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Weed-Competitive Ability of Spring and Winter Cereals in the Northern Great Plains

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The inclusion of winter cereals in spring-annual rotations in the northern Great Plains may reduce weed populations and herbicide requirements. A broad range of spring and winter cereals were compared for ability to suppress weeds and maximize grain yield at Lacombe (2002 to 2005) and Lethbridge (2003 to 2005), Alberta, Canada. High seeding rates ($\geq$ 400 seeds/m^2) were used in all years to maximize crop competitive ability. Spring cereals achieved high crop-plant densities ($>$ 250 plants/m^2) at most sites, but winter cereals had lower plant densities due to winterkill, particularly at Lethbridge in 2004. All winter cereals and spring barley were highly effective at reducing weed biomass at Lacombe for the first 3 yr of the study. Weed suppression was less consistently affected by winter cereals in the last year at Lacombe and at Lethbridge, primarily due to poor winter survival. Grain yields were highest for spring triticale and least for spring wheat at Lacombe, with winter cereals intermediate. At Lethbridge, winter cereals had higher grain yields in 2003 whereas spring cereals had higher yields in 2004 and 2005. Winter cereals were generally more effective at suppressing weed growth than spring cereals if a good crop stand was established, but overlap in weed-competitive ability among cultivars was considerable. This information will be used to enhance the sustainable production of winter and spring cereals in traditional and nontraditional agro-ecological zones.
Nomenclature: Barley, *Hordeum vulgare* L.; triticale, $\times$ *Triticosecale* W.; wheat, *Triticum aestivum* L.
Key words: Crop rotation, cultural weed control, integrated weed management, wheat, barley, triticale, rye.

La inclusión de cereales invernales en rotaciones anuales de primavera en el norte de los Grandes Llanos, quizás reduzca las poblaciones de maleza y los requerimientos de herbicida. Un amplio rango de cereales de primavera e invierno se compararon por su habilidad para suprimir la maleza y maximizar el rendimiento del grano en Lacombe (de 2002 a 2005) y en Lethbridge (de 2003 a 2005), ambos lugares en Alberta. Altas densidades de siembra ($\geq$ 400 semillas/m^2) se usaron en todos los años para maximizar la habilidad competitiva del cultivo. Los cereales de primavera alcanzaron altas densidades de plantas ($\geq$ 250 plantas/m^2) en la mayoría de los sitios, pero los cereales de invierno tuvieron una densidad de plantas menor debido a las heladas, particularmente en Lethbridge en 2004. En Lacombe, durante los primeros tres años del estudio, todos los cereales de invierno y la cebada de primavera fueron altamente efectivos para reducir la biomasa de la maleza. El último año en Lacombe y Lethbridge, la supresión de maleza fue poco afectada por los cereales de invierno debido principalmente a su pobre sobrevivencia invernal. En Lacombe, los rendimientos de grano fueron mayores para el triticale de primavera y menores para el trigo de primavera; los cereales de invierno resultaron con producciones intermedias. En Lethbridge, los cereales de invierno tuvieron un mejor rendimiento de grano en 2003, mientras que los cereales de primavera lo tuvieron en 2004 y 2005. Los cereales de invierno fueron generalmente más efectivos para suprimir el crecimiento de la maleza que los cereales de primavera, siempre y cuando se haya logrado un buen establecimiento; sin embargo, el traslape en la habilidad competitiva de la maleza entre cultivares, fue considerable. Esta información podrá usarse para mejorar la producción sustentable de cereales de invierno y primavera en zonas agro-ecológicas tradicionales y no tradicionales.

The inclusion of winter cereals in spring-annual rotations in the northern Great Plains may reduce weed populations and herbicide requirements because of their greater competitive ability and rotational diversity (Derksen et al. 2002; Thurston 1962). Winter cereals often out-yield spring cereals because early spring growth improves water use efficiency and crop growth duration (Entz and Fowler 1991). The number of cereal types and cultivars available to achieve these benefits is greater when they are utilized as livestock feed or for ethanol than for human food. Therefore, with the increased demand for livestock feed and ethanol on the Canadian prairies, increased opportunities exist to add beneficial winter cereals to crop rotations.

The ability of rye (*Secale cereale* L.) to suppress weed growth is well established (Blackshaw et al. 2007), but few cultivars have been developed and crop area is limited because of limited markets. Rye has been crossed with wheat to produce spring and winter triticales in order to combine the benefits of both cereal types. To date, triticale cultivars have been primarily used for livestock forage, but interest also exists for increased use in livestock concentrates or ethanol.

The objective of this study was to evaluate a broad range of spring and winter cereal types seeded at high rates for their ability to suppress weed growth and maximize grain yield when grown in partial and full weed control management systems.

Materials and Methods

Field experiments were conducted for 4 yr beginning in the fall of 2001 at Lacombe, Alberta, Canada (52°28′N,

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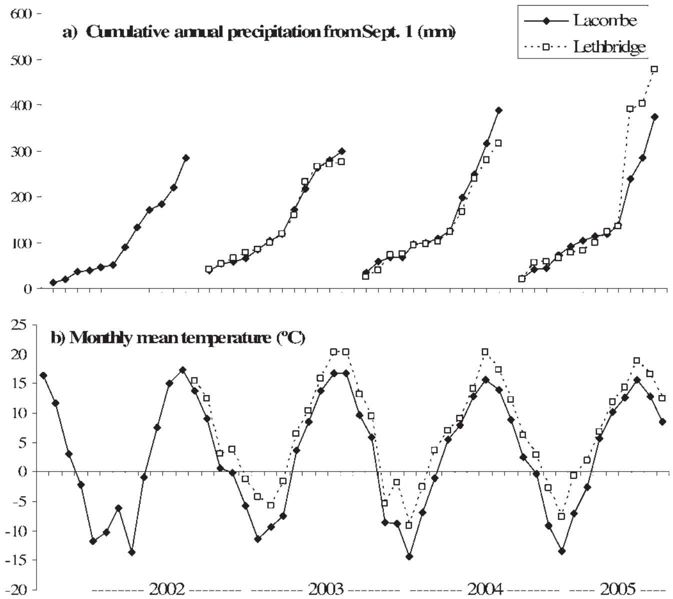

Figure 1. Monthly precipitation and mean temperature at Lacombe and Lethbridge, Canada, 2002 to 2005.

113°44′W) and for 3 yr beginning in the fall of 2002 at Lethbridge, Alberta, Canada (49°38′N, 112°47′W). The year in which crops were harvested is used to designate experiment year in this paper, e.g., the 2002 experiment includes winter cereals planted in 2001 and spring cereals planted in 2002. The experiments at Lacombe were conducted on an Udic Boroll (Orthic Black Chernozem in Canadian system) with loam or clay loam texture, neutral pH (6.7 to 7.4) and high soil organic matter (6 to 11%). The experiments at Lethbridge were conducted on a Typic Boroll (Orthic Dark Brown Chernozem) with clay loam texture, neutral pH (7.5 to 7.9) and moderate soil organic matter (approximately 3%). Long-term average air temperatures are 2.0 C cooler at Lacombe than Lethbridge during the growing season (April to August) and 4.4 C cooler during the winter months (November to March), but snow cover is often absent during winter months at Lethbridge and thus the risk of winterkill is often higher at Lethbridge than at Lacombe. During the period of this study, growing season precipitation (May 1 to July 31) was below normal for the 2002 and 2003 experiments and close to or greater than normal for the 2004 and 2005 experiments (Figure 1). Both locations had been continuously cropped to spring annual crops and managed with no-till practices prior to experiment initiation.

Sites were managed to simulate producer practices under conditions of moderate to high weed pressure. Previous crops were canola (*Brassica napus* L.) at Lacombe and lentil (*Lens culinarus* Medik.) or field pea (*Pisum sativum* L.) at Lethbridge. Weed populations were augmented by broadcasting wild oat (*Avena fatua* L.) seed at 200 seeds/m^2 in mid-October at Lacombe in 2002 and wild oat and canola seed at 100 seeds/m^2 in late fall or early spring at Lethbridge (all years). The natural infestation of weeds was considered to be adequate for the remaining site-years. Each study area was treated with glyphosate a few days prior to seeding at 900 g ae/ha using a motorized sprayer to deliver a carrier volume of 45 L/ha at 275 kPa pressure. All plots received a fall application of 2,4-D at 560 g ae/ha in late September or mid-October to control dicot weeds. Wild oat, tame oat (*Avena sativa* L.), canola, wild buckwheat (*Polygonum convolvus* L.), sow thistle (*Sonchus* spp.), cleavers (*Galium spurium* L.), and hempnettle (*Galeopsis tetrahit* L.) were the most commonly observed weeds at Lacombe; wild buckwheat, redroot pigweed (*Amaranthus retroflexus* L.), flixweed (*Descurainia sophia* L.), kochia (*Kochia scoparia* L.), wild oat, tame oat, canola, and sow thistle were the prominent weeds in Lethbridge.

At each site, a factorial experiment with 11 or 13 cereal types and two herbicide treatments was conducted. Cereal cultivars were selected to represent a broad range of spring and winter cereals. Tall and short cultivars were included for Canada Prairie Spring (CPS) wheat, Canada Western Amber Durum (CWAD) wheat, and all winter cereals because crop height contributes to crop competitiveness (Blackshaw 1994; Lemerle et al. 2001; Mason et al. 2008) and is readily available information (Table 1). Two herbicide treatments were included in the study: partial (fall only) and full (fall and spring) herbicide application. Treatments were arranged in a randomized complete block design with four replicates.

Table 1. Cereal crops evaluated for weed-competitive ability.[a]

Type	Crop	Short cultivar	Tall cultivar
Spring	CWRS wheat	AC Barrie (1994, 101 cm)[b] (common bread wheat variety)	
	Barley	CDC Bold (1999, 67 cm) (two-row general purpose)	Not tested
	Triticale	Not tested	Pronghorn (1995, 109 cm) (dual purpose–grain and forage)
	CPS wheat	Oslo (1987, 79 cm)	AC Crystal (1996, 84 cm)
	CWAD wheat[c]	AC Navigator (2002, 76 cm) (extrastrong gluten strength cultivar)	AC Avonlea (1997, 96 cm) (conventional gluten strength cultivar)
Winter	CWRW wheat	CDC Falcon (1998, 67 cm) (general purpose cultivar; good winter survival)	CDC Osprey (1995, 82 cm) (milling quality cultivar; very good winter survival)
	Triticale	Bobcat (1999, 92 cm) (dual purpose–grain and forage; good winter survival)	Pika (1990, 117 cm) (dual purpose; very good winter survival)
	Rye	AC Rifle (1994, 85 cm)	Prima (1984, 112 cm)

[a] Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; CWAD, Canada Western Amber Durum wheat; CWRW, Canada Western Red Winter wheat.

[b] Year registered, average height in study. Supplementary data was reviewed to verify information in this table (Agriculture and Rural Development. 2009).

[c] Durum wheat not included at Lacombe location as it is not adapted to this agro-climatic area.

High seeding rates were used to maximize crop competitiveness with weeds (O'Donovan et al. 1999): 450 seeds/m^2 (target density of 338 plants/m^2) at Lacombe and 400 seeds/m^2 (target density of 300 plants/m^2) at Lethbridge. All sites were direct-seeded using a ConservaPak air drill with sideband application of recommended rates of fertilizer (45 to 150 kg N/ha, 5 to 45 kg P/ha and 0 to 24 kg K/ha). All fertilizers were applied at seeding for both winter and spring cereals except at Lacombe in 2005, which also received a broadcast application of urea at 58 kg N/ha in early spring (all treatments). Plot size was 4 m by 16 m with an interrow spacing of 0.23 m.

The spring herbicide treatment consisted of a tank mix of clodinafop (56 g ai/ha) and thifensulfuron/tribenuron (15 g ai/ha) or clodinafop (56 g ai/ha), fluroxypyr (144 g ai/ha), and MCPA (560 g ai/ha) for wheat, rye, and triticale, and tralkoxydim (200 g ai/ha), bromoxynil (280 g ai/ha), and MCPA (280 g ai/ha) for barley. Herbicides were applied with a motorized plot sprayer calibrated to deliver 45 L/ha at 275 kPa pressure.

Crop density was determined by counting all crop plants within two areas (two rows by 1 m) within each plot after full crop emergence. In winter wheat plots, counted areas were staked and recounted in the spring to determine winter survival. Weed density was determined by counting all dicot and monocot weeds within two 0.25-m^2 quadrats within each plot between mid-May and mid-June. Aboveground plant biomass was determined by harvesting all plant material from four 0.25-m^2 quadrats in each plot in July or August. Dry weights of crop plants, dicot weeds and monocot weeds were determined separately. At maturity, whole plots were either direct-combined or swathed and then combined when sufficiently dry. Grain yields are reported on a 14% moisture basis.

Data from each site were analyzed using the Mixed procedure of SAS (Release 8.01, SAS Institute Inc., Cary, NC), with cereal type, herbicide treatment, and the interaction of cereal type and herbicide treatment included as fixed effects and block as a random effect. Crop parameters under full herbicide management were analyzed for all years at each location, with cereal type included as a fixed effect and block, year, and the interaction of cereal type and year included as random effects. If required, data were log or square-root transformed to ensure that error terms were normally distributed and variances were homogeneous. However, weed biomass data generally violated these assumptions even when transformed. Assumptions could often be met by analyzing weed biomass data independently for each herbicide treatment. In situations where assumptions were still not met, treatment effects were generally clear and only means and standard errors were estimated. Means were compared with planned contrasts (nonorthogonal) and the Dunnett-Hsu test ($P < 0.05$) or a Protected LSD test ($P < 0.05$).

Table 2. Comparison of crop plant densities among cereal types.

Type[a]	Spring crop plant density						
	Lacombe				Lethbridge		
	2002	2003	2004	2005	2003	2004	2005
	Plants/m^2						
CWRS wheat	320	300	310	240	250	340	250
Barley	400 a	280	330	270	210	390	270
Spring triticale	330	330	290	260	230	330	290
Short CPS wheat	270	270	260 a[b]	220	180 a	400	290
Tall CPS wheat	350	290	280	240	180 a	380	260
Short CWAD wheat	Not tested				240	280	190 a
Tall CWAD wheat					220	360	230
Short CWRW	260 a	420 a	170 a	280	170 a	30 a	170 a
Tall CWRW	210 a	430 a	220 a	200	200 a	70 a	180 a
Short WT	230 a	350 a	190 a	220	160 a	40 a	150 a
Tall WT	280	370 a	190 a	260	150 a	80 a	120 a
Short rye	220 a	360 a	220 a	320 a	180 a	110 a	160 a
Tall rye	230 a	360 a	170 a	290	160 a	80 a	140 a
Spring average	330	290	290	250	220	360	250
Winter average	240	380	190	260	170	70	150
P(type)	***	***	***	***	***	***	***
Standard error	13	14	12	13	12	27	12
Contrasts							
Spring vs. winter	***	***	***	NS	**	***	***
Short vs. tall	*	NS	NS	NS	NS	*	NS
WT vs. CWRW	NS	***	NS	NS	NS	*	NS
Rye vs. CWRW	NS	***	NS	***	***	***	***

[a] For description of cereal types, see Table 1. Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; WT, winter triticale; CWRW, Canada Western Red Winter wheat; CWAD, Canada Western Amber Durum wheat.

[b] Lowercase a indicates that value is significantly ($P < 0.05$, Dunnett-Hsu test) different from spring wheat.

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, NS, not significant.

Results and Discussion

Crop Stand Establishment. Crop plant densities for spring cereals ranged from 180 to 400 plants/m^2, with substantially less than 300 plants/m^2 only obtained at Lethbridge in 2003 (Table 2). These densities were higher than typically present on commercial fields (100 to 200 plants/m^2). The ability of crops to compete with weeds follows a pattern of diminishing improvement with increasing crop density (Mohler 2001). For cereals, most of the increase in competitive ability is obtained at densities less than 200 plants/m^2 (Blackshaw et al. 2000; Lemerle et al. 2004; O'Donovan et al. 1999). Thus, crop plant densities of spring cereals were adequate for effective weed competition, even though target densities of $\geq$ 300 plants/m^2 were not always achieved.

Crop plant densities for winter cereals ranged from 30 to 430 plants/m^2 (Table 2). Crop densities were very low at Lethbridge in 2004 due to poor fall emergence and high rates of winterkill caused by dry fall conditions and limited snow cover. Crop plant densities were exceptionally low for short winter wheat and winter triticale at this site, but were similar among winter cereal types during the remaining site-years. Crop densities are generally lower for winter than spring cereals due to dry soil conditions at seeding and winterkill (Lafond and Fowler 1989). Stand reductions that fall below 140 plants/m^2 for winter cereals will reduce the potential for maximum grain yield (Holen et al. 2001). These factors also tend to reduce stand uniformity (observed in all years at Lethbridge and in 2004 at Lacombe). Thus, weed competitiveness of winter cereals was severely compromised by crop stand at Lethbridge in 2004 and somewhat compromised at

Lacombe in 2004 and Lethbridge in 2003 and 2005. In retrospect, a higher seeding rate should have been used for winter cereals to compensate for overwinter losses. Increased seeding rate improved stand establishment and yield stability in other studies in this region (Beres et al. 2010).

Cereal Type and Herbicide Effects on Weeds. Winter cereals were more effective at reducing dicot weed biomass than were spring cereals at Lacombe (Table 3). The density of dicot weeds was highest in 2002 and was not affected by cereal type. However, dicot weed biomass was lower for barley and all winter cereals except short winter wheat compared with Canada Western Red Spring (CWRS) wheat. Rye had negligible dicot weed biomass, compared with other treatments. Spring-applied herbicide reduced dicot weed biomass to zero for winter cereals and barley, and to very low levels for spring wheat and triticale. In 2003, dicot weed biomass in the partial herbicide treatment was higher in short CPS wheat and lower in tall winter cereals, compared to CWRS wheat. Dicot weed biomass was negligible in the full herbicide treatment. Dicot weeds were at low levels in 2004, with appreciable biomass only obtained for short CPS wheat in the partial herbicide treatment. The density of dicot weeds was also quite low in the spring of 2005, but biomass was significantly greater than zero in all treatments, with only modest impact of cereal type or herbicide treatment. Overall, rye was the most effective cereal type for reducing dicot biomass, followed by winter triticale, but neither was highly effective in 2005. Barley was the most effective spring cereal for suppressing dicot weeds.

Similar to dicot weeds, monocot weeds (predominantly wild oat) were more effectively reduced by winter than spring cereals at Lacombe in all years except 2005 (Table 3). Monocot weeds were absent or at very low levels in winter cereals in 2002 and 2003, but were significantly greater than zero for most of the spring cereals in the partial herbicide treatment. In 2004, monocot weed biomass in the no–spring-herbicide treatment was also low for winter triticale and rye, significantly less than that for winter wheat. Short CPS wheat had greater monocot weed biomass than CWRS wheat in the partial herbicide treatment, and was the only cereal type with appreciable monocot weed biomass in the full herbicide treatment. In 2005, the density of monocot weeds was lower for winter triticale and rye than for CWRS wheat, and monocot weed biomass was lower for winter triticale and rye than for winter wheat. Winter wheat cultivars had among the highest levels of monocot weed biomass, with or without spring herbicide. Spring herbicide application was not highly effective at reducing monocot weed biomass, with only a statistically weak ($P < 0.1$, not presented in Table 3) reduction in monocot weed biomass with spring herbicide application for spring triticale, tall CPS wheat, and short winter wheat.

The maximum density of dicot weeds at Lethbridge was only about one-third of that at Lacombe, whereas the maximum biomass of dicot weeds at Lethbridge never exceeded 86 kg/ha, substantially lower than at Lacombe (Tables 3 and 4). Dicot weed biomass in the partial herbicide treatment was greater for short CPS wheat and short winter wheat than for other cereal types in 2003 and 2005. In 2004, dicot weed biomass was generally greater for winter than for spring cereals.

Monocot weeds at Lethbridge were at low levels in 2003 and at high levels in 2004 and 2005 (Table 4). Only short winter wheat had appreciable biomass of monocot weeds in 2003. In 2004, the density of monocot weeds was high for spring cereal crops and very low for winter cereals. However, the average monocot weed biomass in the partial herbicide treatment was greater with winter than with spring cereals, with the greatest biomass in the treatments with the poorest crop stands—short winter wheat and short winter triticale. Monocot weeds emerged in winter cereals after density counts were completed (May 17) and achieved high biomass due to poor crop stands. Herbicide application substantially reduced monocot weed biomass in spring cereals, but not in winter cereals, which was attributed to the importance of crop competition for herbicide efficacy (Blackshaw et al. 2006). In 2005, monocot weed biomass was not strongly affected by cereal type or herbicide treatment, but was less for tall than for short cultivars with or without spring herbicide application and less for spring than for winter cereals with spring herbicide application.

Overall, weed suppression by winter cereals was generally less than by spring cereals at Lethbridge. However, tall winter triticale and rye had similar weed suppression to spring cereals. Early seeding dates for spring cereals in 2004 and 2005 likely contributed to effective weed suppression by spring cereals at Lethbridge.

Relative Weed-Competitive Ability. Relative weed biomass was calculated at each site (average/maximum biomass in the partial herbicide treatment) to compare the effectiveness and consistency of different cereal types in the suppression of weeds (Figure 2). In general, cereal types affected dicot and monocot weeds similarly: short CPS wheat and short winter wheat were ineffective at suppressing either dicot or monocot weeds (average relative biomass > 0.5), tall winter triticale and rye were effective at suppressing both dicot and monocot weeds (average relative biomass ≤ 0.15), and CWRS wheat, tall CPS wheat, and short winter triticale were moderately effective at suppressing both dicot and monocot weeds (average relative biomass 0.18 to 0.34). Barley and spring triticale were highly effective at suppressing dicot weeds, but only moderately effective at suppressing monocot weeds.

Few studies have compared the competitive ability of winter and spring cereals. In the United Kingdom, Thurston (1962) found that winter cereals (rye or wheat) controlled wild oat more effectively than spring barley due to establishment of a dense crop stand in early spring that reduced the growth of wild oat seedlings. The effective control of weeds by winter cereals at Lacombe in 2002, 2003, and 2004 can be attributed to a similar mechanism. Poor weed control at Lethbridge was primarily due to poor crop stands, and thus was also consistent with the same mechanism. Effectiveness and reliability of winter cereals at weed suppression may be improved by use or development of more winter-hardy cultivars, optimum seeding practices, and high seeding rates (Beres et al. 2010).

The ranking in weed-competitive ability among spring or winter cereal types was generally consistent with previous

Table 3. Effect of cereal type on weed plant density and biomass in the partial and full herbicide treatments at Lacombe.[a]

Type	2002 Weed density	2002 Biomass Partial	2002 Biomass Full	2003 Weed density	2003 Biomass Partial	2003 Biomass Full	2004 Weed density	2004 Biomass Partial	2004 Biomass Full	2005 Weed density	2005 Biomass Partial	2005 Biomass Full
	No./m^2	kg/ha	kg/ha	No./m^2	kg/ha	kg/ha	No./m^2	kg/ha	kg/ha	No./m^2	kg/ha	kg/ha
Dicot weeds												
CWRS wheat	203	1,086	29 ± 8[b]	68	64	0	4 ± 1	1 ± 1	4 ± 4	5	188	39
Barley	233	210 a[c]	0	65	55	0	3 ± 1	0	0	3	64	62
Spring triticale	198	601	7 ± 4	52	32	0	8 ± 3	2 ± 2	0	10	22	35
Short CPS wheat	234	2,218	93 ± 32	62	921 a	10 ± 6	6 ± 2	533 ± 330	36 ± 22	5	285	51
Tall CPS wheat	202	823	15 ± 9	46	97	3 ± 3	7 ± 2	31 ± 24	0	9	406	149
Short CWRW	215	267	1 ± 1	226 a	33	1 ± 1	3 ± 1	1 ± 1	0	5	281	84
Tall CWRW	242	201 a	0	92	4 a	2 ± 1	3 ± 1	25 ± 12	0	9	354	37
Short WT	255	60 a	0	96	14	0	2 ± 1	0	3 ± 2	3	373	121
Tall WT	215	54 a	0	69	2 a	0	1 ± 0	0	0	4	100	12
Short rye	190	6 a	0	124	5	0	2 ± 0	9 ± 9	1 ± 1	2	36	58
Tall rye	337	1 a	0	132	2 a	0	3 ± 1	0	0	2	125	50
Spring average	213	758	29	58	101	3	6	113	8	6	125	58
Winter average	238	37	0	115	6	1	2	6	1	4	160	49
Transformation	Log10(x + 1)		ND	Log10(x + 1)		ND	ND	ND	ND	Log10(x + 1)		
P (type)	NS	***	ND	*	***	ND	ND	ND	ND	**	*	NS
Standard error[c]	0.07	0.19	ND	0.16	0.32	ND	ND	ND	ND	0.11	0.25	0.27
Contrasts												
Spring vs. winter	NS	***	ND	***	***	ND	ND	ND	ND	*	NS	NS
Short vs. tall	NS	*	ND	NS	***	ND	ND	ND	ND	*	NS	NS
WT vs. WW	NS	**	ND	NS	NS	ND	ND	ND	ND	NS	NS	NS
Rye vs. WW	NS	***	ND	NS	NS	ND	ND	ND	ND	**	*	NS
Monocot weeds												
CWRS wheat	6 ± 2	64 ± 13	12 ± 8	6	20	0	11	149	7 ± 7	51	616	182
Barley	6 ± 1	0 ± 0	0	5	42	3 ± 3	8	78	0	46	382	77
Spring triticale	8 ± 1	49 ± 5	0	3	13	0	7	85	0	81	850	209
Short CPS wheat	9 ± 2	109 ± 19	17 ± 11	4	69	0	12	865 a	127 ± 75	75	757	558
Tall CPS wheat	11 ± 3	155 ± 45	5 ± 4	4	4	0	9	148	0	39	698	111
Short CWRW	1 ± 1	3 ± 3	0	4	4	2 ± 2	4	233	0	19	1,895	848
Tall CWRW	0	0	0	4	4	19 ± 13	5	88	0	20	507	1,004
Short WT	0	0	0	3	5	0	5	8	0	11 a	409	749
Tall WT	0	0	0	2	1	0	3 a	0	0	9 a	104	162
Short rye	0	0	0	2	1	0	3 a	3	0	9 a	254	432
Tall rye	1 ± 0	0	0	3	3	0	8	1	0	4 a	204	131
Spring average	8	75	7	4	21	1	9	207	27	56	650	201
Winter average	0	1	0	3	3	3	4	28	0	11	446	492
Transformation	ND	ND	ND	Log10(x + 1)		ND	Log10(x + 1)	Sqrt(x + 0.5)	ND	Log10(x + 1)	Sqrt(x + 0.5)	
P (type)	ND	ND	ND	NS	NS	ND	**	***	ND	***	*	**
Standard error[d]	ND	ND	ND	0.22	0.44	ND	0.12	3.4	ND	0.17	6.3	4.8
Contrasts												
Spring vs. winter	ND	ND	ND	NS	**	ND	***	***	ND	***	NS	**
Short vs. Tall	ND	ND	ND	NS	NS	ND	NS	*	ND	NS	NS	*
WT vs. CWRW	ND	ND	ND	NS	NS	ND	NS	**	ND	NS	**	*
Rye vs. CWRW	ND	ND	ND	NS	NS	ND	NS	**	ND	**	**	**

[a] For type descriptions, see Table 1. Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; WT, winter triticale; CWRW, Canada Western Red Winter wheat; CWAD, Canada Western Amber Durum wheat; ND, not determined; Sqrt, square root.

[b] Mean ± standard error.

[c] Lowercase a indicates that value is significantly ($P < 0.05$, Dunnett-Hsu test) different from spring wheat.

[d] Standard error of transformed data.

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, NS, not significant.

Table 4. Effect of cereal type on weed plant density and biomass in the partial and full herbicide treatments at Lethbridge.[a]

Type	2003			2004			2005		
		Biomass			Biomass			Biomass	
	Weed density	Partial	Full	Weed density	Partial	Full	Weed density	Partial	Full
	No./m^2	kg/ha		No./m^2	kg/ha		No./m^2	kg/ha	
Dicot weeds									
CWRS wheat	28	0	0	31	5	2 ± 1[b]	19 ± 4	23 ± 13	2 ± 2
Barley	17	0	0	34	1	1 ± 1	7 ± 2	1 ± 1	0
Spring triticale	58	6	4 ± 4	30	3	2 ± 2	9 ± 1	0	0
Short CPS wheat	48	27	0	36	10	6 ± 5	11 ± 3	44 ± 24	1 ± 1
Tall CPS wheat	39	5	0	41	1	0	11 ± 3	0	0
Short CWAD wheat	18	2	0	26	10	0	13 ± 4	26 ± 13	0
Tall CWAD wheat	25	1	0	28	7	5 ± 3	13 ± 3	11 ± 2	0
Short CWRW	123 a[c]	44 a	2 ± 2	6 a	39	11 ± 10	3 ± 1	86 ± 22	6 ± 3
Tall CWRW	49	22	0	5 a	41	7 ± 7	1 ± 1	5 ± 5	18 ± 9
Short WT	74	0	10 ± 10	6 a	18	16 ± 15	1 ± 0	0	4 ± 1
Tall WT	106	3	0	7 a	14	5 ± 2	0	1 ± 1	3 ± 2
Short rye	72	3	3 ± 2	4 a	33	13 ± 11	1 ± 0	0	0
Tall rye	87	2	0	4 a	7	11 ± 6	1 ± 1	0	0
Spring average	30	3	1	32	4	2	12	15	0
Winter average	82	5	3	5	22	10	1	15	5
Transformation	Log10(x + 1)		ND	Log10(x + 1)		ND	ND	ND	ND
P(type)	***	*	ND	***	NS	ND	ND	ND	ND
Standard error[d]	0.16	0.37	ND	0.16	0.47	ND	ND	ND	ND
Contrasts									
Spring vs. winter	***	NS	ND	***	***	ND	ND	ND	ND
Short vs. Tall	NS	NS	ND	NS	NS	ND	ND	ND	ND
WT vs. CWRW	NS	**	ND	NS	NS	ND	ND	ND	ND
Rye vs. CWRW	NS	**	ND	NS	NS	ND	ND	ND	ND
Monocot weeds									
CWRS wheat	1 ± 1	0	0	129	547	5	67	937	487
Barley	1 ± 1	0	0	178	255	9	40	493	416
Spring triticale	0	0	0	162	665	6	59	1,056	742
Short CPS wheat	0	0	0	197	728	55	61	2,002	827
Tall CPS wheat	0	0	0	157	765	16	67	1,344	622
Short CWAD wheat	1 ± 1	0	0	178	509	21	51	3,159	1,381
Tall CWAD wheat	0	0	0	189	689	31	45	1,607	702
Short CWRW	0	114 ± 27	0	1 a	2,541	2,274 a	66	2,625	1,920 a
Tall CWRW	1 ± 1	7 ± 4	0	2 a	1,450	792 a	60	1,868	1,277
Short WT	1 ± 1	0	2 ± 2	3 a	2,205	1,340 a	66	2,576	1,472
Tall WT	4 ± 1	1 ± 1	4 ± 3	3 a	370	330 a	84	492	772
Short rye	4 ± 1	1 ± 1	1 ± 1	3 a	527	400 a	31	1,241	1,248
Tall rye	3 ± 1	0	2 ± 1	2 a	414	400 a	40	1206	666
Spring average	0	0	0	169	564	15	55	1,311	691
Winter average	2	21	1	2	933	710	55	1,450	1,150
Transformation	ND	ND	ND	Log10(x + 1)			Log10(x + 1)		
P(type)	ND	ND	ND	***	*	***	NS	**	*
Standard error[d]	ND	ND	ND	0.14	0.17	0.32	0.11	0.15	0.13
Contrasts									
Spring vs. winter	ND	ND	ND	***	*	***	NS	NS	**
Short vs. Tall	ND	ND	ND	NS	NS	NS	NS	**	**
WT vs. CWRW	ND	ND	ND	NS	NS	NS	NS	NS	NS
Rye vs. CWRW	ND	ND	ND	NS	**	NS	*	NS	NS

[a] For type descriptions, see Table 1. Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; WT, winter triticale; CWRW, Canada Western Red Winter wheat; CWAD, Canada Western Amber Durum wheat; ND, not determined.

[b] Mean ± standard error.

[c] Lowercase a indicates that value is significantly ($P < 0.05$, Dunnett-Hsu test) different from spring wheat.

[d] Standard error of transformed data.

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, NS, not significant.

studies: rye > barley ≥ wheat (Blackshaw et al. 2007). The competitive ability of triticale varied in this study: tall winter triticale paralleled rye, but short winter triticale was similar to tall CPS wheat; spring triticale was similar to wheat for monocot suppression but had superior dicot suppression (similar to tall winter triticale and tall rye). In Australia, the competitive ability of triticale was similar to rye (Lemerle et al. 1995).

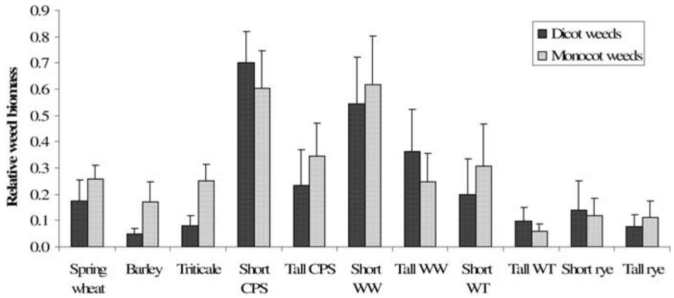

Figure 2. Effect of cereal type on average relative biomass (average/maximum at each site-year) of dicot and monocot weeds at Lacombe and Lethbridge, Canada, 2002 to 2005. CPS, Canada prairie spring; WW, winter wheat; WT, winter triticale. Error bars are standard errors.

Where differences due to cultivar height were evident, short cultivars were less competitive than tall cultivars, a result similar to other studies (Blackshaw 1994; Harker et al. 2009; Lemerle et al. 2001; Mason et al. 2008). However, rye cultivars had the greatest difference in height, but similar levels of weed suppression. CPS wheat cultivars had the least difference in height, but the largest difference in weed suppression. Barley was the shortest crop in this study, but was among the most effective crops for weed suppression. These observations indicate that crop characteristics other than height were more important for competitive ability. Mason et al. (2008) found that cultivar height of spring wheat cultivars accounted for a small amount of variation in low-weed environments, but increased in importance as weed pressure increased. Wicks et al. (1986) found that although a higher proportion of tall than short cultivars of winter wheat were good competitors with weeds, some of the shortest cultivars were among the most competitive. Bertholdsson (2005) found that early crop biomass and potential allelopathic activity were the only parameters that significantly contributed to competitiveness of barley and wheat cultivars. Vigorous early growth, root competitiveness, and allelopathy all contribute to crop competitive ability (Lemerle et al. 2001).

The greater effectiveness of barley and spring triticale to suppress dicot weeds than monocot weeds indicates that the mechanism by which these crops suppress weeds was more effective for dicot than for monocot weeds. One possibility is that the establishment of a dense crop stand in early spring may be more important for suppression of monocot weeds than dicot weeds. Vigorous early growth by spring cereals such as barley and spring triticale may only be partially effective at suppressing monocot weeds, relative to winter cereals.

Yield and Yield Components. Many crop characteristics contribute to yield potential and weed-competitive ability. A cereal type or cultivar with higher than average values for number of spikes, number of kernels per spike, and kernel weight should consistently produce the highest grain yield (Duggan and Fowler 2006). Spring wheat cultivars generally had fewer spikes per m^2, slightly more kernels per spike, and lower kernel weight than barley, which resulted in generally lower grain yields for spring wheat cultivars than for barley at Lacombe but similar grain yields at Lethbridge (Table 5). Barley typically has more spikes per m^2 than spring wheat, which results in earlier canopy closure to light penetration and a subsequent increase in competitiveness with weeds (Lanning et al. 1997). However, most of the variation in competitive ability among wheat and barley cultivars is due to differences in early plant vigor and allelopathic activity (Bertholdsson 2005). Triticale cultivars had among the greatest number of kernels per spike, which contributed to high grain yields for spring triticale. This feature appears critical for the high grain yield observed for most of the triticale cultivars as other yield components such as spikes per plant for spring triticale or spikes per m^2 for all triticale cultivars were lower than the other cereal types. Winter triticale had poor winter survival, particularly for the short cultivar at Lethbridge (Table 2), and low kernel weight, which contributed to low or intermediate grain yields (Table 5). Winter wheat (CWRW) produced more kernels per spike than spring wheat, and had a higher or similar harvest index, which resulted in higher grain yields for CWRW than for CWRS spring wheat at Lacombe. Grain yields for CWRW and CWRS were similar at Lethbridge but grain yields of the tall CWAD and CPS cultivars were higher at Lethbridge. Entz and Fowler (1991) reported consistently higher yields for winter wheat over spring wheat and attributed the performance to higher kernel weight, harvest index, and kernels per unit area. However, abiotic stress was more evident in our study as kernel weight was similar or greater for spring wheat, but this only occurred in one site-year of the Entz and Fowler (1991) study. Rye cultivars had low to intermediate grain yields, but high competitive ability, which was associated with high density of spikes per m^2, intermediate number of kernels per spike and low kernel weight. Early plant vigor and allelopathic activity also contribute to the competitive ability of rye (Blackshaw et al. 2007; Lemerle et al. 2001).

Grain yields of winter cereals at Lacombe were intermediate to those of spring wheat and spring triticale (Table 5). Grain yields were similar for spring and winter cereals at Lethbridge. However, the effect of cereal types on grain yield were strongly affected by year at Lethbridge: grain yields of winter cereals were about 50% higher than that of spring cereals in 2003, but about 25% lower in 2004 and 2005 (data not presented). Entz and Fowler (1991) found that winter wheat generally out-yielded spring wheat because early spring growth improved water use efficiency and crop growth duration. The substantial yield benefit of winter cereals at Lethbridge in 2003 was likely due to the same factors, but poor crop stands and ineffective monocot weed control reduced grain yield of winter cereals in 2004 at Lethbridge, whereas cooler temperatures at Lacombe and high growing-season precipitation in 2005 at Lethbridge likely reduced the potential water use efficiency and crop growth duration benefits.

Grain yield responses to herbicide treatment depended on both site and cereal type (Table 6). For spring cereals at Lacombe, spring-applied herbicide provided the largest and most consistent benefit for short CPS wheat and the least benefit for barley. Spring-applied herbicide did not significantly increase grain yield of winter cereals except for short winter wheat in 2005. At Lethbridge, spring-applied herbicide did not increase grain yield in 2003 because of limited weed pressure. In 2004 and 2005, some cereal types were not

Table 5. Effect of cereal type on yield components and grain quality in the full herbicide treatment.[a]

Cereal type[b]	Spikes		Kernels		Grain yield	Harvest index	Total biomass	Test weight	Crude protein
	Per plant	Per m^2	Per spike	mg/kernel	t/ha		t/ha	kg/hL	%
Lacombe									
CWRS wheat	2.0	532	26	36	4.5	0.40	9.5	78.7	14.6
Barley	2.1	626	24	47	6.1	0.51	10.4	66.7	12.9
Spring triticale	1.4	395	42	43	7.1	0.50	11.8	67.2	10.5
Short CPS wheat	1.8	419	35	35	5.0	0.47	9.0	72.4	13.4
Tall CPS wheat	1.7	440	36	37	5.2	0.44	10.2	73.8	12.2
Short CWRW	1.8	561	33	31	5.6	0.52	9.1	79.7	12.1
Tall CWRW	1.9	561	31	31	5.5	0.45	10.5	79.3	12.1
Short WT	1.5	376	47	33	5.5	0.47	10.3	68.2	10.3
Tall WT	1.5	373	43	37	5.3	0.38	12.2	68.1	10.4
Short rye	2.4	680	30	27	4.9	0.45	9.5	69.9	9.1
Tall rye	2.1	567	36	29	5.1	0.41	11.2	71.4	8.2
Standard error	0.2	39	3	1	0.3	0.02	0.6	0.9	0.5
$LSD_{P = 0.05}$	0.5	108	10	2	0.9	0.04	1.7	2.5	1.4
Lethbridge									
CWRS wheat	2.2	541	27	34	5.1	0.38	11.5	78.4	15.6
Barley	2.4	685	22	44	5.7	0.44	11.7	67.8	13.9
Spring triticale	1.4	384	34	40	5.2	0.38	13.2	68.8	11.2
Short CPS wheat	2.0	527	30	34	5.0	0.41	10.6	74.3	13.5
Tall CPS wheat	2.0	484	31	37	5.6	0.41	12.7	76.7	13.3
Short CWAD wheat	2.0	382	27	44	4.4	0.43	10.2	79.4	14.5
Tall CWAD wheat	2.0	490	26	43	5.3	0.41	11.3	77.5	15.4
Short CWRW	4.4	621	29	29	4.2	0.47	7.2	76.7	12.7
Tall CWRW	3.1	511	31	33	4.3	0.41	9.5	78.6	13.1
Short WT	3.2	430	36	31	3.3	0.36	8.6	66.3	12.3
Tall WT	3.6	441	32	38	4.0	0.30	12.0	68.5	12.1
Short rye	3.2	577	28	30	3.3	0.36	10.8	71.8	9.4
Tall rye	3.8	523	30	30	3.6	0.34	10.7	72.4	9.2
Standard error	0.3	42	2	2	0.2	0.03	0.9	0.4	0.2
$LSD_{P = 0.05}$	0.8	117	6	6	0.7	0.08	2.6	1.3	0.7

[a] For type descriptions, see Table 1. Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; WT, winter triticale; CWRW, Canada Western Red Winter wheat; CWAD, Canada Western Amber Durum wheat; ND, not determined.

[b] Cereal type was highly significant ($P < 0.001$) for all response variables described in this table.

Table 6. Response of grain yield to spring herbicide application.[a]

Type	Increase in grain yield due to spring herbicide application						
	Lacombe				Lethbridge		
	2002	2003	2004	2005	2003	2004	2005
	% of treatment receiving only fall 2,4-D (no spring herbicide application)						
CWRS wheat	16	13	−1	7	−20	26	42 a[b]
Barley	6	−4	0	16	−3	16	38 a
Spring triticale	12	0	11 a	34 a	−8	59 a	26 a
Short CPS wheat	13	27 a	19 a	28	−1	31	41 a
Tall CPS wheat	21	9	2	8	−1	51 a	36 a
Short CWAD wheat	Not tested				−12 a	73 a	60 a
Tall CWAD wheat	Not tested				−4	28 a	43 a
Short CWRW	−7	−4	6	40 a	−5	169 a	13
Tall CWRW	9	−13	2	14	−4	55 a	33 a
Short WT	7	−4	2	1	3	6	14
Tall WT	9	1	1	7	−8	−17	6
Short rye	−4	−3	0	4	12	22	3
Tall rye	2	0	5	5	1	−1	−13
Average	7 a	1	4 a	15 a	−4	31 a	26 a

[a] Abbreviations: CWRS, Canada Western Red Spring wheat; CPS, Canada Prairie Spring wheat; WT, winter triticale; CWRW, Canada Western Red Winter wheat; CWAD, Canada Western Amber Durum wheat.

[b] Lowercase a indicates significant change ($P < 0.05$, *t* test).

affected by spring herbicide treatment (tall winter triticale, tall rye), but others had substantial gains in grain yield due to a spring herbicide treatment (spring cereals, winter wheat). These responses are consistent with previous studies that found that more competitive crops are less likely to have a yield benefit from herbicides or to suffer yield losses if herbicides are applied at reduced rates or eliminated (Beres et al. 2010; Blackshaw et al. 2006). Spring herbicide application also increased the density of spike and total crop dry matter, but had little or no impact on kernel number, kernel weight, test weight, or grain protein concentration (data not presented).

Crop Quality and End-Use Suitability. The CWAD, CWRS, and milling-type winter wheat cultivars are bred for high grain protein concentration, kernel weight, and grain volume weight (test weight). The tall CWAD and CWRS cultivars produced similar yields, test weights, and protein levels, and displayed similar competitive ability with weeds at Lethbridge.

Spring triticale and tall winter triticale had the highest biomass yields (Table 5) concomitant with high competitive ability with weeds, which positions this as the cereal type with the greatest potential for production of silage or cellulosic ethanol.

Grain from soft white spring wheat and, to a lesser extent, CPS and CWRW wheat, is the preferred feedstock for current bioethanol production on the Canadian prairies because of high starch content and grain volume weight; and lower grain protein concentration (Table 5). Triticale and rye also have low grain protein concentrations, but there is currently low industry uptake because of concerns of ergot susceptibility and high viscosity mash during fermentation processes. Further study is required to determine the potential of these crops for bioethanol production.

Potential exists to obtain superior weed suppression and productivity with winter cereals on the Canadian prairies. However, good crop establishment will be critical for effective weed suppression and high crop productivity, particularly in regions with inconsistent snow cover. Benefits of winter cereals would be enhanced by improvements in winter survival through cultivar development and agronomic practice. The effectiveness of dense stands of competitive crops to suppress weeds was often high, but still varied from year to year due to environmental impacts on weed and crop growth. Multiple tactics and strategies in addition to crop competition will be required to achieve stable crop production under variable environmental and weed population conditions.

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