and Arnaudin, 2014; Turkington et al., 2004, 2015). The yield gains could therefore be related to plant responses to prothioconazole that improved plant defense systems against abiotic stress. Prothioconazole is purported to play a role in enhancing plant frost tolerance through changes to the mesocotyl (Anonymous, 2009).

For most winter wheat responses, the fungicide effect did not vary with the seed treatment used (Table 3). However, the seed treatment by foliar fungicide interaction had a weak effect on spring plant density ($P < 0.10$) (Table 3). A small increase in plant density (13 plants m^{-2}) occurred in the absence of foliar fungicides with the inclusion of the insecticide component, imidacloprid. In the presence of the fall foliar fungicide, most levels of seed treatment improved spring plant density; however, no benefit was observed in seed treatments containing imidacloprid (Table 6). Foliar fungicide application increased spring plant density (13 plants m^{-2}) compared to no fungicide applied when seed was treated only with metalaxyl. The interaction also influenced grain test weight, but differences observed were very small and would not be of any practical or biological importance (Tables 3 and 6).

The lack of benefit observed in the metalaxyl alone seed treatment suggests that the *Pythium* spp. (Anonymous, 2015c) targeted by this seed treatment were likely less of a concern in the current study. In contrast, products containing the fungicide tebuconazole or the insecticide imidacloprid did increase yield, and in addition to grain yield, the combination seed treatment also provided the highest net returns. Tebuconazole is a fungicide that is used for a range of wheat leaf diseases and thus may have impacted leaf disease management via its systemic nature (Anonymous, 2015c; Poole and Arnaudin, 2014). Although, none of the seed treatments had an effect based on leaf disease severity at GS83 (Table 3), they, along with the fall-applied fungicide, may have had an effect on general plant health in the late fall and following spring that may have contributed to the higher observed yields. For example, at Lacombe in May 2012, plots with fall-applied fungicide appeared to have less mid-canopy leaf yellowing, primarily due to powdery mildew, compared to the check (Fig. 3). Similar visual impacts were observed at the Lethbridge test site in 2011, where the combination seed treatment appeared to produce a more consistent spring stand vs. no seed treatment and no foliar fungicide (Fig. 1). However, we were unable to definitively attribute these responses to biotic pressures such as disease or insect pests. This suggests that treatment effects may have played a greater role in enhancing plant defense systems to abiotic responses rather than to biotic pressure. This was evident in the companion paper where winter wheat stand establishment and productivity improved with a dual fungicide/insecticide seed treatment and was most notable in weak agronomic systems, that is, treatments with a lower seeding rate and smaller seed size (Beres et al., 2016). Similar results were not as apparent in the current study where a small increase in plant density was only notable in the absence of the fall foliar fungicide. This may relate to the higher seeding rates and the unsized seed lots used for all plots in the present study vs. the Beres et al. (2016) winter wheat study, which looked at the impact of seed size (small, medium, and large), seeding rate, and seed treatment. Previous research in other crops with neonicotinoid insecticide seed treatments has suggested the occurrence of non-insecticidal seed treatment benefits. A study of soybean (*Glycine max* L.) seed treated with thiamethoxam reported accelerated germination and larger seedlings concomitant with buffering against the negative effects of water deficit (Cataneo et al., 2010). A Canadian study on eastern Canadian spring wheat reported that a dual fungicide (difenoconazole and metalaxyl) and an insecticide (thiamethoxam) enhanced the frost tolerance of seedlings (Larsen and Falk, 2013).

Fig. 3. (A) No seed treatment, fall-applied fungicide treatment of winter wheat (Cultivar CDC Buteo), 31 May 2012 Lacombe, AB, Canada; and (B) No seed treatment, no fall-applied fungicide treatment of winter wheat (cultivar CDC Buteo), 31 May 2012 Lacombe, AB, Canada.

Cropping System Stability

The average yield response relative to stability for each winter wheat production system was assessed by plotting mean grain yield and the coefficient of variation for each of the seed treatment by fall-applied foliar combination (Fig. 4). The biplot confirmed that seed treatments containing imidacloprid or tebuconazole produced high grain yield. A secondary feature, however, was that all the data points in Group 1 that reflected both high yield and greater stability required the application of fall foliar fungicide. The dual seed treatment and imidacloprid alone produced above-average grain yield, but with greater instability in the absence of a fall foliar fungicide. Moreover, all treatments in the Group III representing low and highly variable grain yield were treatments lacking fall foliar fungicides, seed treatments, or both (Fig. 2a). Grain yield appears to improve and stabilize slightly for the poorest performing treatments, check and metalxyl, when a fall foliar fungicide was incorporated. Although not as apparent, a similar trend was observed for spring plant density where systems with high and stable plant stands seemed to benefit from the fall foliar fungicide (Fig. 4). Comparable results have also been reported in areas with milder winters and warmer, more humid growing seasons. For example, in Ontario, Schaafsma and Tamburic-Ilincic (2005) reported that most fungicide seed treatments increased yield, but seed and soil-borne disease levels and causal agents were not assessed. Similarly, in Georgia, Buck et al. (2009) demonstrated that seed treatments with insecticides improved winter wheat yield when the risk of BYDV was high as a consequence of elevated aphid populations. In a soybean study, Gaspar et al. (2014) reported an increase in yield when seed treatments contained a combination of fungicide and insecticide vs. fungicide alone. Also in soybean, Cox and Cherney (2014) reported stand establishment was increased at all four study sites vs. the untreated control with a combination fungicide/insecticide treatment. In contrast, the fungicide treatment alone only increased establishment vs. the untreated control at two of four sites. At the two sites where soybean grain yield was affected by seed treatments, only the combination seed treatment increased yield (Cox and Cherney 2014).

An assessment of system stability underscores the potential role for seed treatments in winter wheat systems as well as the potential benefit provided by fall-applied foliar fungicides. From purely a disease or economical perspective, the recommendation to use a foliar fungicide applied in fall would be readily dismissed. However, the stability responses suggest that performance indicators of a successful crop production system should be broadened. The literature clearly establishes that seed-applied fungicides/insecticides provide benefits (Anonymous, 2009; Buck et al., 2009; Cataneo et al., 2010; Ford et al., 2010) to the plant that extends beyond biotic pressures. Perhaps those

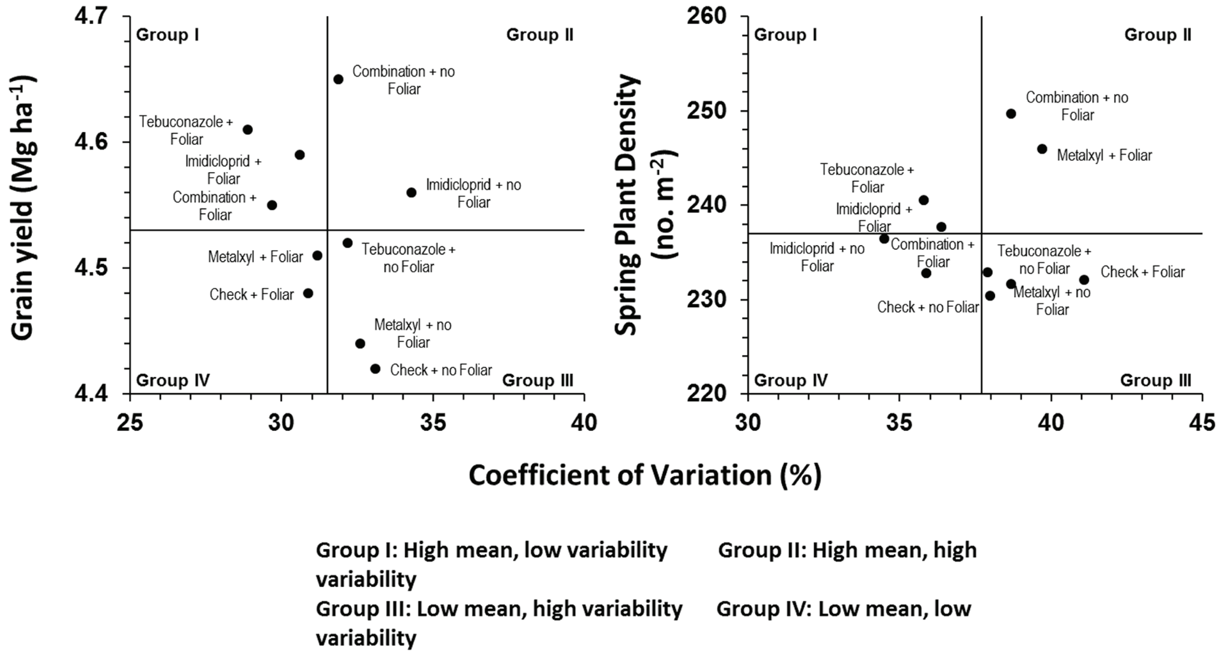

Fig. 4. Biplots summarizing mean treatment responses versus coefficient of variation (CV) for combinations of seed treatment and foliar fungicide (Prothioconazole, Bayer CropScience, Calgary, AB) for grain yield and spring plant density at 26 sites in Manitoba, Saskatchewan, and Alberta, Canada, from the fall of 2010 to the summer of 2013. Abbreviations are as follows: (1) The first part of the label represents the seed treatment used; (2) The second part of the label represents whether a fall-applied foliar fungicide was used. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: Low mean, high variability; Group IV: Low mean, low variability.

same benefits can be realized when the same active ingredients are applied in-crop. It may be that we created greater stability in systems that lacked seed treatment by delivering the active ingredient in-crop in the fall as an alternative to seed-applied active ingredients. The problem is that this approach is costlier (\$37 ha^{-1}) compared to the seed-applied method. Future studies should explore crop responses to timing and methods of application for prothioconazole. The fall-applied foliar system was deemed cost prohibitive when compared to not applying any fungicide, but it is important to recognize that most wheat production systems, particularly in humid or high production environments, will typically incorporate a fungicide application. Thus, the more appropriate consideration in the future should weigh the benefits of a fall compared to spring application. Moreover, economic parameters/methods are needed to quantify the "value" of cropping system stability.

CONCLUSIONS

The current study was conducted to identify alternative seeding and crop management practices that may impact winter wheat stands and grain yield under the growing conditions of the northern Great Plains. In the current study, we wanted to know if fungicide/insecticide seed treatments influenced stand establishment and grain yield in winter wheat. Winter wheat producers can improve yield and net returns through the incorporation of a dual fungicide/insecticide seed treatment. Stability parameters for grain yield and spring plant density may be further improved by using a foliar fungicide applied in fall. The benefits of a fall foliar fungicide application would have to be explored further in the context of an added input or as an alternative to a spring application as the net returns of a fall foliar vs. no application in the system render the input cost-prohibitive.

ACKNOWLEDGMENTS

This project was funded through AAFC's Developing Innovative Agri-Products (DIAP), which leveraged funds provided by Duck's Unlimited Canada, Alberta Winter Wheat Producer's Commission, Saskatchewan Winter Cereals Development Commission, and Winter Cereals Manitoba Inc. Expert technical support provided by R. Dyck, S. Simmill, S. Daniels, D. Yagos, C. Kirkham, D. Cross, N., Rauhala, D. Clark, J. Busaan, L. Michielsen, P. Reid, E. Sroka, J. Zhuidof, G. Semach, C. Gampe, M. Markortoff, G. Finlay, H. Schell, G. Collier, J. Michaelis, and a large regiment of summer students. Special thanks for Bayer Crop Sciences for providing in-kind product and, in particular, Monica Klaas for providing guidance and facilitating with seed treatment preparations. The assistance of Craig Stevenson with regard to the statistical analysis is gratefully acknowledged.

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