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Glyphosate associations with cereal diseases caused by *Fusarium* spp. in the Canadian Prairies

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ABSTRACT

Fusarium pathogens cause important diseases, such as root/crown rot and Fusarium head blight (FHB), in cereal crops. These diseases can be caused by similar *Fusarium* spp. Common root rot (CRR) is widespread in the western Canadian Prairies, whereas FHB has potential of becoming an important disease in this region. There are no commercially available cereal cultivars with good resistance to these diseases. It is therefore important to identify agronomic practices that could affect levels of *Fusarium* pathogens in cereals. This review deals primarily with the effects of tillage systems and glyphosate use on the development of FHB and CRR in wheat and barley in eastern Saskatchewan. Although the FHB study in 1999–2002 indicated that environment was the most important factor determining FHB development, previous glyphosate use and tillage practice were among the production factors with the greatest association with FHB. Overall, disease was highest in crops under minimum-till management. Previous glyphosate use was consistently associated with higher FHB levels caused by the most important FHB pathogens, *Fusarium avenaceum* and *Fusarium graminearum. Cochliobolus sativus*, the most common CRR pathogen, was negatively associated with previous glyphosate use, while *F. avenaceum*, *F. graminearum*, and other fungi were positively associated, suggesting that glyphosate might cause changes in fungal communities. The occurrence and isolation of *F. avenaceum* from cereal residues were greater under reduced-till than conventional-till while *C. sativus* was most common under conventional-till, and *F. graminearum* was lowest under zero-till. Previous glyphosate applications were again correlated positively with *F. avenaceum* and negatively with *C. sativus*. These observations agreed with results from the FHB and CRR studies. These are the first studies that established a relationship between previous glyphosate use and increased *Fusarium* infection of spikes and subcrown internodes of wheat and barley, or *Fusarium* colonization of crop residues. However, because of the close association between noncereal crops, reduced tillage and glyphosate use, it was not possible to completely separate the effects of these factors on *Fusarium* infections. Determining the relative contribution of these popular production trends to the development of diseases caused by *Fusarium* spp. are essential for devising appropriate agronomic recommendations to prevent their further spread in western Canada, and to reduce the impact that these diseases are having in areas where they are already established. The consistent association between previous glyphosate use and *Fusarium* infections also warrants further research to elucidate the nature of this association and the underlying mechanisms determining these effects.

1. Introduction

Fusarium pathogens cause important diseases of cereal crops in western Canada. Root and crown rot (Fernandez and Jefferson, 2004) and Fusarium head blight (FHB), also known as scab or tombstone (Gilbert and Tekauz, 2000), can be especially severe. Common root rot (CRR) is a prevalent disease throughout the western Canadian Prairies (Ledingham et al., 1973). In the province of Saskatchewan, root and crown rot is generally caused by *Cochliobolus sativus* (Ito & Kurib.) Drechsl. ex Dastur (anamorph *Bipolaris sorokiniana* [Sacc.] Shoemaker) and *Fusarium* spp. (Fernandez and Jefferson, 2004). *Fusarium avenaceum* (Fr.:Fr.) Sacc. (teleomorph *Gibberella avenacea* Cook) is one of such species found in underground and ground-level tissue of common (*Triticum aestivum* L.) and durum (*T. turgidum* L. ssp. *durum* [Desf.] Husn.) wheat (Fernandez and Jefferson, 2004; Fernandez and Zentner, 2005; Fernandez et al., 2007a). This pathogen is also frequently isolated from discoloured roots of noncereal crops, being found at high-

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est levels in pulse crops (Fernandez, 2007). Many of the *Fusarium* isolates in discolored subcrown internodes or crowns are also associated with FHB in wheat and barley (*Hordeum vulgare* L.) (Fernandez et al., 2002a,b).

Of the several *Fusarium* species that can cause FHB, the most important pathogen in North America is *F. graminearum* Schwabe (teleomorph *G. zeae* [Schwein.] Petch). This pathogen produces mycotoxins harmful to humans and livestock. The most commonly found mycotoxin in infected grain is deoxynivalenol (DON). Tolerance levels for *Fusarium*-damaged kernels (FDK) are very low due to processing problems and potential food safety concerns. For example, FDK greater than 0.25% by weight will cause Canada Western Red Spring (CWRS) class of wheat, to be downgraded from CWRS #1 to CWRS #2. A FDK value of over 1% down grades it to CWRS #3, and over 2% to CWRS #4 (Canadian Grain Commission, 2007). For malting barley, the tolerance for FDK is nil for Super Select and 0.2% for Select, whereas FDK for feed barley is 1%. These low tolerance levels cause significant economic losses to producers in affected areas.

Relative to other *Fusarium* pathogens, *F. graminearum* has been less commonly isolated from infected cereal spikes and kernels in western regions of the Canadian Prairies than in areas where this disease has been historically more prevalent. The other *Fusarium* pathogens commonly found in Saskatchewan are also mycotoxin producers. Among these are *F. avenaceum*, *F. culmorum* (W.G. Smith) Sacc., and *F. poae* (Peck) Wollenw., with *F. avenaceum* reported as the most, or one of the most, common species in infected spikes and kernels of wheat and barley (Clear et al., 2000; Fernandez et al., 2003, 2007d; Pearse et al., 2007b; Turkington et al., 2002). Although neither *F. avenaceum* nor *F. poae* produce DON, they produce other harmful mycotoxins (Abramson et al., 2002).

Unfavourable weather conditions have caused FHB to occur at lower levels in the last few years in Saskatchewan (Pearse et al., 2007a,b) than in the late 1990s and early 2000s when province-wide surveys showed the disease to be well established in wheat and barley in eastern regions of the province and spreading westward (Fernandez et al., 1999, 2000, 2001, 2002a,b; Pearse et al., 2003). Thus, FHB still has potential to spread further west, and adversely impact production and marketing opportunities for wheat and barley throughout the western Prairies when conditions are favourable for its development.

There are no commercially available wheat or barley cultivars with good resistance to FHB registered in western Canada (Fernandez et al., 2005, 2007d). Chemical treatment has proven inconsistent or ineffective in controlling FHB and/or preventing its spread.

Because of the continued importance of FHB in the eastern Prairies, and its potential to spread westward, strategies need to be designed to stop or reduce the rate of spread, and to decrease the damage it causes in areas where it is already well established. Understanding the impact of agronomic practices on disease and inoculum levels should form part of comprehensive strategies aimed at controlling FHB. A comprehensive strategy should also include the role of *Fusarium* infection of crop roots and crowns as sources of fungal inoculum and its potential carryover from one growing season to the next.

The adoption and use of conservation tillage (minimum- till and zero-till) practices have become widespread throughout western Canada (Zentner et al., 2002). These tillage methods are heavily dependent on the use of glyphosate formulations for weed control. Thus, it is also important to determine the possible impact that this increased use of glyphosate might have on the development of FHB.

Several studies have examined the effect of tillage practice on FHB or FDK and associated DON levels in wheat in other regions in North America and elsewhere (Dill-Macky and Jones, 2000; Krebs et al., 2000; Miller et al., 1998; Schaafsma et al., 2001; Yi et al., 2001). These findings vary with respect to the impact that tillage and amount of crop residue have on disease levels, with no difference among tillage systems often observed (Miller et al., 1998; Teich and Nelson, 1984). There are few reported studies on the impact of tillage system on FHB in barley. In studies conducted in Quebec, Rioux et al. (2005) found that DON content was greater in barley grown under minimum till than conventional-till management.

The effect of herbicides on FHB development has not been extensively examined. Teich and Hamilton (1985) and Teich and Nelson (1984) reported that there was no significant difference in disease levels in wheat fields with or without herbicides, but they did not identify the specific herbicides used. Difficulties in evaluating the possible effect of glyphosate or other herbicides on FHB include a lack of information regarding type, time and dose of herbicide applied, and lack of adequate glyphosate-free controls.

Severity of CRR was not affected by tillage method (Bailey et al., 2001; Conner et al., 1987) or declined in reduced tillage systems (Bailey et al., 2000; Tinline and Spurr, 1991). Furthermore, higher levels of *C. sativus*, and lower levels of *Fusarium* spp., in wheat or barley roots were reported with changes from less to more intensive tillage (Bailey et al., 2000, 2001; Windels and Wiersma, 1992). Although the effect of several herbicides on CRR pathogens was examined (Hsia and Christensen, 1951; Isakeit and Lockwood, 1989; Tinline and Hunter, 1982), the impact of glyphosate usage on this disease has not been reported.

The overall objective of our research was to identify agronomic practices associated with the development of high FHB levels in wheat and barley. Because of the possible impact that *Fusarium* spp. in underground plant tissue might have on the development of FHB and persistence of inoculum in the field, the objectives included an examination of the impact of agronomic practices on fungal populations in subcrown internodes. A comprehensive approach to understanding disease development includes examining the role of crop residues as reservoirs of inoculum for infection and fungal carryover from one season to the next, and how pathogen populations on these residues are affected by agronomic practices.

This information should help identify cultural and management practices that might decrease *Fusarium* populations in live and dead crop tissue, and thus lead to recommendations regarding practices that can reduce damage to wheat and barley from FHB on the Canadian Prairies. A better understanding of the factors affecting pathogen inoculum and crop infection is important for devising highly efficacious strategies to reduce inoculum levels, disease development, and further spread of cereal diseases caused by *Fusarium* spp.

The studies reported here were conducted on commercial fields in eastern Saskatchewan. Surveying commercial fields allows examination of plants in a large area, with little or no interference from fields under other agronomic practices, a common concern in experimental plot trials. Although surveys of commercial fields allow examination of a wide range of crops under different combinations of agronomic practices, they can also suffer from confounding effects of the various practices.

This review focuses on the impact of tillage system and glyphosate use on FHB and CRR diseases. Because glyphosate use is dependent on tillage frequency, these two factors are usually confounded. In order to isolate the effects of tillage frequency from those of glyphosate use, the latter was analyzed as an effect nested within tillage system. Only the most important findings concerning tillage and glyphosate associations with FHB, CRR and fungal populations on crop residues are presented here. Comprehensive reports of associations with other agronomic practices, such as cropping sequence, have been previously published (Fernandez et al., 2005, 2007a,c,d, 2008).

2. Materials and methods

Commercial fields (experimental units) were selected randomly within Crop Districts 1B and 5A in south-east and east-central Saskatchewan to represent the most common cropping practices in the area. A description of the study area was provided by Fernandez et al. (2005).

In late July to early August, spikes at the mid-milk to dough stage of plant development (growth stage 75–83, Zadoks et al., 1974) were taken at random from each field and the percentage of spikes with FHB-like symptoms (incidence) determined. Disease severity was estimated visually based on the percentage of spikelets discolored on each spike. Individual spikelets/lemma showing discoloration were removed, surface-disinfested, plated on modified potato dextrose agar (Burgess et al., 1988; Fernandez and Chen, 2005), and incubated for 7 days under fluorescent and near-UV lights at 22 °C day/15 °C night, 16 h photoperiod to confirm infection by *Fusarium* spp. and for species identification. *Fusarium* spp. were identified by colony and spore morphology and reproductive structures (Samson et al., 2002; Watanabe, 2002). All isolates identified as *F. graminearum* produced perithecia. A FHB index was calculated for each of the wheat and barley crops sampled based on the presence of *Fusarium* isolates in the tissue plated and on the percentage isolation of the most common *Fusarium* spp., i.e. *F. avenaceum* (FHB-*Fav*), *F. graminearum* (FHB-*Fg*), *F. poae* (FHB-*Fp*), and *F. sporotrichioides* Sherb. (FHB-*Fspo*).

Grain samples from most of the fields sampled were obtained from cooperating producers in 2000 and 2001. Kernels with FDK-like symptoms were visually identified in a 50 g subsample, removed, and weighed. The percentage of FDK-like symptoms was determined based on total weight of the sample. A subsample of kernels with FDK symptoms was plated as above, and fungi growing out of kernels were identified. A percentage “total FDK” was then calculated based on the percentage isolation of *Fusarium* spp. Percentage FDKs were also calculated based on the percentage isolation of the most common species (FDK-*Fav*, FDK-*Fg*, FDK-*Fp*, and FDK-*Fspo*).

Plants were selected at random in each field surveyed and carefully removed from the soil to determine CRR. Subcrown internodes were rated for extent of brown to black discoloration on a 0–3 scale (Ledingham et al., 1973) and a subcrown internode discoloration index was calculated for each field based on the incidence and severity of discoloration. The most discolored segment of each subcrown internode was then surface-disinfested, plated and incubated as above. Fungi growing out of subcrown internodes were identified and percentage isolation of each fungus calculated.

Residues of crops grown the previous year were sampled to identify and quantify fungal populations in each field. Pieces were cut from each residue sample (cereal pieces included a node), washed thoroughly and air-dried before surface-disinfesting, plated and incubated as described above. The percentage occurrence of each fungus was based on the proportion of fields sampled where the fungus was isolated at least once. The mean percentage isolation of a fungus in a field was the total number of isolates of the fungal species divided by the number of plated residue pieces from that field.

Crops/fields were categorized according to agronomic practice from information provided by cooperating producers. Wheat and barley crops were categorized into FHB “susceptible” and “intermediate” cultivars. Susceptible cultivars were those rated as “poor”, and intermediate cultivars were those rated as “fair” or “fair+” in the Saskatchewan Varieties of Grain Crops publication (SAFRR, 2005). For tillage system, fields were categorized by the total number of tillage operations performed in the previous three years. Fields under conventional-till had a total of seven or more tillage operations, and those under minimum-till had one to six operations (i.e., up to two tillage passes per year), while there were no tillage operations performed in fields under zero-till management. Residue cover was not estimated for any field. Fields were also categorized according to whether they received any application of glyphosate herbicide in the previous 18 months. Some of the glyphosate had been applied on glyphosate-tolerant canola (*Brassica* spp.). No other glyphosate-tolerant crop was grown in any of the fields sampled.

The FHB, FDK, CRR severity, and fungal data were analyzed as described by Fernandez et al. (2005, 2007a,c,d, 2008).

3. Results

3.1. Fusarium head blight

Fusarium graminearum was the most common pathogen isolated in all four years of the study (41.3%) from common and durum wheat; however, various other *Fusarium* species were also isolated from spikes or kernels. Tillage significantly affected the proportion of fields with a high FHB index, and/or the mean FHB index in three of four years (Tables 1 and 2), with the mean FHB index generally highest under minimum-till and lowest under zero-till.

Previous glyphosate application, nested within tillage system, was the only agronomic factor significantly associated with higher FHB levels every year of the study (Tables 3 and 4). Glyphosate’s effect on the FHB index was not influenced by environmental conditions as much as for other agronomic factors whose effects on disease levels were not consistent from year to year. Under minimum-till, application of glyphosate at least once in the previous 18 months significantly increased the mean FHB index and the

Table 1
Effect of tillage system on the frequency of common and durum wheat crops in high and low classes based on the Fusarium head blight (FHB) index, in eastern Saskatchewan, from 1999 to 2002 (adapted from Fernandez et al., 2005).

Year	No. of fields	FHB class	Tillage system			Chi-square
			Conventional	Minimum	Zero	
1999	33	High	10	15	8	4.03 (0.13)[a]
	55	Low	11	19	25	
2000	55	High	11	28	16	3.20 (0.20)
	62	Low	17	27	18	
2001	95	High	9	64	22	4.72 (0.09)
	93	Low	8	50	35	
2002	47	High	1	29	17	na[b]
	158	Low	5	83	70	

[a] Values in parentheses are probabilities of obtaining a larger value of chi-square by chance alone.

[b] na: chi-square test not performed due to fewer than five observations in one cell.

Table 2
Effect of tillage system on the mean Fusarium head blight (FHB) index in common and durum wheat crops sampled in eastern Saskatchewan, from 1999 to 2002 (adapted from Fernandez et al., 2005).

Year	No. of fields	Tillage system			Probability[a]
		Conventional (%)	Minimum (%)	Zero (%)	
1999	88	0.33 a[b]	0.22 ab	0.09 b	0.07
2000	117	1.99 ab	3.39 a	1.80 b	0.08
2001	188	8.90 ab	9.51 a	6.25 b	0.04
2002	205	0.28	0.52	0.31	0.36
Mean		2.99	4.21	2.10	

[a] Probability of achieving a larger value of *F* by chance alone.

[b] Mean FHB index within a year followed by a different letter are significantly different according to least significant differences.

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Table 3
Effect of glyphosate application (previous 18 months) across tillage systems on the mean Fusarium head blight (FHB) index in common and durum wheat crops sampled in eastern Saskatchewan, from 1999 to 2002 (adapted from Fernandez et al., 2005).

Year	No. of crops	Glyphosate use	Tillage system		
			Conventional (%)	Minimum (%)	Zero (%)
1999	39	Yes	0.71 (<0.01)[a]	0.27 (0.08)	0.10 (ns)
	28	No	0.15	0.12	0.00
2000	80	Yes	2.93 (ns)	4.30 (<0.01)	1.82 (ns)
	47	No	1.55	1.92	0.42
2001	143	Yes	8.28 (ns)	11.53 (<0.01)	6.36 (ns)
	45	No	9.45	5.00	0.42
2002	133	Yes	0.14 (ns)	0.75 (<0.01)	0.23 (ns)
	74	No	0.36	0.19	0.52

[a] Values in parentheses are probabilities of achieving a larger value of *F* by chance alone; ns indicates probability >0.10.

proportion of fields in the high FHB index class every year. Previous glyphosate application did not always cause a significant ($P > 0.10$) increase in the mean FHB index under conventional-till or zero-till management although the mean FHB index was consistently higher and statistically significant in 1999 for conventional-till ($P \leq 0.01$) wheat grown on fields previously treated with glyphosate.

Tillage system did not affect the mean percentage FDK of common and durum wheat in 2000 or 2001, whereas previous glyphosate use significantly increased the proportion of fields with a high percentage FDK, and/or the mean percentage FDK (Fernandez et al., 2005).

For two-rowed and six-rowed barley, *Fusarium* species other than *F. graminearum* were most common. The percentage FHB attributed to *F. graminearum* was 29%, 47% for *F. sporotrichioides*, 35% for *F. poae*, and 38% for *F. avenaceum*. In most cases, the interaction of tillage with cultivar susceptibility was significant. For total FHB index, FHB-*Fg* and FHB-*Fspo*, susceptible cultivars had the lowest disease levels under conventional-till, whereas cultivars with intermediate resistance had the lowest levels under zero-till; this resulted in barley grown under minimum-till having similar or higher disease levels than when grown under the other tillage systems (Table 5). Barley grown under minimum-till management had a significantly higher percentage total FDK, FDK-*Fg*, and FDK-*Fp* than barley grown under zero till and conventional-till combined (Fernandez et al., 2007d).

The use of glyphosate was associated with increased levels of all *Fusarium* pathogens in barley, although effects varied with tillage system (Table 6). Glyphosate use was associated with a significantly

Table 4
Effect of glyphosate application (previous 18 months) across tillage systems on the frequencies of common and durum wheat crops in high and low classes based on the Fusarium head blight (FHB) index, in eastern Saskatchewan, from 1999 to 2002 (adapted from Fernandez et al., 2005).

Year	No. of crops	Glyphosate use	Tillage system								
			Conventional			Minimum			Zero		
			FHB class			FHB class			FHB class		
			High	Low	Chi-square	High	Low	Chi-square	High	Low	Chi-square
1999	39	Yes	5	2	na[a]	13	9	na	8	2	na
	28	No	5	9		2	9		0	3	
2000	80	Yes	5	4	na	28	12	5.70 (0.02)[b]	14	17	na
	47	No	6	13		10	15		2	1	
2001	143	Yes	4	4	na	53	26	12.53 (<0.01)	22	34	na
	45	No	5	4		11	24		0	1	
2002	133	Yes	0	2	na	22	44	4.64 (0.03)	14	51	na
	74	No	1	3		7	39		5	19	

[a] na: chi-square test not performed due to fewer than five observations in one or more cells.
[b] Values in parentheses are probabilities of obtaining a larger value of chi-square by chance alone.

Table 5
Effect of tillage system on total Fusarium head blight (FHB) index, and on that attributed to *F. avenaceum* (FHB-*Fav*), *F. graminearum* (FHB-*Fg*), *F. poae* (FHB-*Fp*), and *F. sporotrichioides* (FHB-*Fspo*) in barley crops sampled in eastern Saskatchewan, 1999–2002 (adapted from Fernandez et al., 2007d).

Effect/contrast	No. of crops	FHB-total	FHB-*Fav*	FHB-*Fg*	FHB-*Fp*	FHB-*Fspo*
				P-value[a]		
Crop susceptibility[b] × tillage system[c]		0.020	0.853	0.049	0.066	0.003
Crop susceptibility × CT vs. MT, ZT		0.006	0.630	0.014	0.311	0.001
				Mean % (SE)[d]		
Susceptible cultivars						
CT	20	1.1 (0.3)	0.5 (0.2)	0.1 (0.1)	0.4 (0.3)	0.4 (0.1)
MT	47	2.1 (0.5)	0.4 (0.1)	0.7 (0.3)	0.1 (<0.1)	0.9 (0.2)
ZT	18	2.2 (0.6)	0.4 (0.1)	0.5 (0.3)	0.3 (0.2)	1.2 (0.5)
Intermediate cultivars						
CT	13	1.9 (0.4)	0.3 (0.1)	0.3 (0.1)	0.1 (<0.1)	1.3 (0.3)
MT	65	1.4 (0.3)	0.2 (<0.1)	0.2 (<0.1)	0.2 (0.1)	0.7 (0.2)
ZT	24	0.5 (0.1)	0.2 (0.1)	<0.1 (<0.1)	0.1 (<0.1)	0.2 (0.1)

[a] Probability of having a larger difference by chance alone.
[b] Categorization of cultivars into "susceptible" ("poor") and "intermediate" ("fair" or "fair+") is based on data presented in Varieties of Grain Crops (Saskatchewan Agriculture, Food and Rural Revitalization, 2005) for each of the cultivars.
[c] CT: conventional-till; MT: minimum-till; ZT: zero-till.
[d] Standard error of the mean.

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Table 6
Effect of glyphosate use (previous 18 months) on total Fusarium head blight (FHB) index, and FHB index attributed to *F. avenaceum* (FHB-*Fav*), *F. graminearum* (FHB-*Fg*), *F. poae* (FHB-*Fp*), and *F. sporotrichioides* (FHB-*Fspo*), of barley crops within each tillage system, sampled in eastern Saskatchewan, 1999-2002 (adapted from Fernandez et al., 2007d).

Tillage system[a]	Glyphosate use[b]	No. of crops	FHB-total	FHB-*Fav*	FHB-*Fg*	FHB-*Fp*	B-*Fspo*
					P-value[c]		
CT			0.017	0.841	0.121	0.071	0.001
MT			0.465	0.010	0.375	0.585	0.801
ZT			0.015	0.604	0.100	0.378	0.025
					Mean % (SE)[d]		
CT	No	14	0.8 (0.3)	0.4 (0.2)	0.1 (0.0)	0.0 (0.0)	0.4 (0.2)
CT	Yes	7	2.8 (0.7)	0.4 (0.2)	0.4 (0.2)	0.6 (0.3)	1.5 (0.4)
MT	No	47	1.4 (0.3)	0.1 (0.0)	0.2 (0.1)	0.2 (0.0)	0.7 (0.3)
MT	Yes	76	1.7 (0.3)	0.3 (0.1)	0.4 (0.2)	0.2 (0.1)	0.7 (0.1)
ZT	No	7	0.5 (0.3)	0.3 (0.3)	0.0 (0.0)	0.1 (0.0)	0.0 (0.0)
ZT	Yes	36	1.3 (0.3)	0.3 (0.1)	0.2 (0.1)	0.2 (0.1)	0.7 (0.2)

[a] CT: conventional-till; MT: minimum-till; ZT: zero-till.

[b] No: no glyphosate applied; Yes: glyphosate applied at least once in the previous 18 months.

[c] Probability of having a larger difference by chance alone.

[d] Standard error of the mean.

Table 7
Correlation between number of glyphosate applications in previous 18 months and Fusarium head blight index attributed to *F. avenaceum* (FHB-*Fav*) and *F. graminearum* (FHB-*Fg*), for all barley crops, and for susceptible cultivars and cultivars with intermediate resistance, grown under minimum-till, sampled in eastern Saskatchewan, 2000–2002 (adapted from Fernandez et al., 2007d).

	No. of crops	FHB-*Fav*	FHB-*Fg*
All crops	112	0.234 (0.019)[a]	0.146 (0.151)
Susceptible[b]	47	0.115 (0.456)	0.163 (0.289)
Intermediate	62	0.439 (0.000)	0.347 (0.005)

[a] Correlation coefficients (*r*) values in parentheses are probabilities of obtaining a higher value of *r* by chance alone.

[b] Categorization of cultivars into “susceptible” (“poor”) and “intermediate” (“fair” or “fair+”) is based on data presented in Varieties of Grain Crops (SAFRR, 2005) for each of the cultivars.

higher level of FHB-*Fav* in barley grown under minimum-till compared with barley grown in untreated fields. Similarly, barley grown under zero-till had a significantly higher total FHB index, FHB-*Fg*, and FHB-*Fspo* after previous applications of glyphosate. Barley grown under conventional-till also had significantly higher FHB-total, FHB-*Fp*, and FHB-*Fspo* in fields that had received glyphosate compared with those that had not.

Correlations between the number of glyphosate applications applied to barley fields in the previous 18 months and FHB caused by *F. graminearum* (FHB-*Fg*) and *F. avenaceum* (FHB-*Fa*) (Table 7) showed that the impact of this herbicide on disease levels was greater for barley cultivars with intermediate resistance than for susceptible cultivars.

3.2. *Common root rot*

The most commonly isolated fungus from wheat and barley subcrown internodes was *C. sativus*, followed by the genus *Fusarium*. Most of the *Fusarium* spp. isolated from subcrown internodes were also isolated from spikes and kernels.

Levels of most fungi in common wheat were affected by tillage, although not in a consistent manner. Significant tillage effects for *F. culmorum* and *F. graminearum* were only observed in wheat planted after another cereal crop, where *F. graminearum* was favoured by minimum-till and *F. culmorum* was lowest under zero-till management (Table 8). Reduced tillage had a positive effect on *F. avenaceum* populations in subcrown internodes of wheat, although this tillage effect was only observed in wheat grown after an oilseed crop.

Table 8
Effect of tillage system by previous crop/summerfallow on the common root rot index (CRRI), and mean percentage isolation of fungi from discoloured subcrown internodes of common wheat crops sampled in eastern Saskatchewan, in 1999–2001 (adapted from Fernandez et al., 2007a).

Effect/contrast	No. of crops	CRRI	*Cs*[a]	*Fav*	*Fc*	*Fg*
				P-value[b]		
Summerfallow: CT vs. MT[c]		0.049	0.253	0.781	0.311	0.179
Cereal: CT vs. MT, ZT		0.166	0.602	0.836	0.129	0.010
Cereal: MT vs. ZT		0.198	0.284	0.144	0.062	0.010
Oilseed: CT vs. MT, ZT		0.127	0.000	0.011	0.749	0.205
Oilseed: MT vs. ZT		0.446	0.027	0.259	0.476	0.911
Pulse: MT vs. ZT		0.077	0.144	0.888	0.984	0.608
				Mean % (SE)[d]		
Summerfallow (CT)	18	1.5 (0.1)	66.3 (3.7)	1.9 (1.1)	0.2 (0.2)	1.3 (0.9)
Summerfallow (MT)	14	1.2 (0.1)	59.0 (5.1)	2.4 (1.5)	0.0 (0.0)	0.0 (0.0)
Cereal (CT)	10	1.1 (1.6)	40.7 (8.5)	3.6 (1.5)	1.7 (1.6)	0.0 (0.0)
Cereal (MT)	52	1.3 (<0.1)	39.1 (3.6)	5.0 (1.1)	1.5 (0.6)	1.3 (0.5)
Cereal (ZT)	17	1.4 (0.1)	32.8 (4.5)	2.9 (1.0)	0.3 (0.2)	0.0 (0.0)
Oilseed (CT)	31	1.3 (0.1)	50.4 (3.5)	2.4 (0.9)	0.7 (0.5)	1.7 (0.6)
Oilseed (MT)	84	1.3 (<0.1)	37.1 (2.3)	4.6 (0.8)	1.2 (0.6)	0.8 (0.3)
Oilseed (ZT)	54	1.2 (0.1)	28.7 (2.9)	6.2 (1.1)	1.0 (0.4)	0.8 (0.5)
Pulse (MT)	34	1.3 (<0.1)	38.4 (3.9)	8.1 (1.4)	1.2 (0.7)	1.7 (0.8)
Pulse (ZT)	25	1.2 (0.1)	29.1 (4.9)	8.4 (2.0)	1.2 (0.6)	1.1 (0.5)

[a] *Cs*: *Cochliobolus sativus*; *Fav*: *F. avenaceum*; *Fc*: *F. culmorum*; *Fg*: *F. graminearum*.

[b] Probability of having a larger difference by chance alone.

[c] CT: conventional-till; MT: minimum-till; ZT: zero-till.

[d] Standard error of the mean.

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Table 9
Effect of tillage system on the common root rot index (CRRI) and percentage isolation of the most common fungi isolated from subcrown internodes, for all barley crops and for those preceded by a cereal or an oilseed crop, sampled in eastern Saskatchewan, 1999–2001 (adapted from Fernandez et al., 2007c).

Effect/contrast	No. of crops	CRRI	*Cs*[a]	*Fus* spp.	*Fav*	*Fc*	*Fe*	*Fg*
P-value[b]								
All previous crops		0.074	0.001	0.011	0.026	0.663	0.445	0.008
CT vs. MT, ZT[c]		0.016	0.000	0.006	0.012	0.907	0.187	0.005
Mean % (SE)[d]								
CT	28	1.9 (0.1)	62.6 (3.2)	14.6 (2.3)	3.4 (0.9)	3.0 (1.3)	6.3 (1.7)	0.2 (0.2)
MT	82	1.6 (<0.1)	49.0 (2.1)	20.5 (1.7)	4.6 (0.7)	3.6 (0.9)	8.5 (1.2)	2.1 (0.6)
ZT	23	1.6 (0.1)	45.8 (3.9)	25.7 (2.6)	7.2(1.4)	2.2 (1.9)	11.7 (2.2)	2.0 (1.0)
P-value								
Cereal		0.138	0.045	0.000	0.114	0.004	0.258	0.178
CT vs. MT, ZT		0.513	0.032	0.001	0.090	0.227	0.070	0.058
Mean % (SE)								
CT	11	1.9 (0.2)	65.9 (5.5)	8.4 (1.8)	1.9 (0.9)	0.6 (0.4)	5.1 (1.5)	0.0 (0.0)
MT	31	1.6 (0.1)	50.6 (3.6)	16.0 (1.8)	4.1 (0.9)	3.3 (1.1)	6.5 (1.4)	1.3 (0.5)
ZT	8	1.7 (0.1)	48.9 (6.4)	19.0 (2.2)	3.8 (1.5)	0.0 (0.0)	12.3 (2.6)	0.0 (0.0)
P-value								
Oilseed		0.904	0.003	0.551	0.014	0.025	0.401	0.700
CT vs. MT, ZT		0.553	0.001	0.411	0.007	0.518	0.892	0.491
Mean % (SE)								
CT	9	1.6 (0.1)	63.8 (5.5)	17.5 (5.2)	3.6 (1.7)	5.0 (3.5)	6.1 (3.8)	0.6 (0.6)
MT	39	1.6 (0.1)	44.4 (3.1)	21.9 (3.0)	5.0 (1.1)	3.0 (1.1)	8.5 (1.8)	2.6 (1.0)
ZT	10	1.6 (0.1)	42.0 (6.2)	27.0 (4.6)	8.7 (2.0)	0.2 (0.2)	13.8 (4.0)	2.2 (1.5)

[a] *Cs*, *Cochliobolus sativus*; *Fus* spp., total *Fusarium* spp.; *Fav*, *F. avenaceum*; *Fc*, *F. culmorum*; *Fe*, *F. equiseti*; *Fg*, *F. graminearum*.
[b] Probability of having a larger difference by chance alone.
[c] CT, conventional-till; MT, minimum-till; ZT, zero-till.
[d] Standard error of the mean.

While CRRI and *C. sativus* isolations from subcrown internodes of barley were favoured by conventional-till management, colonization by *Fusarium* spp., especially *F. avenaceum* and *F. graminearum*, increased under reduced tillage (Table 9).

The effect of glyphosate on fungi isolated from subcrown internodes of wheat and barley varied with tillage system. Previous glyphosate applications were associated with a significantly ($P \leq 0.05$) lower percentage isolation of *C. sativus* in wheat grown after a crop under minimum-till (44% and 35%, for unsprayed fields, $n = 51$, and for sprayed fields, $n = 110$, respectively). In contrast, there was a higher level of *F. avenaceum* in wheat grown in glyphosate-sprayed than glyphosate-free fields under conventional-till and zero-till, although this was only significant ($P \leq 0.01$) for the latter (for fields under conventional-till: 2% for unsprayed, $n = 26$, and 5% for sprayed, $n = 14$; for fields under zero-till: 1%, $n = 6$, for unsprayed, 7%, $n = 81$, for sprayed).

Glyphosate was associated with higher levels of total *Fusarium* spp., *F. culmorum* and *F. graminearum*, but lower levels of *C. sativus*, on barley grown under minimum-till (Table 10). Levels of *F. avenaceum* also tended to be higher in glyphosate-sprayed than in glyphosate-free fields. The same effects of glyphosate on fungal isolations observed under minimum-till were generally observed under conventional-till and/or zero-till; although they were not always significant ($P > 0.10$). The exception was for *F. avenaceum* in barley which was present at higher levels in the glyphosate-sprayed than the glyphosate-free zero-till fields.

3.3. Crop residues

A variety of fungal species were isolated from crop residues, including the same *Fusarium* spp. found in discolored underground tissue and spikes affected by FHB, although at different relative frequencies.

Table 10
Effect of glyphosate use (previous 18 months) on the common root rot index (CRRI) and percentage isolation of fungi within each tillage system, for barley crops sampled in eastern Saskatchewan, 1999–2001 (adapted from Fernandez et al., 2007c).

Tillage system[b]	Glyphosate use[c]	No. of crops	CRRI	*Cs*[a]	*Fus* spp.	*Fav*	*Fc*	*Fe*	*Fg*
P-value[d]									
CT			0.165	0.125	0.229	0.448	0.923	0.472	1.000
MT			0.934	0.033	0.027	0.296	0.056	0.667	0.092
ZT			0.494	0.219	0.765	0.021	0.325	0.377	0.815
Mean % (SE)[e]									
CT	No	9	2.0 (0.2)	59.6 (6.1)	16.2 (4.7)	4.0 (1.9)	4.5 (3.4)	5.8 (3.1)	0.0 (0.0)
CT	Yes	7	1.8 (0.2)	51.5 (4.0)	24.4 (4.5)	5.4 (1.7)	5.2 (2.9)	11.2 (4.9)	0.0 (0.0)
MT	No	26	1.7 (0.1)	56.3 (3.0)	15.5 (2.3)	3.4 (0.9)	1.5 (0.5)	8.3 (2.1)	0.9 (0.4)
MT	Yes	55	1.6 (0.1)	46.2 (2.6)	23.0 (2.3)	5.1 (0.9)	4.6 (1.3)	8.8 (1.5)	2.7 (0.8)
ZT	No	2	2.0 (0.1)	61.0 (8.2)	26.8 (8.0)	4.1 (0.1)	0.0 (0.0)	18.5 (4.8)	2.1 (1.6)
ZT	Yes	19	1.6 (0.1)	43.8 (3.5)	25.9(2.8)	7.9 (1.5)	2.6 (2.3)	10.8 (2.5)	2.1 (1.1)

[a] CT, conventional-till; MT, minimum-till; ZT, zero-till.
[b] No, no glyphosate applied; Yes, glyphosate applied at least once in previous 18 months.
[c] *Cs*, *Cochliobolus sativus*; *Fus* spp., total *Fusarium* spp.; *Fav*, *F. avenaceum*; *Fc*, *F. culmorum*; *Fe*, *F. equiseti*; *Fg*, *F. graminearum*.
[d] Probability of having a larger difference by chance alone.
[e] Standard error of the mean.

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Table 11
Correlations between mean percentage isolation of *F. graminearum* (*Fg*) and *F. avenaceum* (*Fav*) from various crop residues compared with Fusarium head blight (FHB) severity or percent *Fusarium*-damaged kernels (FDK) caused by these fungi in common and durum wheat and barley crops categorized by FHB reaction, sampled in eastern Saskatchewan, 2000 and 2001 (adapted from Fernandez et al., 2008).

Crop residue	Current crop	FHB reaction[a]	*Fg* vs. FHB-*Fg*			*Fgv* vs. FDK-*Fg*			*Fav* vs. FHB-*Fav*			*Fav* vs. FDK-*Fav*		
			No. of fields	*r*[b]	*P*[c]	No. of fields	*r*	*P*	No. of fields	*r*	*P*	No. of fields	*r*	*P*
Cereal	Barley	Susceptible	15	0.412	(0.127)	13	0.713	(0.006)	15	0.308	(0.265)	13	0.069	(0.824)
Cereal	Barley	Intermediate	15	0.366	(0.180)	13	0.878	(0.000)	15	0.213	(0.446)	13	0.027	(0.931)
Oilseed	Barley	Susceptible		na[d]			na		20	0.496	(0.026)	20	0.457	(0.043)
Oilseed	Barley	Intermediate		na			na		19	0.270	(0.263)	19	0.195	(0.423)
Cereal	Wheat	Susceptible	16	0.342	(0.195)	15	0.875	(0.000)	16	0.224	(0.404)	15	0.111	(0.694)
Cereal	Wheat	Intermediate	32	0.789	(0.000)	26	0.610	(0.001)	32	0.125	(0.495)	26	−0.160	(0.435)
Oilseed	Wheat	Susceptible		na			na		33	−0.084	(0.643)	32	−0.150	(0.414)
Oilseed	Wheat	Intermediate		na			na		66	0.095	(0.447)	64	0.099	(0.436)
Pulse	Wheat	Susceptible		na			na		19	0.427	(0.068)	16	0.227	(0.398)
Pulse	Wheat	Intermediate		na			na		26	−0.194	(0.342)	25	0.026	(0.901)

[a] Categorization of wheat and barley crops according to their reactions to FHB (Fernandez et al., 2005, 2007d).
[b] Correlation coefficient.
[c] Probability of having a higher r value by chance alone.
[d] na: not applicable.

The FHB index and percentage FDK caused by *F. graminearum* or *F. avenaceum*, obtained from the FHB studies of wheat and barley presented above, were correlated with the mean percentage isolation of each of these pathogens from crop residues (Table 11). For *F. graminearum*, the FHB index and percentage FDK in wheat and barley were positively correlated with its mean percentage isolation from cereal residues, although for the FHB index this was significant only for wheat cultivars with intermediate resistance. For *F. avenaceum*, there were significant positive correlations between its mean percentage isolation from oilseed residues and the FHB index in susceptible barley cultivars grown on oilseed stubble, and between its mean percentage isolation from pulse residues and percentage FDK in common wheat cultivars with intermediate resistance grown on pulse stubble.

The *Fusarium* species isolated from crop residues varied depending on tillage method. The percentage occurrence of *F. avenaceum* was highest under zero-till in cereal residues with another cereal as the current crop (Table 12). *Fusarium culmorum* in cereal residues had the lowest percentage occurrence under zero-till when the current crop was an oilseed; whereas, under these same residue conditions, *F. graminearum* had the lowest percentage occurrence under conventional-till. In contrast, the percentage occurrence of *C. sativus* decreased as the intensity of tillage decreased.

Generally, the mean percentage isolation of the various fungal species among tillage systems was similar to those observed for their percentage occurrence (Table 12). For cereal residues with another cereal as the current crop, the mean percentage isolation of *F. graminearum* was lowest under zero-till, whereas the opposite was true for *F. avenaceum*. In contrast, *C. sativus* had the highest mean percentage isolation under conventional-till and lowest under zero-till, whereas the mean percentage isolation of *F. culmorum* was highest under minimum-till. For cereal residues with an oilseed or pulse as the current crop, the mean percentage isolation of *F. culmorum* was lowest under zero-till, whereas for cereal residues with a pulse as the current crop, *F. graminearum* had again the lowest mean percentage isolation under zero-till.

The close association between tillage operations and glyphosate applications made it difficult to separate their effects on the fungal colonization of residues; however, correlations between glyphosate use and the mean percentage isolation of some fungi under zero-till reflect a negative or positive association with glyphosate, independent of potential tillage intensity effects. There was a significant positive correlation between previous glyphosate applications and *F. avenaceum* ($r = 0.563$, $P = 0.015$) in cereal residues under zero-till, and a significant negative correlation between glyphosate applications and *C. sativus* ($r = -0.589$, $P = 0.010$) when an oilseed was the current crop. The observation that the percentage isolation of *F. avenaceum* and *C. sativus* in crop residues was positively and negatively correlated, respectively, with the number of glyphosate applications under zero-till management suggests that glyphosate might play a role in fungal growth and competition among fungal species in crop residues.

The association of glyphosate with lower *C. sativus* and higher *F. avenaceum* in crop residues is consistent with results from the present CRR studies of wheat and barley, while the positive association of glyphosate use with some of the *Fusarium* pathogens, such as *F. avenaceum*, is also consistent with results from the present FHB studies.

4. Discussion

The prevalence of *Fusarium* pathogens responsible for FHB and FDK development was different in wheat than in barley. *Fusarium graminearum* was the most commonly isolated species only in common and durum wheat.

Our results from these FHB studies agree with those showing that average DON levels in wheat were higher under minimum-till than under either zero-till or conventional-till management (Schaafsma et al., 2001). Other studies have indicated that tillage had no effect on FHB (Teich and Nelson, 1984; Miller et al., 1998), or that the incidence of *F. graminearum*-infected wheat grain and DON content (Krebs et al., 2000) or FHB levels (Yi et al., 2001) were lowest under conditions of high disturbance tillage. For barley, Rioux et al. (2005) reported that barley grown under minimum-till had a higher DON content than when grown under conventional-till.

The significant positive association of previous glyphosate application with FHB development suggests that the lower disease levels observed under zero-till compared to minimum-till management were not related to previous glyphosate application, but to factors intrinsic to zero-till management such as the lack of disturbance of residues which appears to have impacted inoculum levels and/or its availability for head infection.

Our observations on tillage effects on the relative prevalence of these pathogens in subcrown internodes of wheat and barley agree with studies conducted elsewhere. The higher CRRI and *C. sativus* levels with increasing tillage intensity observed after some cropping sequences are similar to results reported by Bailey et al. (2000,

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Table 12
Effect of tillage system by cropping sequence on percentage occurrence and mean percentage isolation of fungi from various crop residues categorized by the crop grown in the sampling year, sampled in eastern Saskatchewan, 2000 and 2001 (adapted from Fernandez et al., 2008).

Contrast	Crop residue	Current crop	Tillage system[b]	No. of fields	Percentage occurrence				Mean percentage isolation (SE)[a]			
					Fav[c]	*Fc*	*Fg*	*Cs*	*Fav*	*Fc*	*Fg*	*Cs*
									%			
	Cereal	Cereal	CT	11	82	18	46	91	14.8 (2.9)	0.5 (0.3)	10.5 (4.7)	26.9 (6.6)
			MT	56	95	38	57	77	21.9 (2.3)	5.7 (1.5)	7.1 (1.2)	11.3 (1.5)
			ZT	19	100	32	37	58	37.0 (5.4)	1.5 (0.5)	3.1 (1.3)	6.3 (1.7)
									P-value[d]			
CT vs. MT, ZT					0.199	0.226	0.926	0.033	0.001	0.001	0.274	0.009
MT vs. ZT					0.078	0.639	0.124	0.144	0.015	0.011	0.033	0.033
									%			
	Cereal	Oilseed	CT	9	22	56	11	67	4.6 (3.5)	8.3 (3.2)	2.8 (2.6)	19.4 (6.7)
			MT	41	44	46	39	78	7.9 (2.0)	7.6 (1.7)	5.9 (1.5)	16.5 (2.8)
			ZT	33	42	15	36	49	8.1 (2.2)	1.3 (0.5)	6.8 (2.1)	10.6 (2.7)
									P-value			
CT vs. MT, ZT					0.170	0.157	0.030	0.840	0.379	0.247	0.229	0.403
MT vs. ZT					0.900	0.002	0.814	0.009	0.964	0.001	0.723	0.137
									%			
	Cereal	Pulse	MT	30	33	27	27	70	3.9 (1.2)	4.2 (1.5)	7.8 (3.2)	15.0 (2.5)
			ZT	12	17	8	8	67	3.5 (2.7)	0.7 (0.7)	1.4 (1.3)	9.7 (2.6)
									P-value			
MT vs. ZT					0.244	0.120	0.120	0.838	0.892	0.046	0.085	0.154
									%			
	Oilseed	Cereal	CT	22	91	0	1	1	24.8 (3.9)	0.0 (0.0)	0.4 (0.4)	0.2 (0.2)
			MT	86	94	2	9	2	22.2 (1.7)	0.1 (0.1)	0.6 (0.3)	0.2 (0.2)
			ZT	46	89	4	7	4	29.4 (3.4)	0.3 (0.2)	0.4 (0.2)	0.2 (0.1)
									P-value			
CT vs. MT, ZT					0.911	0.054	0.505	0.801	0.820	0.082	0.775	0.920
MT vs. ZT					0.337	0.556	0.564	0.557	0.075	0.408	0.449	0.796

[a] Value in parentheses are standard errors of the mean.
[b] CT: conventional-till; MT: minimum-till; ZT: zero-till.
[c] *Fav*: *F. avenaceum*; *Fc*: *F. culmorum*; *Fg*: *F. graminearum*; *Cs*: *Cochliobolus sativus*.
[d] Probability of having a larger difference by chance alone.

2001), Mathieson et al. (1990), and Tinline and Spurr (1991). The higher levels of *C. sativus* and lower levels of *F. avenaceum* in more intensive tillage systems are similar to observations by Windels and Wiersma (1992); however, they did not observe a tillage effect on *F. acuminatum* or *F. culmorum*. In other regions of Saskatchewan, *F. avenaceum* in underground wheat tissue was also associated with reduced tillage management and continuously cropped diversified rotations (Fernandez et al., 2007b). In studies of noncereal crops conducted in eastern Saskatchewan, tillage operations were also positively associated with the occurrence of *C. sativus*, and negatively associated with *F. avenaceum* in roots of lentil (*Lens culinaris* Medik.), flax (*Linum usitatissimum* L.) and canola plants grown in rotation with wheat or barley (Fernandez, 2007).

Our observation that tillage system effects were dependent on the previous cropping practices suggests that tillage effects on CRR, or the fungi isolated from discoloured subcrown internodes, might be attributed to different factors across the different practices.

The lower population of *F. graminearum* under zero-till than conventional-till, in cereal residues when the current crop was another cereal, is consistent with observations that *F. graminearum* developed in parallel with the mineralization of residues (Yi et al., 2002). The lower recovery of *F. culmorum* from cereal residues under zero-till than conventional-till (when the current crop was an oilseed) agrees with its lower occurrence reported in culm bases of winter wheat in ploughless than in conventional tillage treatments by Weber et al. (2001), and with its greater isolation from barley subcrown internodes in our study as tillage intensity increased. In contrast to the above, *F. avenaceum* was favoured under reduced tillage. Tillage system effects on this fungus are similar to those observed in the subcrown internodes of barley and common wheat in the present studies, although the tillage effect on wheat depended on the cropping sequence.

These studies document the positive association of glyphosate with pathogenic *Fusarium* spp., including *F. avenaceum*, *F. culmorum* and *F. graminearum*, in spikes/kernels and subcrown internodes of wheat and/or barley, and in residues of these crops almost a year after harvest. The exact nature of these associations was not determined.

Previous research has shown that herbicides, including glyphosate, can inhibit or stimulate the growth of fungal pathogens, and can either increase or decrease disease development through direct or indirect means (Altman, 1993; Levesque and Rahe, 1992). Levesque and Rahe (1992) showed evidence that herbicides can have a direct effect on various components of the soil microflora, such as plant pathogens, antagonists, or mycorrhizae, which can potentially increase or decrease the incidence of plant disease. Pathogens able to infect weeds can also increase their inoculum potential after weeds have been sprayed with herbicides, which could subsequently affect host crops.

The observation that *Fusarium* infections increased in fields previously sprayed with glyphosate agrees with reports of the association of glyphosate with *Fusarium* colonization of other crops. Although no previous studies examined the effect of glyphosate on FHB or *F. graminearum* in cereals, several studies have shown a

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stimulatory effect of glyphosate on *Fusarium* populations (Kawate et al., 1997; Kremer et al., 2005; Levesque and Rahe, 1992; Rahe et al., 1990; Sanogo et al., 2001), including *F. avenaceum* and *F. culmorum* (Brown and Sharma, 1984; Levesque et al., 1987). For example, Levesque et al. (1987) reported that glyphosate increased root colonization of various treated weeds by *F. avenaceum* and *F. oxysporum* Schltdl.:Fr., as well as increasing the propagule density of these species in soil. Johal and Rahe (1984) and Rahe et al. (1990) showed that the glyphosate-induced root colonization by *Fusarium* spp. and other pathogens was the cause, and not the result, of plant death following application of certain doses of glyphosate, and that the efficacy of glyphosate depended on the synergistic action of these species and others in the soil. Kawate et al. (1997) reported that *Fusarium* populations were greater in the rhizosphere soil from glyphosate-treated than from untreated henbit (*Lamium amplexicaule* L.), and suggested that weed control with glyphosate in the spring may provide *Fusarium* pathogens an energy source for survival and proliferation. Glyphosate-treated quackgrass (*Elymus repens* [L.] Gould) was also rapidly colonized by *F. culmorum*, which subsequently caused damage to the following barley crop (Lynch and Penn, 1980). Brown and Sharma (1984) reported that flax plants treated with glyphosate were rapidly colonized by several species of fungi, including *F. culmorum*. Glyphosate could also act directly on plants by inhibiting their phenolic metabolism which could potentially affect plant resistance; thus, causing them to be more susceptible to pathogenic organisms. Sub-lethal doses of glyphosate induced susceptibility to *F. oxysporum* f. sp. *radicis-lycopersici* Jarvis & Shoemaker in two resistant tomato cultivars whose root tissue was invaded by the pathogen soon after glyphosate treatment (Brammal and Higgins, 1988).

Glyphosate applied to glyphosate-tolerant soybean significantly increased the isolation frequency of the causal agent of sudden death syndrome, *F. solani* (Mort.) Sacc. f. sp. *glycines* Roy (Sanogo et al., 2001), and *Fusarium* populations on roots and in the rhizosphere of plants (Kremer et al., 2005). Glyphosate applications could cause increased disease levels in soybean through enhanced pathogen activity in the rhizosphere of treated plants caused by glyphosate or plant metabolites in root exudates (Kremer et al., 2005).

Laboratory studies have also shown stimulatory activity of glyphosate on *Fusarium*. Krzysko-Lupicka and Orlik (1997) reported that *Fusarium* spp. grew out of soil suspensions only when these were plated on nutrient media in which glyphosate had been used as the sole source of C or P, but not on nutrient media alone.

Glyphosate was also shown to have a differential effect on fungi, thus potentially altering the outcome of competition between them (Wardle and Parkinson, 1992). Our studies showed a significant negative association of previous glyphosate use with *C. sativus*, suggesting changes in populations of the most common root rot fungi associated with the use of this herbicide. The observation of negative associations of previous glyphosate use with *C. sativus* under conventional-till and zero-till management systems suggests that changes in population of this pathogen might be due to the herbicide and unrelated to tillage management.

We could not determine if the higher *Fusarium* levels in subcrown internodes associated with previous glyphosate use was due to effects on fungal inoculum, host susceptibility, or the lower levels of *C. sativus* with which the *Fusaria* might be competing. There are no previous reports of glyphosate effects on infection of underground tissue of wheat or barley by *C. sativus*. Furthermore, these studies could not determine how much of the increased levels of *Fusarium* might be due to other factors, such as microenvironment, in these systems or other factors associated with tillage frequency. Increases in populations of *F. avenaceum* and *F. graminearum* might cause more severe crown and root rot as well as spike infection in subsequently grown cereal crops. Because *Fusarium* infections in crown/roots would be less affected by environmental conditions than spike infections, they might maintain high levels of inoculum in years not conducive to FHB development and thus contribute to the further spread of this disease in the Canadian Prairies.

These are the first studies showing a significant association of previous glyphosate application with FHB and underground tissue infections by *C. sativus* and *Fusarium* spp. Based on the observations made across four years in eastern Saskatchewan, growing susceptible crops under minimum-till management in fields where glyphosate has been previously applied, resulted in the most damage from FHB in years conducive to disease development. The barley study also showed that the greatest FHB levels occurred in continuous cropping systems than when summerfallow was included in the rotation (Fernandez et al., 2007d). For CRR, we conclude that growing wheat or barley under reduced tillage systems that include glyphosate applications will likely increase infection by *Fusarium* spp. These studies also show that the highest *Fusarium* populations occur when noncereal crops are grown in rotation with wheat or barley (Fernandez et al., 2007a,c).

Thus, current production practices relying on reduced tillage management and increased glyphosate use, and continuous cropping sequences that include noncereal crops, are potentially associated with increases in cereal diseases caused by *Fusarium* spp. The similar impact of production factors on FHB and CRR points to the importance of agronomic practices vis-a-vis the environment in the development of wheat and barley diseases. The observation that similar crop production factors are associated with common pathogenic *Fusarium* spp. in subcrown internodes and spikes or kernels of barley suggests that measures aimed at reducing crown/root rot caused by *Fusarium* spp. might also help reduce FHB development in cereal crops.

4.1. Recommendations for future research

The FHB and FDK levels observed in our studies varied from low to high for this region, but on average, disease levels were lower than those normally found in eastern Canada and the eastern Prairies where FHB recently occurred in epidemic proportions. It is unknown if cereal crops, grown in areas with traditionally higher FHB levels and where *F. graminearum* is the predominant pathogen, are likely to be impacted by the same crop production factors, including previous glyphosate use.

The nature of these studies also does not permit separation of the role of tillage intensity from glyphosate use on relative levels of fungal pathogens in cereal spikes and underground tissue. It is also not possible to completely separate the role of tillage system/glyphosate use versus cropping sequence on *Fusarium* populations in cereal tissue. Since correlations between the isolation frequency of fungi in crop residues and tillage operations were often of opposite sign to correlations between their isolation frequency and number of previous glyphosate applications, it is not possible to determine which factor(s) played the most important role in the tillage system effects on fungal colonization of residues.

Determining the relative contribution of tillage, herbicide application, and cropping sequence on FHB and CRR development in wheat and barley should help in understanding the role that each of these plays in disease levels and the relative frequency of the various pathogens. It should also help elucidate the mechanisms responsible for the changes in *Fusarium* populations under different tillage/input systems. Further research on the associations observed in these studies is warranted considering the continuing adoption of conservation tillage practices and glyphosate use, and the increased development of important wheat diseases caused by *Fusarium* spp. The increasing importance of noncereal crops in cereal-based systems in western Canada and other parts of the world, and the importance of *F. avenaceum* as a crown/root pathogen of cereal and noncereal crops and a FHB pathogen of

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cereal crops, indicates that the impact of noncereal crops on diseases caused by *Fusarium* spp. merits further investigation.

Determining the mechanism(s) responsible for the associations of previous glyphosate applications with spike and root infections by two of the most important FHB pathogens, *F. graminearum* and *F. avenaceum*, will likely help in the control of these important crop diseases. This is especially relevant considering that increased incorporation of glyphosate-tolerant crops in rotations with cereal crops increases the use of glyphosate. Further information might allow for improved recommendations for lowering populations of *Fusarium* pathogens in affected areas, as well as preventing their further spread in western Canada.

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