Canadian Journal of Plant Science
Revue canadienne de phytotechnie

**The role of genetics, growth habit, and cultural practices in
the mitigation of Fusarium head blight**

Journal:	<i>Canadian Journal of Plant Science</i>
Manuscript ID	CJPS-2016-0336.R1
Manuscript Type:	Article
Date Submitted by the Author:	27-Jan-2017
Complete List of Authors:	Ye, Zesong; University of Manitoba Faculty of Agricultural and Food Sciences Brule-Babel, Anita; University of Manitoba, Plant Science Graf, Robert; Agriculture & Agri-Food Canada, Mohr, Ramona; Brandon Research Centre (Brandon, Manitoba) , AAFC Beres, Brian; Agriculture and Agri-Food Canada, Sustainable Production Systems
Keywords:	Triticum aestivum L., Fusarium head blight, Fungicide, Seed treatment, DON

SCHOLARONE™
Manuscripts

**The role of genetics, growth habit, and cultural practices in the mitigation of
Fusarium head blight**

Ye, Z.¹, Brûlé-Babel, A.L.^{*,1}, Graf, R.J.², Mohr, R.³, and Beres, B.L.^{*,2}

¹*Department of Plant Science, 66 Dafoe Road, University of Manitoba, Winnipeg, MB R3T*

*2N2;*²*Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, 5403-*

*1st Avenue South, Lethbridge, Alberta, Canada T1J 4B1;*³*Agriculture and Agri-Food Canada,*

Brandon Research and Development Centre, Box 1000A, RR #3, Brandon, MB, Canada R7A

5Y3;

*Corresponding authors: E-mail brian.beres@agr.gc.ca

E-mail anita.brule-babel@umanitoba.ca

Ye, Z., Brûlé-Babel, A. L., Graf, R. J., Mohr, R., and Beres, B. L. 2016. **The role of genetics, growth habit, and cultural practices in the mitigation of *Fusarium* head blight** Can. J. Plant Sci. xx:xx–xx. Field trials were conducted under natural infection and artificial inoculation from 2012 to 2014 at seven sites across the Canadian prairies to determine genetic and management effects on *Fusarium* head blight (FHB) in wheat production systems. A system of management, which consisted of 1) a control of no fungicide was compared to 2) the seed treatment (ST) thiamethoxam+difenoconazole+metal-axyl-M+S-isomer, 3) an in-crop foliar fungicide (tebuconazole+prothioconazole), or 4) ST+foliar fungicide, was integrated with four wheat cultivars of contrasting growth habit and levels of FHB resistance. Results indicated the cultivars expressing improved FHB resistance, Carberry (spring wheat) and Emerson (winter wheat), were superior over susceptible cultivars, Harvest (spring wheat) and CDC Falcon (winter wheat), in reducing *Fusarium* damaged kernel (FDK) and deoxynivalenol (DON) levels, and displayed higher yield under high *Fusarium* pressure. Winter wheat displayed higher overall yield, with Emerson producing the highest and most stable yields across environments. Application of foliar fungicide, with or without the ST, increased grain yield, seed mass and test weight; and lowered FDK and DON. Seed treatment alone increased test weight, spring plant density of both winter wheat varieties, and kernel weight in Emerson. A management strategy of foliar fungicide and/or ST+foliar fungicide generally produced higher yields with greater stability, particularly for susceptible cultivars in high FHB environments. The results of this study reinforce that integration of FHB resistant cultivars with appropriate cultural practices is required to reduce the risk of FHB and optimize grain yield, and is further enhanced with a winter vs. spring growth habit.

Keywords: *Triticum aestivum* L., *Fusarium* head blight, fungicide, seed treatments, FDK, DON
Abbreviations: **DON**, deoxynivalenol; **FDK**, *Fusarium* damaged kernel; **ST**, seed treatment;

Fusarium head blight (FHB) is one of the most important fungal diseases in wheat because of its direct detrimental effects on grain yield, quality and marketability. Severe FHB epidemics can cause up to 70% yield loss (Haidukowski et al. 2005). In addition to reduced yield and grain quality, the most common causal agent of this disease, *Fusarium graminearum* Schwabe [telomorph: *Gibberella zeae* Schwein (Petch)], produces deoxynivalenol (DON) and its acetylated derivatives, 3-acetyl DON (3-ADON) and 15-acetyl DON (15-ADON) (Nicholson et al. 2003; Osborne and Stein 2007). Deoxynivalenol can threaten human and animal health because of haematic and anorexic syndromes, and neurotoxic and immunotoxic effects in mammals (Haidukowski et al. 2005). Feeding farm animals such as swine with DON contaminated grain causes weight loss, feed refusal, and vomiting when sufficient doses are ingested (Pestka 2007).

The effects of FHB management strategies such as cultural practices, fungicide application, biological control, planting resistant cultivars, or modifying the cropping system have been studied. However, a single control strategy usually fails to control the disease sufficiently. Commercial cultivars of wheat vary in their response to FHB. Fungicide application plays an important role in controlling FHB (Simpson et al. 2001). However, results of FHB control with fungicides have been variable. Successful control of FHB using triazole-based fungicides has been reported (Amarasinghe et al. 2013; Mesterházy et al. 2003; Paul et al. 2008; Wegulo et al. 2011), but several studies have also shown that azoxystrobin application led to increased DON contamination of grain in artificially inoculated field trials (Mesterházy et al. 2003; Pirgozliev et al. 2003; Simpson et al. 2001). Integration of triazole-based fungicides, alone or in combination, with moderately resistant cultivars tended to be more effective in reducing FHB index and DON accumulation in grain when compared with susceptible cultivars

(Amarasinghe et al. 2013; Mesterházy et al. 2003; Wegulo et al. 2011). In addition, fungicide effectiveness was more stable in resistant cultivars. The variability of fungicide efficacy in controlling FHB could be due to the timing of the fungicide application, fungicide selection and application technology, virulence of the *Fusarium* isolates, and level of resistance in cultivars planted (Mesterházy et al. 2003).

Seed treatments using tebuconazole + imazalil, fludioxonil and difenoconazole resulted in significant reductions in the attack of soil-borne *Fusarium* spp. to roots and coleoptiles of seedlings in a trial carried out under greenhouse conditions (Jørgensen et al. 2012). Some fungicide seed treatments increased winter wheat plant stands and grain yield; however, the effectiveness of the same seed treatments in managing FHB were inconsistent (Schaafsma and Tamburic-Ilincic 2005). May et al. (2010) reported that fungicidal seed treatment did not always improve seedling emergence and had no significant effect on grain yield. In general, the effects of fungicidal seed treatment on wheat yield and FHB mitigation is not fully understood. Current recommendations are that an integrated approach including cultural control, cultivar resistance, crop rotation, and fungicide application be used to protect wheat from FHB.

The objectives of this study were to determine the influence of cultivar selection combined with seed- and foliar- applied fungicides on grain yield of spring and winter wheat; and to investigate the effectiveness of integrating fungicide application and cultivar resistance in controlling FHB and DON accumulation in grain.

MATERIALS AND METHODS

To create a range of *Fusarium* responses, a management factor, which consisted of 1) a control of no fungicide were compared to 2) a seed treatment (ST) thiamathoxam+difenoconazole+metal-axyl-M+S-isomer, 3) an in-crop foliar fungicide

(tebuconazole+prothioconazole), or 4) ST+foliar fungicide, was integrated with four wheat cultivars of contrasting growth habit and differential levels of resistance to FHB. The cultivars consisted of two winter wheats, Emerson (Graf et al. 2013) (resistant to FHB) and CDC Falcon (Fowler 1999) (susceptible to FHB); and two spring wheats, Carberry (DePauw et al. 2011) (moderately resistant to FHB) and Harvest (Fox et al. 2010) (susceptible to FHB).. Plots were established at seven locations across the Canadian prairies in multiple years. The Carman, MB and Winnipeg, MB sites served as *Fusarium* artificial inoculation sites; all other sites were natural infection sites (Table 1).

The experimental design was a four replicate split plot. The main plot effect was assigned to the wheat cultivars and the management (ST/fungicide) treatments were assigned to the sub plot. At Carman and Winnipeg, an uninoculated, untreated control was also included (Table 2). The model for the study using Patterson's syntax (Piepho et al. 2004) is as follows:

GENETICS (MAIN PLOT) x MGMT (ST & FUNGICIDE TRTS) : SITE + SITE · INPUT + SITE · GENETICS · MGMT + REPLICATE · SITE + ***REPLICATE · GENETICS · SITE*** + ***REPLICATE · GENETICS · MGMT · SITE***

where the fixed effects are stated before the colon and random effects are after the colon. The (REPLICATE · GENETICS · SITE + REPLICATE · GENETICS · FUNGICIDE · SITE) terms are boldfaced and italicized to indicate the site specific main plot error term and residual error term, respectively. The dot operator is used to define crossed effects. The 'x' indicates two completely cross-classified factors with separate main effects and an interaction effect.

The plot size varied according to the available seeding equipment at each location. For example, plots at Winnipeg and Carman were planted at a rate of 400 seeds m⁻² into standing flax stubble and consisted of six rows, spaced 17 cm apart, and 3 m in length. Plots at other locations

YE ET AL. – GxExM EFFECTS ON FHB AND YIELD

were seeded directly into standing canola stubble at a rate of 400 seeds m⁻² using a zero till plot seeder equipped with a cone splitter. Fertilizer amendments were based on soil test recommendations for each site in each year to achieve a target yield of 5.5 Mg ha⁻¹.

The seed treatment Cruiser Maxx® Cereals was applied to seeds prior to seeding using the Manufacturer's recommended rate of 3.25 mL/kg of seed - Thiamethoxam: 30.7g/L; Metalaxyl-M: 9.5g/L; Difenoconazole: 36.9g/L; Sedaxane: 8.0g/L. The foliar fungicide Prosaro 421 SC™ spray application was performed at 455-574 mL/ha when 75% of the main stem spikes were fully emerged and up to 50% of the spikes on the main stem were at anthesis. At Winnipeg and Carman, plots were spray-inoculated one to two days after foliar fungicide application. With the exception of the uninoculated-untreated plots, all other plots at Carman and Winnipeg were inoculated with a *F. graminearum* macroconidia suspension (5×10^4 spores/ml) of four isolates (two 15-ADON and two 3-ADON) at a rate of 1 L/plot when wheat reached 50% anthesis (Zadoks GS 65). The uninoculated plots were sprayed with 1L of distilled water. In order to make a full coverage of spikes, a second inoculation was performed three days after the first inoculation so that later spikes were inoculated at the appropriate stage. An overhead mist irrigation system was switched on one hour after inoculation to maintain a humid environment conducive to the development of FHB symptoms. The irrigation system was programmed to irrigate field plots for 10 minutes every hour for 10 hours daily for five to seven days to promote FHB symptom development.

Spring plant density was measured by counting two-one meter sections of different rows within each plot before the seedlings started tillering (Zadok's growth stage 10-13) and converted to the number of plants m⁻². Plots were harvested after the wheat reached physiological maturity. The wind speed of the combine was reduced to retain as many *Fusarium*

damaged kernels (FDK) as possible. Grain yield of each plot was determined on a clean grain basis and corrected to 13% moisture. Grain samples were evaluated for Fusarium infection levels by determining percentage of FDK and deoxynivalenol (DON) accumulation. Kernels with a shrunken, pinkish or whitish appearance, or with mycelial growth, were considered as FDK. Percentage of FDK was expressed as number of FDK/ total seeds counted x 100%. A sample of 50g grain from each plot was ground using a UDY Cyclone sample mill (model 3010-060; UDY Corporation, Fort Collins, Colorado) until flour could pass through a 0.85 mm screen and then thoroughly mixed. Deoxynivalenol (DON) was extracted by adding 50 ml of deionized water into a subsample of 10g flour, and then quantified using EZ-Quant® Vomitoxin Enzyme-linked Immunosorbent Assay (ELISA) DON identification kit from Diagnostix. Seed mass was calculated by weighing 1000 seeds counted using an automated seed counter. Grain volume (test weight) was determined using a 0.5 L measure cup, positioned under a Cox funnel (Seedburo Equipment Company, Des Plaines, IL). The same volume of grain from each plot was poured into the hopper. The slide on the hopper was removed to uniformly direct the flow of grain into the 0.5 liter cup. A piece of round hardwood striker was used to level the excess grain in the cup. The tared mass of grain remaining in the 0.5 liter cup was doubled to calculate test weight (kg hL⁻¹). Protein concentration of the sample from each plot was determined by combustion nitrogen analysis. Grain was milled similar to above until the flour could pass through a 1.0 mm mesh screen. A subsample of 0.25g flour was used for total nitrogen content determination using a LECO Truspec NCNA analyzer (LECO Corporation, Saint Joseph, Michigan) and reported on a constant moisture basis. Protein concentration of each sample was calculated by multiplying total nitrogen content by a typical protein factor for milling wheat (5.7). Management efficacy for DON and yield were calculated as $[(C-F)/C]*100$ and $[(F-C)/F]*100$, receptively, where C is

the check treatment value and F is the management treatment value.

Statistical Analyses

All data were analyzed with MIXED and GLIMMIX procedures of SAS v. 9.4 (Littell et al. 2006; SAS Institute 2013) with the effects of replicate and site (location by year combinations) as random, and the effects of genetics, and management (ST/fungicide treatments) as fixed. Exploratory analyses revealed that residual variances were heterogeneous among sites. The AIC (Akaike's information criterion) model fit criterion confirmed that the preceding model parameterization was better than a model not modeling residual variance heterogeneity. Variance heterogeneity was modeled using the repeated statement for PROC MIXED with group option set to site or random statement for PROC GLIMMIX with group option set to site and covariance structure set to R-side (residual).

A preliminary PROC MIXED analysis was conducted to estimate covariance parameter estimates for plant density, yield, seed mass, test weight, and protein concentration. These estimates were 'passed' into a final PROC MIXED analysis using the parms statement (SAS Institute 2013). Using covariance estimate seed values improved computational efficiency and model convergence. DON and FDK data were analyzed with the GLIMMIX procedure of SAS (Littell et al. 2006; SAS Institute 2013) using parameterizations described at the beginning of this section. To properly account for the binomial nature of the DON and FDK data, the analysis was parametrized with a beta error distribution and default logit link function (SAS Institute 2013). Means and SE for class factors were back-transformed from logit scale to original percentage scale using an inverse link function. Pre-planned contrasts were also performed assessing the effect of management for each level of genetics. They are multi-way in nature ie.

they assess all differences among management bounded by available df for the effect of management.

For all analyses, the random effects of site and site x treatment interactions were assessed with a statistical test to determine if the variance estimates was different from zero. Further, the relative sizes of the site x treatment variance estimates were compared to the sum of site and site x treatment interactions. To better understand the site x treatment interactions, best linear unbiased predictors (BLUP) were used to estimate and compare mean responses to treatments at sites with a high level of FHB (FDK > 5%) and low level of FHB (FDK < 5%) (Littell et al. 2002).

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 years and replicates. Means were plotted against CV for each system, and the overall mean of means and CVs was included in the plot 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.

RESULTS

Treatment Effects. Mean values for grain yield and Fusarium related parameters (FDK and DON) at each experimental site are shown in Table 3. Natural infection sites had low Fusarium infection and DON accumulation in grain except the Brandon site. Only Brandon and the artificially inoculated sites Carman and Winnipeg were considered to have sufficient levels of Fusarium infection (FDK > 1%) and DON (> 1ppm) for further analyses (Table 3). In 2012 and 2013, the Fusarium artificially inoculated sites Carman and Winnipeg had an extremely high

percentage of plots with DON levels higher than 1ppm, ranging from 95% to 100%. Although the Brandon site was not artificially inoculated with *F. graminearum*, more than 50% of the plots had DON levels higher than 1ppm in 2012 and 2014, and the value for 2013 was 44%. Levels of FDK were also high at all Carman sites and Winnipeg 2013. Carman sites and Winnipeg 2013 were classified as high Fusarium sites with FDK>5% and DON>5ppm, and all other sites were grouped into low Fusarium sites. Grain yield at other natural infection sites was usually higher than artificially inoculated sites.

The F-test results indicate the genetics and management main effects were significant for all measured variables (Table 4). The genetics x management interaction was only significant for spring plant density and marginally influenced test weight ($P=0.068$). Although the interaction was largely non-significant, cultivar growth habit influenced the response to fungicide application. For example, management effects on the winter wheat cultivars (CDC Falcon and Emerson) influenced plant density, seed mass, and grain quality parameters. Conversely, the spring wheat cultivars, Harvest and Carberry, had notable responses to FDK, DON, yield and test weight (Table 4). As expected, the effect of high Fusarium pressure was significant for all measured variables (Table 4). In contrast, no effects were detected for all variables under low Fusarium pressure. With the exception of yield and protein concentration, the interaction of different levels of Fusarium pressure with genetics influenced most variables, although the response for DON was marginal ($P=0.055$). Site and site x genetics were significant for all measured variables (Table 4). No effect for spring plant density and test weight was observed in the three way interaction site x genetics x management, which was significant for all other variables. The percentage of total variance in the site x genetics interaction for all measured variables ranged from 7% to 39%. In comparison, the three-way interaction of site x genetics x

management accounted for $\leq 4\%$ of the total variation.

When averaged over management treatments, the FHB resistant winter cultivar ‘Emerson’ had higher plant density, grain yield, test weight and protein concentration than the FHB susceptible cultivar ‘CDC Falcon’ in high Fusarium environments (Table 5). In addition, Emerson trended toward lower FDK and DON than CDC Falcon. At low Fusarium sites, the cultivars produced similar plant stands and grain yield, but Emerson had higher test weight and protein concentration than CDC Falcon, which produced greater seed mass than Emerson. Considering genetic means across all high and low FHB sites, Emerson had higher plant density and protein concentration, and lower FDK and DON than CDC Falcon (Table 5).

At both high and low FHB sites, the FHB moderately resistant spring wheat cultivar ‘Carberry’ displayed higher seed mass and test weight than the FHB susceptible cultivar ‘Harvest’ (Table 5). At low FHB sites, grain yield for Carberry was also higher than Harvest. While statistical differences between Carberry and Harvest for FDK and DON were not apparent, there were notable numeric differences that indicate Carberry would display lower FDK and DON than Harvest at high FHB sites (Table 5). Carberry also displayed lower FDK, DON, and higher seed mass and test weight across combined high and low FHB sites (Table 5).

A comparison of management treatment means indicate that seed treatment tended to increase spring plant density in winter wheat (Table 6). Compared to the check, seed treatment also increased seed mass across sites, years and cultivars, and increased test weight of Emerson. Although some responses indicated a cultivar yield response, seed treatment did not increase grain yield consistently, and there was little difference between the check and seed treatment for FDK and DON. Application of foliar fungicide, whether alone or in combination with seed treatment, increased yield, protein concentration, seed mass and test weight in all four cultivars

(Table 6). Both FDK and DON were reduced by foliar fungicide application. There was no difference between foliar fungicide application alone and ST + foliar fungicide applications for all measured variables.

Comparisons of grain yield and DON means for each management treatment in high FHB sites are presented in Table 7. In 2012, while the management effect was not significant in any cultivars for yield at Carman, it was significant for DON in all cultivars except Emerson (Table 7). Compared with the check and ST treatments, application of foliar fungicide resulted in lower DON in spring wheat cultivars and the winter wheat cultivar CDC Falcon ($P < 0.05$). In 2013, compared with the checks, application of foliar fungicide, including foliar fungicide and/or ST+foliar fungicide treatments, significantly increased yield of all cultivars (Table 7). There were no differences observed between foliar fungicide and ST+foliar fungicide for yield. In most cases, seed treatment alone did not influence yield; however, a positive response was noted with CDC Falcon. Foliar fungicide and/or ST+foliar fungicide reduced DON accumulation in all cultivars (Table 7). In Carman 2014, the only treatment difference for spring wheat cultivars was that foliar fungicide caused a greater yield response than the seed treatment (Table 7). The effect of FHB resistance level (moderately resistant cultivar Carberry) on treatment means was significant ($P = 0.0307$), where the lowest DON was observed in the foliar fungicide treatment.

In Winnipeg 2013, foliar fungicide and /or ST+foliar fungicide increased yield in all cultivars under high FHB disease pressure (Table 7). The ST treatment was not different from the check for yield in each cultivar. The lowest DON accumulation was observed in the foliar fungicide or ST+foliar fungicide treatments for each cultivar.

Seed treatment efficacy for yield and DON was inconsistent across all site-years with $DON > 1\text{ppm}$ (Table 8). In Carman 2012, foliar fungicide efficacy for yield and DON was

inconsistent; however, for other site-years, foliar fungicide efficacy was consistent for yield and DON (Table 8). Foliar fungicide efficacy was not necessarily higher in cultivars expressing resistance than in the susceptible cultivars. For instance, in Carman 2013, foliar fungicide efficacy in resistant cultivars (Emerson and Carberry) for yield and DON was lower than for susceptible cultivars (CDC Falcon and Harvest). In many cases, foliar fungicide efficacy for yield and DON was higher in the susceptible cultivars than in resistant cultivars. The trend of ST+foliar fungicide efficacy was similar to foliar fungicide efficacy (Table 8).

Cropping system stability. To visualize the preceding observations, an iteration of the Francis and Kannenberg (1978) biplot grouping method was used to illustrate the variability at sites with high or low Fusarium pressure (Fig. 1). Irrespective of Fusarium pressure, spring plant density for the spring wheat cultivars was always high with little variability. Strong influences of management were not observed, as all treatments tended to cluster around 250 plants m⁻², which is an ideal plant stand for wheat (Fig. 1a). There was a stronger influence of seed treatment noted for the winter wheat cultivars, particularly at high Fusarium sites, as the Emerson treatments containing a seed treatment had higher plant densities and were less variable. A spring plant density of at least 200 plants m⁻² is desirable for winter wheat, and only Emerson achieved this threshold in high Fusarium pressure and both cultivars were below the threshold in low Fusarium sites (Fig. 1a).

Grain yield was consistently higher (>4 Mg ha⁻¹) with greater stability for all Emerson treatments at high Fusarium sites (Fig. 1b). A foliar fungicide, with or without a seed treatment, improved grain yield to an average level (~3.5 Mg ha⁻¹) in the moderately resistant spring wheat cultivar ‘Carberry’, as well as the susceptible winter cultivar ‘CDC Falcon’. Carberry also displayed greater yield stability at high Fusarium sites than both susceptible cultivars, Harvest

and CDC Falcon. Both winter wheat cultivars produced superior yields over the spring wheat cultivars at low Fusarium sites; however, management also improved system stability for Emerson, as above average grain yield with superior stability was observed in treatments with a seed treatment, the foliar fungicide, or both. CDC Falcon displayed similar grain yield performance when managed with a foliar fungicide or the seed treatment + foliar fungicide; however, stability variance remained high and was in the same grouping as the winter wheat checks (Fig. 1b). Harvest displayed higher yield when a foliar fungicide was used under high Fusarium pressure; however, grain yield remained below average and highly variable regardless of FHB pressure (Fig. 1a)

The susceptible cultivars, CDC Falcon and Harvest, always displayed the highest levels of FDK and DON accumulation (Fig. 1b). However, inclusion of a foliar fungicide in Harvest reduced levels to below average. Foliar fungicide also reduced levels for Carberry down to around 10 ppm (Fig. 1b). Management effects were not as apparent in the resistant winter wheat cultivar, Emerson; however, either lower levels and/or improved stability were evident for FDK when using the foliar fungicide with or without the seed treatment (Fig. 1b).

DISCUSSION

Genetics and fungicide treatment elicited crop and disease responses for most measured variables. Particularly in high FHB environments, application of a triazole-based foliar fungicide (tebuconazole + prothioconazole) will tend to elevate or at least protect yield, seed mass and test weight. Foliar fungicides, as well as a dual seed treatment+foliar fungicide management strategy can lower FDK and DON accumulation in the harvested grain. These results confirm the effectiveness of triazole-based fungicide application in maintaining satisfactory yield and

managing FHB and DON contamination of harvested grain. Mesterházy et al. (2003) reported that fungicides containing tebuconazole tended to be more effective in reducing FHB than those without tebuconazole. Paul et al. (2008) analyzed 139 studies for the effect of tebuconazole on FHB index and 101 studies for the effect of tebuconazole on DON contamination of harvested grain in susceptible cultivars and found that the overall mean percent control of DON was 21.6%. However, the efficacy of tebuconazole was variable. In this study, seed fungicide efficacy for yield and DON was also inconsistent (Table 8). Foliar fungicide and/or seed treatment+foliar fungicide efficacy was inconsistent for yield in Carman 2012; otherwise, it was more consistent for yield and DON in other years and sites (Table 8). Variation in the efficacy of triazole-based fungicides in managing DON contamination has also been noted in another study. Amarasinghe et al. (2013) reported that in some grain samples treated with prothioconazole and prothioconazole + tebuconazole there was a higher DON content than the controls without fungicide application, although these fungicides successfully reduced DON in most of the treatments. They explained that fungicide application reduced FHB symptoms and increased seed size sufficiently that diseased seeds were not lost in harvest and thus, could contribute to a higher percentage of FDK and DON in the samples. This may explain why fungicide efficacy in the cultivars with improved resistance in our study was not consistent compared to the susceptible cultivars. Previous studies (Mesterházy et al. 2003; Wegulo et al. 2011) report fungicide efficacy in reducing FHB index; FDK and DON was consistently higher in the moderately resistant cultivars compared to susceptible cultivars. Variability of fungicide treatment effects may be due to differences in weather conditions in environments. For example, rainy weather during fungicide application may result in low efficacy (Šíp et al. 2010). Other sources of variability include fungal virulence, level of cultivar resistance, and timing and

coverage of the fungicide application (Mesterházy et al. 2003).

The effect of a dual fungicide-insecticide seed treatment on FHB management and grain yield is less documented than foliar applied fungicide. In this study, the seed treatment using Cruiser Maxx® Cereals (thiamethoxam, difenoconazole, metalaxyl-M and S-isomer) was not effective in increasing yield and reducing FDK and DON. However, seed treatment significantly increased seedling stand density in the two winter wheat cultivars and improved yield and reduced variability of Emerson. These observations parallel other studies that report seed treatment benefits to wheat plant density and yield (Beres et al. 2016; Turkington et al. 2016), and may relate to enhanced resistance to abiotic stress as a response to the neonicotinoid insecticide in combination with difenoconazole. Moreover, any apparent differences observed in winter wheat plant density responses between high and low FHB sites would be an artifact of local abiotic conditions occurring throughout the winter and have less to do with direct FHB pathogen activity.

Other direct benefits were less apparent for the seed treatment. Not surprisingly, our results suggest that seed treatment is not effective in controlling FHB under high disease pressure, as residual activity may not persist long enough to mitigate infection by FHB spores. However, if there is concern that a seed lot may contain *Fusarium* damaged kernels, seed treatments can be effective. To prevent *Fusarium* seedling blight, seed treatment is suggested when growing wheat in fields with high levels of *Fusarium* inoculum. *Fusarium*-infested seed results in poor seedling emergence and reduces tillering, therefore, significant yield reductions can occur (Gilbert et al. 2003). Seed treatments using bitertanol, difenconazole, triticonazole, maneb, fludioxonil or guazatine significantly improved germination and reduced *Fusarium* seedling blight in three field trials with 5-45% infested seeds; however, no significant

improvements in yield were observed (Jørgensen et al. 2012). The effect of seed treatment on emergence or grain yield was reduced as the levels of Fusarium infection dropped (May et al. 2010). In another two field trials with more than 90% infested seeds, fludioxonil significantly improved germination rate and yield was increased by 1.2-1.5 t/ha compared with the control. However, seed treatments with fludioxonil failed to reduce FHB symptoms and DON contamination in the harvested grain (Jørgensen et al. 2012). Different findings were observed in another study, where fludioxonil was reported to minimize infection and the spread of mycotoxins in wheat spikes (Klix et al. 2009). The seed lots used in this study were deemed healthy, with no Fusarium seedling blight observed. Therefore, lack of significant seed treatment effects in this study may be a function of the use of healthy seed and an environment that was not conducive to pathogens that affect young seedlings. In general, seed treatments were not consistent in improving agronomic performance under response to high Fusarium pressure; however, there appears to be some synergy in winter wheat when used in conjunction with foliar fungicides, as the biplots indicated either higher yield or yield consistency with this management practice.

In this study, the level of genetic resistance to FHB in wheat cultivars was highly important. The resistant cultivar 'Emerson' had lower FDK and DON, and significantly higher plant density, yield, test weight and protein concentration than CDC Falcon at high Fusarium sites. Similarly, Carberry had lower FDK and DON, and significantly higher test weight and seed mass than Harvest at high Fusarium sites. McMullen et al. (1997) reported that using moderately resistant cultivars alone resulted in an 86% reduction in field severity of FHB and a 64.7% reduction in DON compared to susceptible cultivars. Lower mycotoxin levels in cultivars with improved resistance may be due to an inhibition of the spread of the fungus within the spike as

well as a detoxification of the DON produce by the fungus (Peiris et al. 2011). In the current study, application of Prosaro or Prosaro+Cruiser combined with improved cultivars (Emerson and Carberry) resulted in higher yields than when these treatments were applied to susceptible cultivars (CDC Falcon and Harvest) at all sites/years except Carman 2012. Similar results were observed for DON. Moreover, the greater response to management of Carberry over Emerson suggests a stronger genetic response in Emerson, as it consistently displayed lower levels of DON with or without enhanced management. Alternatively, the level of genetic resistance may be similar in both cultivars but the earlier development and maturity of Emerson added a potential escape mechanism over Carberry's spring growth habit. Application of prothioconazole + tebuconazole at flowering to moderately resistant cultivars resulted in lower FHB and DON and higher yields (McMullen et al. 1997; Wegulo et al. 2011). These findings suggest that a combination of cultivar resistance and fungicide application in an integrated management strategy can result in better control of FHB and DON contamination than either individual disease control measure on its own. For the uninoculated, untreated plots at Winnipeg, a low percentage of spikes were infected due to inoculation drift or natural inoculum, but the DON concentrations in the moderately resistant cultivars were less than 1 ppm (data not shown). This indicates that in years with low FHB disease pressure, farmers can still benefit from growing moderately resistant cultivars, reducing the need for fungicide application, as genetic resistance alone may be adequate in preventing economic loss due to FHB occurrence.

Our objective was to explore the impact and role of cultivar genetics and triazole fungicide application to manage FHB in wheat. In this study, application of foliar fungicide and/or seed + foliar fungicide significantly increased grain yield. Moreover, DON accumulation in grain was also reduced. Without any fungicide treatment (check), cultivars expressing FHB

resistance usually had higher yield and lower DON than susceptible cultivars at high Fusarium sites. These results suggest that integrating cultivar resistance and fungicide application is critical for reducing the risk of FHB infection and subsequent downgrading of grain. The impact of the genetic component may only be a feature fully expressed when FHB pressure is high, as was the case for yield potential of Emerson winter wheat over the susceptible cultivar, CDC Falcon. While FHB resistant cultivars integrated with fungicide management were impactful for disease mitigation and yield protection, these strategies under high FHB pressure failed to reduce DON content to a level below the maximum limit (1 ppm) allowed for some uses, which makes the infected grain difficult to market. Although progress is clearly evident, these results underscore the urgency to breed cultivars with even greater resistance to FHB. Other methods that have proven to have possible effects on FHB control in wheat, such as previous crop residue management, crop rotations with non-hosts and removal of fallow phases, and biological control should be integrated into a holistic strategy to minimize the risk of FHB.

ACKNOWLEDGEMENTS

This work was funded by the Western Grains Research Foundation's endowment fund and the Natural Sciences and Engineering Research Council of Canada. In-kind support was provided by Agriculture and Agri-Food Canada and the University of Manitoba. We gratefully acknowledge the technical skill and field implementation provided by M. Meleshko, R. Larios, Farming Smarter, K. Coles, R. Dyck, G. Finlay, M. Gretzinger, M. Markortoff, and S. Simmill. Special thanks to Dr. F.C. Stevenson for statistical analyses.

REFERENCES

YE ET AL. – GxExM EFFECTS ON FHB AND YIELD

- Amarasinghe, C. C., Tamburic-Ilincic, L., Gilbert, J., Brûlé-Babel, A. L. and Dilantha Fernando, W. G. 2013. Evaluation of different fungicides for control of Fusarium head blight in wheat inoculated with 3ADON and 15ADON chemotypes of *Fusarium graminearum* in Canada. *Canadian Journal of Plant Pathology* **35**(2):200-208.
- Beres, B. L., Turkington, T. K., Kutcher, H. R., Irvine, B., Johnson, E. N., O'Donovan, J. T., Harker, K. N., Holzapfel, C. B., Mohr, R., Peng, G. and others. 2016. Winter wheat cropping system response to seed treatments, seed size, and sowing density. *Agronomy Journal* **108**(3):1101-1111.
- DePauw, R. M., Knox, R. E., McCaig, T. N., Clarke, F. R. and Clarke, J. M. 2011. Carberry hard red spring wheat. *Canadian Journal of Plant Science* **91**(3):529-534.
- Fowler, D. B. 1999. CDC Falcon winter wheat. *Canadian Journal of Plant Science* **79**(4):599-601.
- Fox, S. L., Townley-Smith, T. F., Thomas, J. B., Humphreys, D. G., Brown, P. D., McCallum, B. D., Fetch, T. G., Menzies, J. G., Gilbert, J. A., Fernandez, M. R. and others. 2010. Harvest hard red spring wheat. *Canadian Journal of Plant Science* **90**(4):503-509.
- Francis, T. R. and Kannenberg, L. W. 1978. Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. *Canadian Journal of Plant Science* **58**:1028-1034.
- Gilbert, J., Conner, R. L., Fernandez, M. R. and McLaren, D. 2003. Role of spring wheat seed infested with *Fusarium graminearum* in spread and development of Fusarium head blight and effects on agronomic performance. *Canadian Journal of Plant Pathology* **25**:73-81.
- Graf, R. J., Beres, B. L., Laroche, A., Gaudet, D. A., Eudes, F., Pandeya, R. S., Badea, A. and Randhawa, H. S. 2013. Emerson hard red winter wheat. *Canadian Journal of Plant Science* **93**(4):741-748.
- Haidukowski, M., Pascale, M., Perrone, G., Pancaldi, D., Campagna, C. and Visconti, A. 2005. Effect of fungicides on the development of Fusarium head blight, yield and deoxynivalenol accumulation in wheat inoculated under field conditions with *Fusarium graminearum* and *Fusarium culmorum*. *Journal of the Science of Food and Agriculture* **85**(2):191-198.
- Jørgensen, L. N., Nielsen, L. K. and Nielsen, B. J. 2012. Control of seedling blight in winter wheat by seed treatments – impact on emergence, crop stand, yield and deoxynivalenol. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science* **62**(5):431-440.

- Klix, M., Oostendorp, M., Zeun, R. and Biddle, A. J. 2009. Seed treatment as an additional tool to minimize mycotoxin contamination in cereals. *Proc. BCPC Symposium Proceedings*.
- Littell, R. C., Milliken, G. A., Stroup, W. W., Wolfinger, R. D. and Schabenberger, O. 2006. SAS for mixed models. SAS Institute. Inc, Cary, NC:814.
- Littell, R. C., Stroup, W. W. and Freund, R. J. 2002. SAS for linear models. Sas Institute.
- May, W. E., Fernandez, M. R. and Lafond, G. P. 2010. Effect of fungicidal seed treatments on the emergence, development, and grain yield of *Fusarium graminearum*-infected wheat and barley seed under field conditions. *Canadian Journal of Plant Science* **90(6)**:893-904.
- McMullen, M., Jones, R. and Gallenberg, D. 1997. Scab of wheat and barley: a re-emerging disease of devastating impact. *Plant Disease* **81(12)**:1340-1348.
- Mesterházy, Á., Bartók, T. and Lamper, C. 2003. Influence of wheat cultivar, species of *Fusarium*, and isolate aggressiveness on the efficacy of fungicides for control of *Fusarium* head blight. *Plant Disease* **87(9)**:1107-1115.
- Nicholson, P., Chandler, E., Draeger, R. C., Gosman, N. E., Simpson, D. R., Thomsett, M. and Wilson, A. H. 2003. Molecular tools to study epidemiology and toxicology of *Fusarium* head blight of cereals. *European Journal of Plant Pathology* **109**:691-703.
- Osborne, L. E. and Stein, J. M. 2007. Epidemiology of *Fusarium* head blight on small-grain cereals. *International Journal of Food Microbiology* **119(1-2)**:103-108.
- Paul, P. A., Lipps, P. E., Hershman, D. E., McMullen, M. P., Draper, M. A. and Madden, L. V. 2008. Efficacy of triazole-based fungicides for *Fusarium* head blight and deoxynivalenol control in wheat: a multivariate meta-analysis. *Phytopathology* **98(9)**:999-1011.
- Peiris, K. H. S., Pumphrey, M. O., Dong, Y. and Dowell, F. E. 2011. *Fusarium* head blight symptoms and mycotoxin levels in single kernels of infected wheat spikes. *Cereal Chemistry Journal* **88(3)**:291-295.
- Pestka, J. J. 2007. Deoxynivalenol: Toxicity, mechanisms and animal health risks. *Animal Feed Science and Technology* **137(3-4)**:283-298.
- Piepho, H. P., Büchse, A. and Richter, C. 2004. A mixed modelling approach for randomized experiments with repeated measures. *Journal of Agronomy and Crop Science* **190(4)**:230-247.
- Pirgozliev, S. R., Edwards, S. G., Hare, M. C. and Jenkinson, P. 2003. Strategies for the control of *Fusarium* head blight in cereals. *European Journal of Plant Pathology* **109(7)**:731-742.

- SAS Institute. 2013. SAS/STAT 13.1 User's Guide. SAS Institute Inc., Cary, NC.
- Schaafsma, A. W. and Tamburic-Ilincic, L. 2005. Effect of seeding rate and seed treatment fungicides on agronomic performance, Fusarium head blight symptoms, and DON accumulation in two winter wheats. *Plant Disease* **89**(10):1109-1113.
- Simpson, D. R., Weston, G. E., Turner, J. A., Jennings, P. and Nicholson, P. 2001. Differential control of head blight pathogens of wheat by fungicides and consequences for mycotoxin contamination of grain. *European Journal of Plant Pathology* **107**(4):421-431.
- Šíp, V., Chrpová, J., Veškrna, O. and Bobková, L. 2010. The impact of cultivar resistance and fungicide treatment on mycotoxin content in grain and yield losses caused by Fusarium head blight in wheat. *Czech Journal of Genetics and Plant Breeding* **46**(1):21-26.
- Turkington, T. K., Beres, B. L., Kutcher, H. R., Irvine, B., Johnson, E. N., O'Donovan, J. T., Harker, K. N., Holzapfel, C. B., Mohr, R., Peng, G. and others. 2016. Winter wheat yields are increased by seed treatment and fall-applied fungicide. *Agronomy Journal*.
- Wegulo, S. N., Bockus, W. W., Nopsa, J. H., De Wolf, E. D., Eskridge, K. M., Peiris, K. H. S. and Dowell, F. E. 2011. Effects of integrating cultivar resistance and fungicide application on Fusarium head blight and deoxynivalenol in winter wheat. *Plant Disease* **95**(5):554-560.

Table 1. Field trials conducted across Western Canadian prairies from 2012 to 2014

Year	Sites	FHB infection types	Fusarium species
2012-2013	Bow Island, AB	Natural infection	N/A
2012-2014	Lethbridge, AB	Natural infection	N/A
2012	White City, SK	Natural infection	N/A
2012-2014	Brandon, MB	Natural infection	N/A
2012-2014	Carman, MB	Artificial inoculation	<i>F.graminearum</i>
2012-2014	Winnipeg, MB	Artificial inoculation	<i>F.graminearum</i>
2013	Rosebank, MB	Natural infection	N/A

For Review Only

1

Table 2. Management treatments for integration with wheat cultivar in field trials conducted across 14 site-years in the Canadian Prairies from 2012 to 2014.

Treatments	Product name	Active ingredients and application rates	Company
Check-untreated	N/A ^a	N/A	N/A
Seed treatment (ST)	Cruiser Maxx® Cereals	3.25 mL/kg of seed - Thiamethoxam: 30.7g/L; Metalaxyl-M: 9.5g/L; Difenconazole: 36.9g/L; Sedaxane: 8.0g/L.	Syngenta
Foliar fungicide	Prosaro™ 421 SC	prothioconazole and tebuconazole, 455-574 mL/ha	Bayer Crop Science
ST+foliar fungicides	Cruiser Maxx® Cereals	See above	Syngenta
	+Prosaro™ 421 SC	See above	Bayer Crop Science
Uninoculated-untreated (Carman & Winnipeg only)	N/A	N/A	N/A

2 ^aNot applicable

3

Table 3. Site-year means for Fusarium damaged kernels (FDK), deoxynivalenol(DON) and grain yield across all treatments and cultivars

Location / Year	FDK (%)	DON (ppm)	DON (% plots) ^a	Yield (Mg ha ⁻¹)
Bow Island, AB				
2012	0.1	0.1	0	6.23
2013	0.2	0.3	0	6.87
Lethbridge, AB				
2012	0.1	0.1	0	6.07
2013	0.6	0.4	11	3.80
2014				7.89
White City, SK, 2012	0.1	0.1	0	6.58
Brandon, MB				
2012	1.8	1.7	55	2.34
2013	0.8	1.3	44	3.41
2014	1.6	3.9	84	3.71
Carman, MB				
2012	7.0	9.1	97	3.91
2013	17.5	24.7	100	3.55
2014	5.4	8.7	38	2.63
Rosebank, MB, 2013	0.2	0.3	0	4.16
Winnipeg, MB				
2012	1.1	2.5	95	4.63
2013	13.2	17.8	100	3.84
2014				3.23

4

YE ET AL. – GxExM EFFECTS ON FHB AND YIELD

Table 4. Analysis of variance and contrasts from inoculated and uninoculated field trials^a conducted across 14 site-years from 2012 to 2014 to determine the effect of integrating cultivar resistance and management practices on FHB control and agronomic performance in wheat

Effect / Contrast	Plant density (no. m ⁻²)	FDK(%)	DON (ppm)	Yield (Mg ha ⁻¹)	Kernel wt.(g)	Test wt.(kg hL ⁻¹)	Protein conc.(g kg ⁻¹)
	(P value)						
Genetics (G)	< 0.001	0.025	0.003	0.001	< 0.001	0.017	< 0.001
Management (M)	0.037	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.036
G x M ^c	0.027	0.172	0.287	0.554	0.862	0.068	0.151
CDC Falcon	0.025	0.472	0.398	0.065	0.001	< 0.001	0.047
Emerson	0.002	0.964	0.910	0.161	0.003	0.066	0.036
Harvest	0.432	< 0.001	< 0.001	< 0.001	0.109	0.033	0.454
Carberry	0.731	0.010	0.007	0.001	0.085	0.019	0.703
High vs. low ^b							
G x M	< 0.001	0.003	0.055	0.173	< 0.001	< 0.001	0.117
High	0.001	0.020	0.020	0.022	0.013	< 0.001	0.023
Low	0.737	0.469	0.728	0.858	0.303	0.683	0.184
	(Variance estimate) ^d						
Site (S)	3278**	0.237**	0.355**	2.68**	15.5**	6.89**	1.07**
S x G	1671**	0.029**	0.028**	0.46**	3.7**	4.37**	0.23**
	(34)	(11)	(7)	(15)	(19)	(39)	(18)
S x G x M	11	0.009**	0.017**	0.02**	0.2**	0.01	0.01**
	(< 1)	(3)	(4)	(1)	(1)	(< 1)	(1)

^a Sites with mean ≥ 1 ppm DON were included in the analysis.

^b High Fusarium sites had mean DON ≥ 5 ppm and FDK $> 5\%$ (Carman 2012, 2013 and 2014 and Winnipeg 2013). Low Fusarium sites = all other sites.

^c Management effect was tested for each level of genetics.

^d * $0.05 \geq P \geq 0.01$; ** $P < 0.01$. Number in bracket is percentage of the total variance associated with the effect of site.

Table 5. Means of variables measured at 14 Prairie site-years from 2012 to 2014, averaged across management treatments.

Variable / Sites	CDC Falcon	Emerson	Harvest	Carberry	LSD (P=0.05)
<i>Spring plant density (no. m⁻²)</i>					
All sites ^c	164a ^a	186a	271b	266b	35
High Fusarium sites	137a	192c	260b	250b	15
Low Fusarium sites	173a	185a	275b	271b	14
<i>FDK (%)</i>					
All sites	18.3	14.4	17.1	14.9	
SE ^b	(2.8)	(2.3)	(2.6)	(2.3)	
High Fusarium sites	26.5	11.9	19.1	12.6	
SE	(6.0)	(3.2)	(4.5)	(3.2)	
Low Fusarium sites	12.2	17.4	15.2	17.5	
SE	(3.1)	(4.2)	(3.8)	(4.2)	
<i>DON (ppm)</i>					
All sites	22.8	16.3	19.7	17.1	
SE	(3.9)	(3.0)	(3.5)	(3.1)	
High Fusarium sites	30.5	12.0	22.0	16.6	
SE	(7.1)	(3.6)	(5.5)	(4.5)	
Low Fusarium sites	16.5	21.6	17.5	17.6	
SE	(4.4)	(5.4)	(4.6)	(4.6)	
<i>Yield (Mg ha⁻¹)</i>					
All sites	4.74ab	5.04b	3.94c	4.27ac	0.53
High Fusarium sites	3.36a	4.12b	2.93a	3.26a	0.53
Low Fusarium sites	5.19a	5.34a	4.28c	4.61b	0.22
<i>Kernel wt. (mg)</i>					
All sites	29.0a	27.8a	30.8c	33.0b	1.6
High Fusarium sites	24.1a	24.4a	24.9a	28.6b	1.5
Low Fusarium sites	31.0a	29.1c	33.2d	34.7b	0.5
<i>Test wt. (kg hL⁻¹)</i>					
All sites	78.2a	79.7ab	78.0a	80.4b	1.7
High Fusarium sites	73.4a	77.8b	72.7a	77.9b	0.8
Low Fusarium sites	79.7a	80.3c	79.5a	81.2b	0.5
<i>Protein conc. (g kg⁻¹)</i>					
All sites	124a	130c	149b	150b	4
High Fusarium sites	133a	138b	158c	157c	4
Low Fusarium sites	121a	127b	146d	148c	2

^aMeans followed by the same letter within a row are not significantly different at P = 0.05

^bLSD (P=0.05) was not available for back-transformed FDK and DON means. A standard error (SE) was presented as a measure of precision for these variables and it appears immediately below the corresponding mean in brackets.

^cHigh FHB site-years = all Carman sites and Winnipeg 2013. Low FHB sites = all other sites-years.

YE ET AL. – GxExM EFFECTS ON FHB AND YIELD

Table 6. Management effects on cultivar, Fusarium and agronomic responses across 14 site-years in Alberta, Saskatchewan, and Manitoba from 2012-2014.

Variable / Genetics	Check	Seed Treatment (ST)	Foliar Fungicide	ST + Foliar	LSD (P=0.05)
<i>Spring plant density (no. m⁻²)</i>					
CDC Falcon	160a ^a	171b	159a	167a	9
Emerson	179a	196b	183ac	187ac	9
Harvest	272a	267a	271a	275a	9
Carberry	268a	264a	265a	268a	9
FDK(%)	16.7	16.9	15.3	15.5	
SE ^b	(2.5)	(2.5)	(2.3)	(2.3)	
DON (ppm)	20.0	19.9	17.8	17.7	
SE ^c	(3.4)	(3.4)	(3.2)	(3.1)	
Yield (Mg ha ⁻¹)	4.35a	4.43a	4.60b	4.61b	0.10
Kernel wt. (mg)	29.6a	30.0b	30.5c	30.5c	0.3
<i>Test wt. (kg hL⁻¹)</i>					
CDC Falcon	77.9a	78.1a	78.4b	78.6b	0.3
Emerson	79.5a	79.9b	79.8b	79.8b	0.3
Harvest	77.7a	77.9ab	78.0b	78.1b	0.3
Carberry	80.3a	80.3a	80.6b	80.5ab	0.3
Protein conc. (g kg ⁻¹)	138a	138a	139b	139b	1

^aMeans followed by the same letter within a row are not significantly different at P=0.05.

^bLSD (P=0.05) was not available for back-transformed FDK and DON means. A standard error (SE) was presented as a measure of precision for these variables and it appears immediately below the corresponding mean in brackets.

22

Table 7. Grain yield and DON means for each management level at high FHB sites

Location / Year / Genetics	Yield (Mg ha ⁻¹)						DON (ppm)								
	Check	Seed Trt (ST)	Foliar Fungicide	ST + Foliar	LSD0.05	p value	Check	SE ^a	Seed Trt (ST)	SE ^a	Foliar Fungicide	SE ^a	ST + Foliar	SE ^a	p value
Carman 2012															
CDC Falcon	4.66a ^b	4.32a	4.48a	4.24a	0.58	0.4828	26.8	(1.6)	29.7	(1.7)	24.5	(1.5)	23.1	(1.5)	0.0013
Emerson	4.84a	4.67a	4.39a	4.90a	0.64	0.4104	18.7	(1.5)	17.5	(1.4)	18.9	(1.3)	17.5	(1.3)	0.6758
Harvest	3.55a	3.17a	3.27a	3.34a	0.58	0.6092	27.9	(1.6)	26.3	(1.6)	16.8	(1.2)	17.2	(1.3)	<.0001
Carberry	3.01a	3.13a	3.04a	3.07a	0.58	0.9787	21.0	(1.4)	21.7	(1.4)	15.3	(1.2)	13.7	(1.1)	<.0001
Carman 2013															
CDC Falcon	1.52a	2.07b	1.80ab	2.22b	0.44	0.0124	62.8	(3.8)	55.1	(3.9)	47.9	(3.9)	50.1	(3.9)	0.034
Emerson	3.87a	4.20ab	4.41b	4.19ab	0.44	0.1128	36.5	(3.7)	31.3	(3.6)	29.0	(3.5)	32.3	(3.6)	0.4809
Harvest	2.64a	2.61a	3.93b	4.10b	0.44	<.0001	53.3	(3.9)	51.4	(3.9)	32.9	(3.6)	29.8	(3.5)	<.0001
Carberry	3.38a	3.28a	4.24b	4.18b	0.44	<.0001	39.2	(3.8)	37.5	(3.8)	24.8	(3.3)	26.6	(3.4)	0.0085
Carman 2014^c															
Harvest	2.05a	2.04a	2.48a	2.37a	0.48	0.1582	20.3	(1.1)	20.0	(1.1)	19.9	(1.1)	20.0	(1.1)	0.7761
Carberry	2.62ab	2.31a	2.80b	2.75ab	0.48	0.1687	20.4	(1.1)	21.3	(1.1)	20.0	(1.1)	20.2	(1.1)	0.0307
Winnipeg 2013															
CDC Falcon	3.49a	3.49a	4.07b	3.76ab	0.34	0.0043	37.3	(2.4)	43.6	(2.5)	36.0	(2.4)	40.1	(2.5)	0.0639
Emerson	3.89a	3.86a	4.38b	4.42b	0.34	0.0015	20.2	(1.9)	22.8	(2.0)	18.8	(1.9)	18.7	(1.9)	0.2908
Harvest	2.27a	2.30	3.33b	3.31b	0.34	<.0001	46.6	(2.5)	50.8	(2.5)	26.7	(2.2)	25.4	(2.1)	<.0001
Carberry	3.15a	3.27a	3.94b	3.87b	0.34	<.0001	41.4	(2.5)	38.6	(2.4)	22.4	(2.0)	20.0	(1.9)	<.0001

^aLSD (P=0.05) are not available for back-transformed DON means. A standard error (SE) was presented as a measure of precision for these variables and it appears immediately to the right the corresponding mean in brackets.

^bMeans followed by the same letter within a row are not significantly different at P =0.05.

^cWinter wheat cultivars did not overwinter in Carman in 2014.

YE ET AL. – GxExM EFFECTS ON FHB AND YIELD

Table 8. Fungicide efficacy (%) among varieties for grain yield and DON at high Fusarium sites

Location / Year / Genetics	Yield (Mg ha ⁻¹)			DON (ppm)		
	Seed Trt (ST)	Foliar Fungicide	ST + Foliar	Seed Trt (ST)	Foliar Fungicide	ST + Foliar
Carman 2012						
CDC Falcon	-7.72	-3.93	-9.91	-10.66	8.65	13.87
Emerson	-3.85	-10.47	1.03	6.38	-1.45	6.11
Harvest	-11.77	-8.49	-6.09	5.56	39.84	38.29
Carberry	3.73	0.72	1.77	-3.14	27.14	34.98
Carman 2013						
CDC Falcon	26.59	15.41	31.54	12.22	23.69	20.25
Emerson	7.84	12.19	7.63	14.35	20.48	11.61
Harvest	-1.22	32.73	35.50	3.62	38.23	44.16
Carberry	-3.05	20.32	19.16	4.34	36.62	32.15
Carman 2014^a						
Harvest	-0.39	17.33	13.61	1.43	2.02	1.63
Carberry	-13.50	6.42	4.51	-4.71	1.87	0.93
Winnipeg 2013						
CDC Falcon	-0.02	14.13	6.96	-16.90	3.41	-7.43
Emerson	-0.75	11.09	11.90	-12.85	7.32	7.41
Harvest	1.14	31.82	31.41	-9.10	42.64	45.60
Carberry	3.50	20.08	18.56	6.65	45.76	51.56

^aWinter wheat cultivars did not overwinter in Carman in 2014.

FIGURE CAPTION

Fig. 1a,b. Biplots summarizing mean vs. CV for combinations of wheat cultivars/growth habit and management practices for data collected at environments in MB, SK, and AB Canada from the fall of 2011 to the summer of 2014. Abbreviations are as follows: 1) First letters designate cultivar (Har=Harvest; Car=Carberry; Fal=CDC Falcon; Emer=Emerson); 2) Second letters represents management practice (Chk-untreated plots; ST = dual fungicide/insecticidal seed treatment; Fol = foliar fungicide; ST+Fo = dual fungicide/insecticidal seed treatment + foliar fungicide). 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.

254x190mm (96 x 96 DPI)

254x190mm (96 x 96 DPI)