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Influence of crop rotation on common root rot of wheat and barley

Robert L. Conner, Lorne J. Duczek, Gerald C. Kozub, and Allan D. Kuzyk

Research Centre, Agriculture and Agri-Food Canada, Lethbridge, Alberta T1J 4B1; and (L.J.D.) Research Centre, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, Saskatchewan S7N 0X2. Lethbridge Research Centre Contribution No. 3879531.

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Three-year crop rotations involving combinations of wheat, barley and flax were compared for their effect on common root rot [*Cochliobolus sativus*] in subsequent crops of wheat and barley at sites with different cropping histories. Rotations that ended with two or more years of flax reduced the severity of common root rot in both of the cereal crops and decreased the amount of viable inoculum of *C. sativus* in the soil. In wheat and barley, common root rot severity was lower after rotations in which the other cereal had been grown for the final 2 years than after continuous cultivation of the same crop. Severity in barley increased when long-term cropping of wheat, flax or oats was followed by 2 years of barley. At sites where common root rot was severe in barley, 2 years of wheat production usually increased severity in wheat. The virulence of *C. sativus* appeared to be selectively enhanced or depressed by the host crops in the rotations. Significant differences in common root rot severity in resistant and susceptible lines or cultivars of the same crop were usually observed in all rotations. The effect of rotation on the yield of the subsequent wheat or barley crop was inconsistent and not always related to differences in severity. The root rot resistant barley cultivar Bonanza outyielded the susceptible cultivar Gateway at sites where common root rot was generally severe in barley.

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On a comparé l'effet de rotations de trois ans de blé, d'orge et de lin en combinaisons diverses sur la pourriture sèche *(Cochliobolus sativus)* dans les cultures subséquentes de blé ou d'orge, en milieux aux antécédents culturaux variés. Les rotations se terminant avec deux années de lin ou plus ont réduit l'intensité de pourriture sèche chez les deux céréales tout en diminuant l'inoculum actif du *Cochliobolus sativus* dans le sol. Chez le blé ou l'orge, l'intensité de pourriture sèche était moindre suivant des rotations dans lesquelles l'autre céréale avait été cultivée au cours des deux dernières années que dans les situations de monoculture de la même céréale. L'orge était attaquée plus fortement après plusieurs années de blé, de lin ou d'avoine qui avaient été suivies de deux ans d'orge. Aux endroits fortement attaqués de pourriture sèche chez l'orge, deux ans de culture de blé ont généralement suffi pour augmenter l'intensité chez le blé. La virulence du *C. sativus* aussi été sélectivement stimulée ou atténuée selon les cultures dans la rotation. Dans la plupart des rotations, on a décelé des différences significatives d'intensité de pourriture sèche entre les génotypes résistants et les sensibles de la même céréale. L'effet des rotations sur le rendement de la céréale subséquente était variable et pas toujours lié aux différences d'attaques. Le cultivar d'orge résistant Bonanza a produit davantage que le cultivar sensible Gateway aux endroits où la pourriture sèche était généralement intense.

Common root rot, caused primarily by *Cochliobolus sativus* (Ito and Kurib.) Drechsl. ex Dastur., anamorph *Bipolaris sorokiniana* (Sacc. in Sorok.) Shoem., occurs wherever wheat (*Triticum aestivum* L. em Thell.) and barley (*Hordeum vulgare* L.) are grown under dryland conditions in the prairie provinces of Canada. This disease affects yield in wheat and barley primarily by reducing tiller numbers (8, 9, 15, 18, 27). In western Canada, annual yield losses due to common root rot are estimated at 5.7% in wheat (15) and 10.0% in barley (18).

Crop rotation with non-cereal crops for at least 2 years is widely recommended for control of common root rot (16, 19, 26). However, Conner and Atkinson (5) demonstrated that the disease was less severe in barley after more than 5 years of continuous wheat production and less severe in wheat after 5 years of continuous barley production. The impact of reduced severity on yield was not clear because of differences in the yield capacity and common root rot tolerance of the cultivars tested (17, 23). The effect of cropping history on common root rot severity has been attributed to a shift in virulence and selection for more virulent *C. sativus* isolates on the recurring crop species (5). In this study, the term virulence is used to describe host-specific variation in pathogenicity.

This study was undertaken to compare common root rot severity and yield in wheat and barley after 3-year rotations involving wheat, barley, and the non-host crop flax.

Materials and methods

Rotation sites and sequences. At Lethbridge, the wheat (W) and barley (B) sites described by Conner and Atkinson (5) were used. Common root rot susceptible cultivars had been grown at the sites for 6 years: Cypress wheat at site 1 and Galt barley at site 2. At site 3, wheat had been grown for 5 years followed by 1 year of flax (F). The wheat and flax sites were located in the same field, 50 m apart, and the barley site was in another field 1 km from the other two sites. Each site was split in two and the different rotation sequences were initiated on one half in 1988 while the original crop was grown on the other half. The rotation sequences were started on the other half of the site in 1989.

Three sites of comparable area to those at Lethbridge were selected within a field near Vauxhall, Alberta. Oats (*Avena sativa* L.) had been grown for several years in this field. These sites were split as outlined for the Lethbridge location and the same rotation sequences started in 1990 and 1991.

Five three-year rotation sequences were conducted per site (Table 1). The sequences differed among sites at a location. In each year of the rotation, stubble was left undisturbed until the spring when the soil was rototilled before seeding. To minimize mixing of soils from different rotation sequences, all plots with the same rotation treatment were rototilled successively. Prior to rototilling, the fertilizer 27-14-0 (N-P-K) was broadcast at a rate of 250 kg ha^{-1}.

Lines and cultivars. Moderately resistant and susceptible backcross lines of the hard red spring wheat cultivar Neepawa were used. These were backcross-6 derivatives of a cross of Neepawa and the susceptible line S-615, the progeny of which were subsequently backcrossed to Neepawa, using it as the maternal parent (6). Barley cultivars were the moderately root rot resistant Bonanza and the susceptible Gateway (17).

Experimental design. For each half of a site, a split-plot design (22) was used to determine the effect of different rotation sequences on common root rot severity and yield of the two wheat lines and the two barley cultivars in the final year. The five rotation sequences formed the main plots in randomized complete blocks and the lines and cultivars were subplot treatments. Four replicate blocks were used in the Lethbridge location and six in Vauxhall. The main plots measured 6 m by 4 m and were separated by 1-m pathways on each side and on the ends. Within each main plot the two barley cultivars and two wheat lines were individually seeded in four-row plots 6 m long by 1 m wide.

Disease and yield assessment. Disease severity and yield were determined in wheat and barley in the year following the three-year rotations. At Lethbridge in 1991 and 1992, common root rot severity in each subplot was determined at anthesis (growth stage 10.5.4, Feekes scale) (14) and at maturity (G.S. 11.4). At Vauxhall in 1993 and 1994, it was determined at the mid-dough stage (G.S 11.2) and at maturity. For the severity determinations at anthesis and mid-dough, at least 20 plants were removed from the first 0.5 m at one end of each subplot and common root rot severity was rated based on the amount of discolouration of the subcrown internode (15) as nil (no lesions), slight (a few small lesions), moderate (extensive lesions covering up to half of the subcrown internode, and severe (very extensive lesions covering over half of the subcrown internode). After harvest, common root rot severity was determined from a 50-plant sample selected at random throughout each subplot. Data on the number of plants in each category were summarized as percentage root rot according to the formula described by Burrage and Tinline (2). A 5-m length of the two center rows per subplot was harvested for yield.

Soil sampling. In the years 1991–94 at the end of the rotation sequence at each site, samples of the top 15 cm of soil were randomly collected before seeding within the main treatment plots from each site where common root rot was to be evaluated that year. These samples were analysed for total available nitrogen and phosphorus. From 1992 to 1994, the number of viable propagules of C. *sativus* in each soil sample was assessed using the dilution plate method on a selective medium (7).

Statistical analysis. For each location and site combination, split-plot analyses of variance were carried out for each year separately (22) and over years to study the effects due to, and interactions among, rotation treatments, wheat line or barley cultivar, and year, for percentage disease at the two sampling dates and for yield. For the analysis over years, effects due to rotation treatment and its interaction with year were included in the main plot part of the analysis while effects due to line or cultivar and their interactions with rotation treatment and year were included in the subplot part of the analysis. The effects of rotation treatment, line or cultivar and year were regarded as fixed. A logit transformation given by $\log_{10}[P/(100\text{-}P)]$ (1) was used on the percentage disease (P) data prior to analysis to stabilize the variance. The data for total available nitrogen and phosphorus and *C. sativus* propagule number were analyzed similarly, except that there was no line-cultivar subplot factor. A logarithmic transformation was applied to the soil variables to stabilize the variance. The analyses were carried out using the General Linear Models (GLM) procedure of SAS (20).

Table 1. Rotation sequences initiated at three sites in Lethbridge in 1988 and 1989 and Vauxhall in 1990 and 1991

	Rotation sequence‡				
Site†	1	2	3	4	5
1	WWW	WWF	WFF	WWB	WBB
2	BBB	BBW	BWW	BBF	BFF
3	FFF	FFW	FWW	FFB	FBB

†At Lethbridge, the crop species grown prior to the initiation of the rotation sequence were wheat (W), barley (B) and wheat-flax (W-F) at sites 1, 2 and 3, respectively; at Vauxhall, oats was grown prior to initiation of the rotation sequences at each site.

‡Crop species on a plot in the first 3 years; wheat lines and barley cultivars were seeded in the fourth year.

Results

The Lethbridge and Vauxhall locations were considered separately because of differences in the long-

Table 2. Mean squares from analyses of variance to study the effects of rotation sequence (R), cultivar-line (C), year (Y) and their interactions on common root rot severity and yield at Lethbridge

		Site 1			Site 2			Site 3		
Source	df	IDR‡	DRM‡	YD†	IDR‡	DRM‡	YD	IDR‡	DRM‡	YD
Y	1	0.772	2.233	149198	5.806	6.860	216069	0.548	2.037	19722
Block (Y)	6	0.190	0.033	541	0.180	0.088	35	0.093	0.149	2019
R	4	0.164NS	0.012NS	389*	0.871**	0.308**	233NS	0.123NS	0.370**	145NS
R × Y	4	0.259NS	0.040NS	78NS	0.044NS	0.180*	204NS	0.204NS	0.063NS	964NS
Error A	24	0.165	0.059	136	0.114	0.045	160	0.137	0.063	545
C	3	10.714**	5.072**	3105**	5.435**	2.298**	1663**	4.883**	8.604**	3751**
C × R	12	0.150NS	0.081*	68NS	0.224**	0.233**	82NS	0.147NS	0.073NS	273NS
C × Y	3	0.181NS	1.505**	2894**	0.489**	0.700**	2198**	0.254*	0.119NS	3662**
C × R × Y	12	0.109NS	0.049NS	95NS	0.138NS	0.070NS	78NS	0.076NS	0.026NS	188NS
Error B	90	0.091	0.040	124	0.094	0.054	143	0.084	0.053	237

IDR = initial disease rating, DRM = disease rating at maturity, YD = yield.
†Mean squares for yield have been divided by 1000.
‡A $\log_{10}$ [P/(100-P)] transformation, where P is the percentage disease, was used to transform disease data.
*, **Significant at P=0.05 and 0.01.
NSNot significant.

term cropping history at the locations. Analyses of variance were conducted over years for each location × site combination with all lines and cultivars included (Tables 2 and 3) and with wheat lines and barley cultivars separately. The analyses indicated that the cultivar × rotation sequence interactions were generally significant (P< 0.05) more frequently for the combined disease data from wheat and barley than when wheat and barley were examined separately. This indicated that disease severity in wheat and barley was differentially affected by rotation sequence. The three-factor year × cultivar × rotation sequence interaction was not significant (P > 0.05), and cultivar effects for the same crop were generally consistent between years. This demonstrated that differences in root rot ratings between resistant and susceptible lines or cultivars of the same crop were usually consistent for rotation sequence and year, and so rotation and line or cultivar means for a crop were presented for each location × site (Tables 4–6).

The analyses of variance for the combined data for wheat and barley showed that yield was significantly influenced by cultivar; there was a cultivar × year interaction (Tables 2 and 3). All other sources of variation had no significant effect on yield.

Significant (P< 0.05) differences in disease severity in wheat or barley among rotation treatments were evident at sites at Lethbridge and Vauxhall. Differences in root rot severity in wheat among the rotation sequences at site 1 were apparent at the final sampling date at Lethbridge and at both sampling dates at Vauxhall (Table 4). Ratings at maturity in Vauxhall, indicated that 2 years of barley following wheat (WBB) was sufficient to reduce root rot severity in wheat at maturity in comparison to continuous wheat (WWW). At Vauxhall, 2 years of flax (WFF)

Table 3. Mean squares from analyses of variance to study the effects of rotation sequence (R), cultivar-line (C), year (Y) and their interactions on common root rot severity and yield at Vauxhall

		Site 1			Site 2			Site 3		
Source	df	IDR‡	DRM ‡	YD†	IDR‡	DRM‡	YD	IDR‡	DRM‡	YD
Y	1	13.717	31.716	30845	5.297	24.788	139373	2.615	23.957	43513
Block (Y)	10	0.145	0.165	1147	0.124	0.053	447	0.192	0.173	530
R	4	0.551**	1.319**	775NS	0.559**	0.706**	561NS	0.277NS	1.157**	426NS
R × Y	4	0.019NS	0.049NS	665NS	0.094NS	0.189**	494NS	0.037NS	0.259*	576NS
Error A	40	0.114	0.076	400	0.098	0.040	315	0.109	0.070	483
C	3	7.623**	4.002**	5812**	3.424**	0.622**	517*	8.010**	4.753**	5593**
C × R	12	0.205**	0.151**	242NS	0.148NS	0.037NS	255NS	0.148NS	0.069NS	131NS
C × Y	3	0.108NS	0.562**	4714**	0.045NS	1.031**	935**	0.117NS	1.031**	497*
C × R × Y	12	0.098NS	0.037NS	51NS	0.045NS	0.102*	153NS	0.158NS	0.022NS	156NS
Error B	150	0.088	0.052	293	0.087	0.045	164	0.094	0.043	150

IDR = initial disease rating, DRM = disease rating at maturity, YD = yield.
†Mean squares for yield have been divided by 1000.
‡A $\log_{10}$[P/(100-P)] transformation, where P is the percentage disease, was used to transform disease data.
*, **Significant at P= 0.05 and 0.01.
NSNot significant.

Table 4. Effect of 3-year rotations with wheat (W), barley (B), and flax (F) on subsequent severity of common root rot and yield of wheat and barley at site 1 in Lethbridge (1991–2) and in Vauxhall (1993–4)

	Initial disease rating				Disease rating at maturity				Yield (kg/ha)			
	Lethbridge (W)†		Vauxhall (Oats)†		Lethbridge (W)		Vauxhall (Oats)		Lethbridge (W)		Vauxhall (Oats)	
Crop‡	W	B	W	B	W	B	W	B	W	B	W	B
Crop sequence												
WWW	33a[£¶]	9b	39a	35bc	48ab	30a	61a	59b	2160a	2470a	3105a	2705bc
WWF	27a	9b	29ab	30c	52a	30a	48b	49c	2345a	2785a	3385a	2630c
WFF	23a	10ab	21b	30c	44ab	34a	31c	46c	2325a	2775a	3385a	3035a
WWB	31a	13ab	30a	42ab	49ab	34a	55ab	61ab	2115a	2675a	3405a	2965ab
WBB	24a	16a	29ab	46a	42b	37a	50b	68a	2210a	2580a	3225a	2990ab
SE (24df)[§]	0.085	0.086	0.070	0.067	0.048	0.065	0.053	0.051	95	125	130	110
Cultivars												
Susceptible	55A	15A	46A	52A	67A	42A	62A	67A	2255A	2815A	3255A	2645B
Resistant	11B	8B	16B	23B	28B	25B	36B	46B	2210A	2500B	3350A	3085A
SE (30df)[§]	0.047	0.054	0.034	0.039	0.033	0.028	0.030	0.028	45	50	65	70

†Crop prior to the initiation of the 3-year rotation sequence.
‡Crop in the year after the 3-year rotation sequence.
£Means for the first and final disease ratings are backtransformed values following a $\log_{10}$ [P/(100-P)] transformation where P is the percentage disease.
¶Means for rotation treatment followed by the same lowercase letter within a column are not significantly different ($P > 0.05$) using the least significant difference (LSD) test. Line or cultivar means followed by the same uppercase letter within a column are not significantly different ($P > 0.05$).
§SE of the mean is in $\log_{10}$ units for disease ratings.

production reduced root rot severity in wheat in comparison to continuous wheat (WWW).

At site 1, root rot severity in barley was lower following continuous wheat (WWW) and WWF than after 2 years of barley (WBB) at the initial sampling date at Lethbridge and for both sampling dates at Vauxhall (Table 4). At Vauxhall, any rotation involving just wheat and/or flax resulted in reduced disease severity in barley in comparison to that after 2 years of barley.

The yield of wheat at site 1 was not affected by rotation sequence at either location (Table 4). Rotation treatment significantly influenced barley yields only at Vauxhall, where the WFF rotation out-

Table 5. Effect of 3-year rotations with wheat (W), barley (B), and flax (F) on subsequent severity of common root rot and yield of wheat and barley at site 2 in Lethbridge (1991–2) and in Vauxhall (1993–4)

	Initial disease rating				Disease rating at maturity				Yield (kg/ha)			
	Lethbridge (B)†		Vauxhall (Oats)†		Lethbridge (B)		Vauxhall (Oats)		Lethbridge (B)		Vauxhall (Oats)	
Crop‡	W	B	W	B	W	B	W	B	W	B	W	B
Crop sequence												
BBB	10a[£¶]	29a	19ab	51a	29b	70a	52ab	75a	3025a	3325a	3110ab	3090a
BBW	12a	25a	21ab	46a	31b	70a	47bc	64b	2950a	3390a	3290a	3070a
BWW	15a	24ab	26a	41ab	38a	64ab	54a	68ab	2825a	3390a	3005b	3200a
BBF	11a	25a	18ab	44a	25bc	68a	42c	69ab	2960a	3620a	3170ab	3245a
BFF	11a	18b	17b	34b	20c	57b	33d	51c	2910a	3390a	3305a	3350a
SE (24 df)[§]	0.088	0.066	0.069	0.062	0.046	0.069	0.038	0.058	100	205	90	140
Cultivars												
Susceptible	13A	40A	22A	59A	31A	79A	50A	76A	2895A	3280B	3160A	2820B
Resistant	11A	13B	18B	28B	26B	50B	41B	54B	2970A	3565A	3195A	3565A
SE (30 df)[§]	0.055	0.045	0.036	0.041	0.034	0.033	0.023	0.030	70	75	40	50

†Crop prior to the initiation of the 3-year rotation sequence.
‡Crop in the year after the 3-year rotation sequence.
£Means for the first and final disease ratings are backtransformed values following a $\log_{10}$ [P/(100-P)] transformation where P is the percentage disease.
¶Means for rotation treatment followed by the same lowercase letter within a column are not significantly different ($P > 0.05$) using the least significant difference (LSD) test Line or cultivar means followed by the same uppercase letter within a column are not significantly different ($P > 0.05$).
§SE of the mean is in $\log_{10}$ units for disease ratings.

Table 6. Effect of 3-year rotations with wheat (W), barley (B), and flax (F) on subsequent severity of common root rot and yield of wheat and barley at site 3 in Lethbridge (1991–2) and in Vauxhall (1993–4)

	Initial disease rating				Disease rating at maturity				Yield (kg/ha)			
	Lethbridge (F)[†]		Vauxhall (Oats)[†]		Lethbridge (F)		Vauxhall (Oats)		Lethbridge (F)		Vauxhall (Oats)	
Crop‡	W	B	W	B	W	B	W	B	W	B	W	B
Crop sequence												
FFF	9c[£¶]	6b	19a	19c	25b	28c	27c	30c	2280a	2735a	2885a	2930ab
FFW	24a	10a	18a	27b	44a	32bc	34b	43b	2260a	2500ab	2950a	3095a
FWW	29a	8ab	22a	28b	45a	31bc	40ab	43ab	2180a	2430b	3000a	3035ab
FFB	12bc	8ab	17a	24bc	29b	36ab	37ab	40b	2320a	2525ab	2885a	2720b
FBB	14b	12a	21a	42a	33b	43a	42a	50a	2170a	2455b	2925a	3210a
SE (24 df)[§]	0.071	0.072	0.071	0.055	0.059	0.052	0.044	0.045	105	90	90	120
Cultivars												
Susceptible	31A	12A	20A	40A	50A	40A	38A	46A	2195A	2665A	2950A	2895B
Resistant	8B	6B	18A	17B	22B	29B	33B	36B	2285A	2395B	2905A	3100A
SE (30 df)[§]	0.060	0.045	0.035	0.040	0.034	0.036	0.026	0.026	47	69	52	34

[†]Crop prior to the initiation of the 3-year rotation sequence.
[‡]Crop in the year after the 3-year rotation sequence.
[£]Means for the first and final disease ratings are backtransformed values following a $\log_{10}$ [P/(100-P)] transformation where P is the percentage disease.
[¶]Means for rotation treatment followed by the same lowercase letter within a column are not significantly different ($P > 0.05$) using the least significant difference (LSD) test . Line or cultivar means followed by the same uppercase letter within a column are not significantly different ($P > 0.05$).
[§]SE of the mean is in $\log_{10}$ units for disease ratings.

yielded the WWF and the WWW treatments, but these differences in yield did not appear to be related to large differences in root rot severity.

At site 2 at Lethbridge, initial root rot severity remained low in wheat and no differences occurred among rotation sequences (Table 5). At Vauxhall, the BFF rotation was the most effective in reducing disease severity in wheat at both sampling dates. Final disease severity in wheat at Lethbridge was reduced by the continuous barley (BBB) and BBF treatments to a level intermediate between that in the BWW and the BFF rotations. Wheat yields were higher following the BFF and BBW than the BWW cropping sequence in Vauxhall, but even though the ranking of the yields of the various rotations were similar at Lethbridge, the differences between these treatments were not significant.

At site 2, for all sampling dates and locations, root rot severity in barley was high following continuous barley (BBB); severity was lower following BFF rotation but usually was not significantly different from the BWW treatment (Table 5). Rotations that included only 1 year of either wheat or flax did not consistently reduce root rot severity in barley from the levels in the BBB treatment. Barley yields were not influenced by rotation sequence at site 2 in either location.

Root rot severity in wheat at site 3 for both sampling dates at Lethbridge was higher in the FWW rotation treatment than in any rotation that did not include wheat (Table 6). However, initially no differences in disease severity occurred at site 3 at Vauxhall, and at the final sampling date only the FFF treatment reduced disease ratings in wheat from the level in all other rotation treatments. No differences in wheat yields were detected among rotation treatments at site 3.

Disease ratings in barley were initially low at site 3 at Lethbridge, with only the continuous flax (FFF) treatment resulting in lower root rot ratings than the FBB rotation (Table 6). However, at Vauxhall all the rotations reduced initial disease severity from that in the FBB rotation. At maturity, rotations at Lethbridge that did not include barley reduced disease severity in barley relative to the FBB rotation, and at Vauxhall, root rot ratings at maturity were lower in rotations that included 2 or more years of flax than in the FBB treatment. The yield of barley was higher in the FFF treatment than in the FBB rotation at Lethbridge, but this difference was not evident at Vauxhall.

With only two exceptions, root rot severity was significantly ($P < 0.05$) lower in resistant compared with susceptible lines or cultivars of wheat and barley at each sampling date for all the sites and locations (Tables 4–6). Differences in yield between the resistant and susceptible lines of Neepawa at the different sites and locations were small and not significant. However, Bonanza outyielded Gateway at site 2 in both locations. Bonanza produced higher yields than Gateway at the other sites only when initial root rot severity was high.

Rotation treatment had a major effect on the concentration of viable propagules of *C. sativus* in the soil (Table 7). At sites 1 and 2, rotations that ended

Table 7. Effect of 3-year rotations with wheat (W), barley (B), and flax (F) on the number of viable propagules of *Cochliobolus sativus* and total available nitrogen in the soil

Site and rotation	*C. sativus* (cfu/g soil)[†]		Total N (PPM)	
	Lethbridge 1992	Vauxhall 1993–94	Lethbridge 1991–92	Vauxhall 1993–94
Site 1				
WWW	33ab[£]	146a	33b	13ab
WWF	51a	104a	31b	16a
WFF	14b	52b	20c	16a
WWB	49a	130a	34ab	13ab
WBB	60a	110a	41a	11b
SE (df)[‡]	0.165 (12)	0.064 (40)	0.030 (24)	0.045 (40)
Site 2				
BBB	58a	92a	33a	16b
BBW	43a	109a	32a	15b
BWW	26a	137a	27ab	18b
BBF	26a	89a	25b	20ab
BFF	24a	39b	25b	26a
SE (df)[‡]	0.127 (12)	0.075 (40)	0.032 (24)	0.045 (40)
Site 3				
FFF	2b	8c	24c	40a
FFW	8ab	16bc	35b	14b
FWW	24a	49a	35b	11b
FFB	2b	11c	42ab	13b
FBB	16a	33ab	45a	10b
SE (df)[‡]	0.210 (12)	0.112 (40)	0.036 (24)	0.043 (40)

[†]Means for *C. sativus* counts and total N are backtransformed values following $\log_{10}$ (X+1) and $\log_{10}X$ transformations, respectively.
[£]Means for rotation treatment within a site followed by the same letter within a column are not significantly different ($P>0.05$) using the least significant difference (LSD) test.
[‡]SE of the mean are in $\log_{10}$ units.

with 2 years of flax consistently had the lowest amount of *C. sativus* inoculum per gram of soil. At site 3, the continuous flax (FFF) treatment lowered inoculum levels from those observed in rotations with 2 years of wheat or barley, but the continuous flax treatment was not significantly different from rotations in which 2 years of flax was followed by 1 year of cereal production. The correlation of the counts of *C. sativus* inoculum with the initial disease ratings was 0.54 ($n = 45$, $P < 0.01$), and 0.42 ($n = 45$, $P < 0.01$) for the final ratings.

Cropping sequence did not significantly affect the amount of phosphorus in the soil (data not shown), but it did influence the amount of available nitrogen (Table 7). However, the influence of specific rotations on total available nitrogen was not consistent between locations.

In the first 3 years of data collection, total precipitation was high from June through August. During this period at Lethbridge, rainfall totalled 200 mm in 1991 and 213 mm in 1992. Total rainfall at Vauxhall for this period was 250 mm in 1993 and only 77 mm in 1994. Long-term average rainfall from June through August is 155 mm at Lethbridge and 136 mm at Vauxhall.

Discussion

Two-year rotations with crops other than wheat or barley have been recommended to reduce the severity of common root rot in these crops (16, 21). The present study also demonstrated that growing flax for at least 2 years reduced disease in subsequent crops of wheat and barley. However, rotations ending with 2 or more years of wheat or barley usually reduced disease severity in the other cereal crop to a level intermediate between the low severity in rotations ending with 2 or more years of flax and the high levels following 2 or more years of the original cereal crop. Root rot severity in wheat was usually diminished in rotations combining barley and flax. Disease ratings in barley were also generally lower following rotations that combined wheat and flax. Disease severity was not reduced in wheat or barley grown after only 1 year of flax or the other cereal.

The improved root rot control resulting from growing wheat or barley for at least 2 years and then changing to the other cereal was not due to a reduction in *C. sativus* inoculum. At sites 1 and 2, only rotations ending with 2 years of flax effectively reduced the amount of inoculum. Continuous seeding of flax (FFF) at site 3 was the most effective rotation treatment for reducing *C. sativus* counts, but inoculum levels were similar in rotations in which 2 years of flax were followed by 1 year of either wheat or barley. These observations agree with an earlier finding that cropping wheat or barley increased concentrations of *C. sativus* conidia (3). The cultivation of nonhost crops such as oats or rapeseed (*Brassica napus* L. and *B. rapa* L.) has been reported to reduce inoculum levels (3, 4, 19) as flax was shown to do in this study. Inoculum levels did have an influence on disease severity as indicated by the significant correlation between the two variables. This correlation was largely due to the simultaneous reduction of inoculum levels and common root rot severity in rotations ending with 2 years or more of flax.

This study supports speculation by Conner and Atkinson (5) that shifting from wheat to barley or the reverse results in a gradual selection for increased virulence of *C. sativus* on the introduced cereal with a simultaneous reduction in virulence on the original cereal. El-Nashaar and Stack (10) demonstrated that long-term cropping of wheat resulted in the selection of isolates of *C. sativus* causing increased damage on that crop. Wood (28) reported differences among isolates of *C. sativus* in their ability to induce seedling blight in wheat, oats, and barley, but also identified isolates that were virulent on all three crops. Fetch and Steffenson (11) reported that isolates of *C. sativus* differed in their virulence patterns in causing spot blotch symptoms on different barley genotypes. Kline and Nelson (13) suggested that differences among isolates of *C. sativus* in their ability to cause spot blotch on a gramineous species were under complex genetic control. In this study, the benefits of switching to the alternate cereal crop to reduce common root rot severity were just becoming evident after 2 years. This suggests that the shift in disease severity is gradual and may require more than 2 years of cropping the alternate cereal for a consistent reduction in disease severity in the original cereal along with a corresponding yield response. Another crop rotation study (19), demonstrated that root rot severity in barley started to decline only after two years cropping of nonhost species. Further research on the genetics of virulence of *C. sativus* on wheat and barley might help to explain the underlying mechanism that controls this shift in virulence from one species to another.

Apparently the cropping history at the sites influenced the virulence of *C. sativus* on cereals grown subsequently. At sites 1 and 3 in Lethbridge, *C. sativus* was more virulent on wheat than on barley, but at site 2 it was more virulent on barley than on wheat. Wheat had been grown for 6–7 years at site 1, and for 5 years followed by a year of flax at site 3. Barley had been grown for 6–7 years at site 2. This contrasts with the situation at sites 1 and 3 at Vauxhall, where after years of oat production the *C. sativus* isolates were equally virulent on both wheat and barley. Site 2 at Lethbridge and Vauxhall were similar in that the predominant isolates of *C. sativus* were more virulent on barley than on wheat.

Even though some rotations significantly affected common root rot severity in wheat and barley, a reduction in severity did not usually result in a significant yield response. Wheat yields were not affected by the rotations at sites 1 and 3. In Vauxhall at site 2, the BFF rotation improved wheat yields over the BWW rotation by 10%. At Lethbridge the yield of subsequent barley crops was high following the WFF rotation at site 1, but the differences among rotations were not significant. Differences in barley yields occurred among rotations at site 1 at Vauxhall and site 3 at both locations, but these differences were not always related to root rot severity.

Differences in the level of resistance among lines or cultivars of the same cereal were usually evident regardless of the long-term cropping history at a particular site but these differences did not always produce a significant yield response. Significant differences in yield between the resistant and susceptible lines of Neepawa were not observed at any of the sites. Bonanza produced higher yields than Gateway at sites 1 and 3 only when root rot severity was initially high. However, Bonanza consistently outyielded the susceptible cultivar Gateway at site 2, where root rot was generally severe on barley at both locations. It is difficult to clearly determine if the difference in yield between these barley cultivars was due to common root rot or to other factors, since the cultivars are not closely related and may not have the same yield potential. However, common root rot has been reported to cause more severe losses in barley than it does in wheat (18).

Common root rot is considered most detrimental to plants under moisture stress (12, 24). Except for 1994, moisture levels at the experimental sites were above the long-term average for southern Alberta. Since soil moisture levels were not usually limiting, damage to the root system caused by common root rot would have had a minimal effect on yield.

The effects of rotation on soil nutrient level in the spring were inconsistent and not closely related to differences in yield. The fertilizer applied before seeding must have been sufficient to meet the demands of the crop. Common root rot severity has been shown to be reduced by applications of phosphate fertilizers (25). High soil fertility may have at least partially offset the effect of common root rot on yield in this study.

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