Altering the competitiveness of tame oat (Avena sativa L.) versus wild oat (Avena fatua L.) with phosphorus and seeding rate

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ARTICLE

Altering the competitiveness of tame oat (*Avena sativa* L.) versus wild oat (*Avena fatua* L.) with phosphorus and seeding rate

W.E. May

Abstract: Currently, no in-crop herbicide is registered to control wild oat (*Avena fatua* L.) in tame oat (*Avena sativa* L.). Wild oat must be controlled in tame oat using other agronomic practices. The objective of this research was to determine if side-banded phosphorus (P) in combination with seeding rate would increase the competitiveness of tame oat with wild oat, increasing yield and quality. An experiment was conducted from 2003–2005 at Indian Head, SK. The experimental design was a strip-plot design with four replications. The strips were low and high wild oat density. A two-way factorial, seeding rate (150, 250, 350, and 450 plants m^{-2}), and P rate (0, 15, and 30 kg P_2O_5 ha^{-1}) were seeded across the strips. Phosphorus affected seed density, grain yield, oat biomass, and wild oat fecundity. Seeding rate affected most of the measured variables and interacted with wild oat and year. The application of P increased the competiveness of oat by increasing crop biomass by 7.6% and grain yield by 3.4% and decreasing wild oat seed from 1.26% to 0.76% in the harvested grain. Wild oat decreased grain yield by 23% in 2003, 4.4% in 2004, and 11% in 2005. Increasing the seeding rate increased grain yield by 5% when wild oat was present. Wild oat did not interfere with the uptake of side-banded P. Producers need to use both P fertilization and higher seeding rates to improve the competitiveness of tame oat and the management of wild oat in tame oat.

Key words: Avena sativa, *Avena fatua*, phosphorus, seeding rate, biomass, grain yield.

Résumé : Aucun herbicide n'est actuellement homologué pour lutter contre la folle avoine (*Avena fatua* L.) dans les champs d'avoine (*Avena sativa* L.). Les agriculteurs doivent donc recourir à d'autres moyens pour combattre l'adventice. Les auteurs voulaient déterminer si l'application de phosphore (P) en bandes latérales et la densité des semis permettraient à l'avoine de mieux concurrencer la folle avoine, donc en rehausserait le rendement et la qualité. Dans cette optique, ils ont procédé à une expérience à Indian Head en 2003, 2004 et 2005. Le protocole expérimental consistait en une parcelle linéaire répétée quatre fois, avec une densité faible ou élevée de folle avoine. Les parcelles ont été ensemencées selon un plan bifactoriel incluant la densité des semis (150, 250, 350 et 450 plants par m^2) et le taux d'application de l'engrais P (0, 15 et 30 kg de P_2O_5 par hectare). Le phosphore affecte la densité des semis, le rendement grainier, la biomasse de l'avoine et la fécondité de la folle avoine. La densité des semis affecte la plupart des variables analysées et interagit avec la folle avoine et l'année. L'application d'engrais P rend l'avoine plus compétitive en accroissant sa biomasse de 7,6 % et son rendement grainier de 3,4%, ce qui réduit la proportion de semences de folle avoine dans le grain de 1,26 à 0,76 %. La folle avoine a diminué le rendement grainier de 23 % en 2003, de 4,4 % en 2004 et de 11 % en 2005. En présence de folle avoine, augmenter la densité des semis a accru le rendement grainier de 5 %. La folle avoine n'a pas nui à l'absorption du P appliqué en bandes latérales. Les agriculteurs devraient recourir aux engrais P et à des semis plus denses pour rendre l'avoine plus compétitive et mieux lutter contre la folle avoine dans leurs champs. [Traduit par la Rédaction]

Mots-clés : Avena sativa, *Avena fatua*, phosphore, densité des semis, biomasse, rendement grainier.

Introduction

Weed surveys found that wild oat was the second-ranked weed for western Canada (Leeson et al. 2005). Traditionally, tillage in combination with delayed seeding has been used to control wild oat (*Avena fatua* L.) in tame oat (*Avena sativa* L.). Research in oat captured the

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importance of early seeding to optimise yield and quality (May et al. 2004); however, early seeding requires that any flush of wild oat emerging as the tame oat emerges must be controlled using agronomic practices as no in-crop herbicide is registered to control wild oat in tame oat. High seeding rates are important for suppressing wild oat in barley (*Hordeum vulgare* L.) (O'Donovan et al. 1999), common wheat (*Triticum aestivum* L.) (Carlson and Hill 1985), and canola (*Brassica napus* L.) (O'Donovan et al. 2004). May et al. (2009) found that high seeding rates reduced the seed and biomass production of wild oat and increased the grain yield of tame oat.

The yield response of oat to phosphorus (P) has always been tested in a weed-free environment (Mohr et al. 2007). Phosphorus banded near the seed has promoted early-season growth in cereals (Grant et al. 2001) and Berkenkamp et al. (1984) found that in oat, forage yield was more responsive to P than grain yield. Therefore, P fertilizer may increase early-season growth, making the oat crop more competitive with wild oat and resulting in higher yield and quality.

The addition of P can also affect the competitiveness of wild oat. The addition of P fertilizer increased weed seed production in wheat with cereal crops (Godel 1938). Blackshaw et al. (2004) found in a pot experiment that wild oat absorbed a larger percentage of applied P than wheat and, in a follow-up study, Blackshaw and Molnar 2009 found that the presence of wild oat reduced the positive yield response in wheat from P fertilizer. However, wild oat and tame oat are closely-related species and placing the P in a band near the seed row may give the advantage to the tame oat for exploiting the added P fertilizer.

Godel (1938), using the agronomic cropping system of the time, reported that combining increased seeding rates with P fertilizer improve the control of wild oat in tame oat. Therefore, it is important to determine under the current cropping system if P fertilizer can be combined with increased seeding rates to improve the grain yield of tame oat and the competitiveness of tame oat with wild oat. The objective of this research was to determine if side-banded P in combination with seeding rate would increase the competitive ability, quality, and yield of tame oat in the presence of wild oat in the field.

Materials and Methods

The study was conducted at Indian Head, SK, (50°33′08.37″N, 103°38′39.82″W, elevation 579 m) in 2003, 2004, and 2005. The soil type was an Indian Head heavy clay (Rego Black Chernozem). The plot area had low levels of available P in the soil with 14, 20, and 19 kg P ha^{-1} in 2003, 2004, and 2005, respectively. The experimental design was a strip-plot design with four replications. The strips were two wild oat treatments, weed-free and high-density, with target densities of 0 plants m^{-2} for the weed-free treatment and 100 plants m^{-2} for the high-density treatment. The two wild oat treatments were randomized for each replication. Tame oat was seeded perpendicular to the direction of the wild oat, resulting in a factorial (seeding rate and P rate) strip-plot randomized complete block experimental design. The four seeding rate treatments were 150, 250, 350, and 450 plants m^{-2} and the three P rates were 0, 15, and 30 kg P_2O_5 ha^{-1}.

Wild oat was seeded as early as possible each spring, late April to early May. The wild oat was obtained from the Scott Research Farm and was free of herbicide-resistant mutations (E.N. Johnson, personal communication, University of Saskatchewan, Saskatoon, SK). The seeding date of the tame oat was 15 May 2003, 17 May 2004, and 5 May 2005. Wild and tame oats were seeded directly into standing stubble with a no-till seed drill with hoe-type openers. The wild oat was seeded in one direction and later the tame oat was seeded in a perpendicular direction through both the plots with and without wild oat. Seeding rates were adjusted for germination percentage and an estimated field mortality of 20% was used to arrive at the desired plant densities. The cultivar 'Kaufmann' was used in all 3 yr (Kibite et al. 2003). 'Kaufmann' is a high-yielding milling oat cultivar developed by Agriculture and Agri-Food Canada with improved lodging and disease resistance, and reduced thin seed. Combined with a small increase in height, these improvements made it a suitable cultivar to use in this study. All the fertilizer was side-banded 2.5 cm to the side and 5 cm below the seed. The row spacing for the tame oat was 30 cm. The plot size was 42 m^2 with a length of 11.7 m and a width of 4 m. The previous crops were canola in 2003 and 2005 and wheat in 2004. The source of P was monoammonium phosphate (11–52–0–0). The target level of total nitrogen (N), a combination of residual soil nitrate (0–60 cm soil layer) and fertilizer N, was 80 kg ha^{-1}. Potassium (K) and sulfur (S) were applied according to soil test recommendations. Glyphosate was applied before seeding at 450 g acid equivalent (a.e.) ha^{-1}. All in-crop broadleaf herbicide applications were determined according to weed species and density. Excellent broadleaf weed control was achieved.

Data collection

Soil tests were carried out each year for N, P, K, S, and chlorine (Cl). Spring soil test levels of NO_3-N and SO_4-S were measured to a depth of 60 cm; soil residual phosphate (PO_4-P) and K were measured to a depth of 15 cm. A $NaHCO_3$ extraction procedure (Hamm et al. 1970) was used to estimate residual soil N (NO_3), P, and K.

Oat plant populations were determined 3–5 wk after seeding and oat panicles were counted after panicle emergence. Both plants and panicles of the tame oat were measured in two 1-m sections of the crop row within each plot. Wild oat was counted in eight 0.28-m^2 areas. Tame and wild oat panicle density were measured after the tame oat had headed but before the wild oat seeds had shattered and at the same time, wild and tame oat biomass were collected from the same quadrats. Physiological maturity was reached when kernel moisture was approximately 30%–35%. Lodging was rated in each plot at physiological maturity using a 1–9 scale (1 = standing, 9 = completely lodged). The entire plot was harvested. Each sample was cleaned using a dockage tester as specified by the Official Grain Grading Guide (Canadian Grain Commission 2016). Grain yield was expressed on a clean grain basis with 13% kernel moisture. Kernel weight, expressed as grams per 1000 seeds, was calculated by weighing 700–1000 kernels. Seeds per panicle was calculated using panicles m^{-2}, grain yield, and kernel weight. Seed density (seeds m^{-2}) was calculated using grain yield and kernel weight. Thin seed was recorded as the portion of the grain sample mass that fell through a 1.98 mm × 19.05 mm slotted screen (5/64″ × 3/4″ slotted sieve) and plump seed as the portion of the grain sample mass that stayed on top of a 2.18 mm × 19.05 mm screen (5.5/64″ × 3/4″ slotted sieve). Test weight was measured as specified by the Official Grain Grading Guide (Canadian Grain Commission 2016). Dockage consists of light material, including a portion of the wild oat seed, removed by the Carter dockage tester as specified by the Official Grain Grading Guide (Canadian Grain Commission 2016). Groat percentage was determined using a compressed-air oat laboratory dehulling machine. A 50 g sample was used with a dehulling time of 60 s, an air pressure of 690 kPa, and a blast gate aperture of 1.5–2.0 cm (Doehlert et al. 1999; Doehlert and McMullen 2001). Groat percentage was recorded as the mass of the groat divided by the mass of whole oat multiplied by 100.

Table 1. Monthly precipitation (mm) and soil moisture conditions in spring and monthly mean temperatures at Indian Head during the study.

	2003	2004	2005
Soil moisture reserves (spring)	Very good	Fair	Good
Precipitation (mm)			
April	55	17	6.8
May	24	105	58
June	18	85	99
July	23	75	59
August	11	71	98
5 mo total	131	354	321
% of 30-yr average[a]	49	133	120
Average temperature (°C)			
April	4.3	3.7	5.5
May	11.4	6.8	8.7
June	15.5	12.6	14.8
July	18.6	16.3	16.9
August	19.5	13.1	15.6
5 mo average	16.3	12.2	14
% of 30-yr average	104	78	90

[a]1981–2010 Canadian Climate Normals for Indian Head, SK (Environment Canada 2017).

Statistical analysis

The hypothesis being tested was that P rate and seeding rate and their interaction would improve tame oat yield, quality, and competitiveness with wild oat. Data were analysed with PROC MIXED in SAS (Littell et al. 2006) with seeding rate, P rate, wild oat, and year as fixed effects and replicates as a random effect. Studentized residual panels were used to check the distribution of residuals. Fixed effects, their interactions, and contrasts were considered significant at a 5% level of probability. Orthogonal contrasts were used to characterize the response trend (linear and quadratic) to P rate and seeding rate of the main effect and significant interactions. The null hypothesis for the contrasts was that *p* rate or seeding rate did not have a linear or quadratic effect on the variable.

Results and Discussion

The weather data are presented in Table 1 (Environment Canada 2017). In 2003, very little moisture was received during the growing season while temperatures were near the long-term average. In 2004 and 2005, moisture was above average and temperatures were below average during the growing season.

The effect of seeding rate, P, wild oat, and year on the measured variables is shown in Tables 2 and 3. Seeding rate had an effect on most of the measured variables and interacted with wild oat and year and P had an effect on seed density (seeds m^{-2}), grain yield, tame oat biomass, and the percentage of wild oat in the harvested grain with one significant interaction with wild oat for panicles m^{-2}.

Yield components

Plant density, panicles m^{-2}, and panicles $plant^{-1}$ were all affected by seeding rate and the year × seeding rate interaction but not by P (Table 2). In each year, as expected, there was a linear increase in plant density as the seeding rate increased. In 2003, the plant density was lower than in 2004 and 2005 at all rates except at the seeding rate of 150, when the plant density in 2003 did not differ with the plant density in 2005 [Least significant difference (LSD) = 42] (Table 4). There was a curvilinear decrease in panicles $plant^{-1}$ as the seeding rate increased in 2004 and 2005 but not in 2003 (Table 4). May et al. (2009) also found a curvilinear decrease in panicles $plant^{-1}$ as the seeding rate increased. This lack of a response in 2003 is probably due to the low level of precipitation, which was 50% of normal (Table 1). There was a linear increase in panicles m^{-2} in 2003 and 2004 and a curvilinear response in 2005 (Table 4). Similar to the results from 2003 and 2004, May et al. (2009) observed a linear increase in panicles m^{-2} as the seeding rate increased. In summary, as the seeding rate increased, tillering of each individual plant was reduced, however, the increased plant density resulted in a higher overall panicle density in any given area. The increase in overall panicle density should increase the competitiveness of

Table 2. Analysis of variance for the effect of phosphorus (P), seeding rate (SR), and wild oat (WO) on the plant density, panicle density, seed density, kernel weight, grain yield, test weight, biomass, height, lodging, and maturity of tame oat.

	p value										
	Plant density	Panicles m^{-2}	Panicles $plant^{-1}$	Seed density	Kernel weight	Grain yield	Test weight	Biomass	Height	Lodging	Crop maturity
Seed rate (SR)	**0.001**	**0.001**	**0.001**	0.053	**0.001**	**0.018**	0.452	**0.001**	**0.001**	**0.001**	**0.001**
Phosphorus (P)	0.722	0.946	0.828	**0.004**	0.365	**0.011**	0.378	**0.001**	0.059	0.300	0.114
P × SR	0.532	0.439	0.134	0.475	0.062	0.927	0.400	0.339	0.161	0.565	0.842
Wild oat (WO)	—	0.451	0.297	**0.001**	0.178	**0.001**	0.330	**0.001**	0.778	0.259	**0.002**
WO × SR	—	**0.010**	**0.002**	0.107	0.259	**0.009**	0.576	**0.025**	0.844	0.222	**0.001**
WO × P	—	**0.024**	0.110	0.746	0.515	0.416	0.836	0.146	0.226	0.253	0.230
WO × P × rate	—	0.633	0.883	0.928	0.697	0.775	0.550	0.540	0.184	0.446	0.386
Year	**0.001**	**0.001**	0.629	**0.001**	**0.047**	**0.001**	**0.003**	**0.001**	**0.001**	**0.001**	**0.001**
Year × SR	**0.001**	**0.001**	**0.001**	**0.034**	**0.050**	**0.002**	**0.004**	**0.046**	**0.001**	**0.001**	0.696
Year × P	0.990	0.881	0.992	0.828	0.603	0.800	0.853	0.696	0.950	0.805	0.719
Year × P × SR	0.690	0.237	0.077	0.854	0.916	0.754	0.157	0.233	0.091	0.607	0.371
Year × WO	—	0.359	0.652	**0.002**	0.304	**0.001**	0.973	0.282	0.376	0.274	**0.031**
Year × WO × SR	—	0.301	0.622	0.111	0.493	0.100	0.933	0.865	0.180	0.437	0.647
Year × WO × P	—	0.616	0.459	0.999	0.100	0.733	0.068	0.159	0.435	0.580	0.685
Year × WO × P × SR	—	0.972	0.937	0.884	0.644	0.878	0.342	0.853	0.276	0.887	0.130

Note: *p* values have been bolded when significant; —, no value.

the tame oat by allowing less space and resources for wild oat panicles. In addition, in 2003 with the lower plant density, panicles m^{-2} was still lower in 2003 compared with 2004 and 2005 at all four seeding rates (LSD = 25; Table 4).

The interaction of wild oat × seeding rate also affected panicles m^{-2} and panicles $plant^{-1}$ (Table 2). There was a curvilinear decrease in panicles $plant^{-1}$ as the seeding rate increased (Table 5). At the lowest seeding rate, 150 seeds m^{-2}, the no wild oat treatment had more panicles $plant^{-1}$ than the treatment with wild oat (LSD = 0.14). At the other seeding rates, there was no difference between the wild oat and no wild oat treatments. It appears that competition from the wild oat was limiting the panicles $plant^{-1}$ at low seeding rates. This difference between wild oat and no wild oat treatments was not detected by May et al. (2009). There was a curvilinear increase in panicles m^{-2} for the no wild oat treatment and a linear increase in the wild oat treatment as the seeding rate increased. As expected from the trends in panicles $plant^{-1}$, panicles m^{-2} was significantly higher in the no wild oat treatment compared with the wild oat treatment at the lowest seeding rate, 150 seeds m^{-2} (LSD = 31; Table 5). Competition from wild oat affected panicle development at the lowest seeding rate.

Tame oat seed density was affected by P, year, and year × seeding rate (Table 2). As the rate of P increased, there was a linear increase ($p = 0.002$) in seed density from 10 001 to 10 445 seeds m^{-2} (Table 6). This is the first and only yield component that was affected by P. In contrast, Mohr et al. (2007) found that P applied on oat increased panicle density but seed density was not calculated. In a durum study at Indian Head conducted in years that overlap this study, the addition of P did not increase head density and the numerical increase in seed density from 7286 to 7620 seeds m^{-2} was not statistically significant (May et al. 2008). There does not appear to be a yield component that P fertilizer consistently increases to increase grain yield.

In 2005, there was a curvilinear increase in seed density as the seeding rate increased with seed density peaking between a seeding rate of 250 and 450 seeds m^{-2} (Table 4). There was no response in seed density to seeding rate 2003 and 2004. The seed density in 2005 was greater than the seed density in 2004 at the seeding rates of 250, 350, and 450 seeds m^{-2} (LSD = 563; Table 4). The seed density in 2003 was consistently lower than in 2004 and 2005 at all seeding rates. Seed density was also affected by wild oat and the year × wild oat interaction. The presence of wild oat and the resulting competition reduced the seed density in 2003 and 2005 (Table 7). These results are supported by May et al. (2009), who found that competition from wild oat reduced seed density, especially at low seeding rates.

Kernel weight was affected by year and year × seeding rate but not by wild oat or P (Table 2). Mohr et al. (2007)

Table 3. Analysis of variance for the effect of phosphorus (P), seeding rate (SR), and wild oat (WO) on tame oat plump seed, thin seed, dockage, and groat yield and on the weed density, panicle density, biomass, and mass in harvested grain of wild oat.

	***p* value**							
	Tame oat				Wild oat			
	Plump seed	Thin seed	Dockage	Groat yield	Panicles m^{-2}	Weed density	Biomass	Wild oat in harvested grain
Seed rate (SR)	**0.001**	**0.021**	**0.001**	0.087	**0.000**	0.209	**0.001**	**0.001**
Phosphorus (P)	0.760	0.701	0.087	0.282	0.504	0.988	0.220	0.066
P × SR	0.602	0.323	0.092	0.846	0.517	0.534	0.238	0.868
Wild oat (WO)	**0.001**	0.913	**0.001**	0.775	—	—	—	—
WO × SR	0.184	0.118	**0.001**	0.840	—	—	—	—
WO × P	0.557	0.325	0.310	0.187	—	—	—	—
WO × P × rate	0.583	0.945	0.663	0.482	—	—	—	—
Year	**0.004**	**0.001**	**0.001**	**0.001**	**0.006**	**0.001**	0.764	**0.031**
Year × SR	0.065	0.487	0.361	**0.043**	**0.005**	0.665	**0.007**	**0.001**
Year × P	0.074	0.115	0.071	0.706	0.566	0.692	0.432	0.106
Year × P × SR	0.635	0.181	0.090	0.820	0.715	0.105	0.687	0.208
Year × WO	0.581	0.438	**0.001**	0.060	—	—	—	—
Year × WO × SR	0.412	0.086	**0.002**	0.561	—	—	—	—
Year × WO × P	0.772	0.559	0.618	0.348	—	—	—	—
Year × WO × P × SR	0.548	0.185	0.412	0.679	—	—	—	—

Note: *p* values have been bolded when significant; —, no value.

Table 4. The effect of seeding rate and year on plant density, panicle density, seed density, kernel weight, and grain yield of oat.

	Seeding rate (seeds m^{-2})				Contrasts	
Year	150	250	350	450	Linear	Quadratic
Plant density (plants m^{-2})						
2003	112	141	169	187	***	NS
2004	171	279	357	441	***	NS
2005	140	255	357	464	***	NS
Panicles m^{-2}						
2003	169	218	243	281	***	NS
2004	322	387	473	563	***	NS
2005	346	385	446	524	***	*
Panicles $plant^{-1}$						
2003	1.6	1.6	1.5	1.6	NS	NS
2004	1.8	1.4	1.4	1.3	***	**
2005	2.5	1.5	1.3	1.1	***	***
Seed density (seeds m^{-2})						
2003	5835	5930	6065	6099	NS	NS
2004	12 010	12 000	11 800	11 860	NS	NS
2005	12 220	13 050	13 470	13 040	**	**
Kernel weight (g 1000 $seeds^{-1}$)						
2003	38.9	39.8	39.0	39.0	NS	NS
2004	40.1	40.3	39.4	37.9	**	NS
2005	43.9	43.2	42.9	42.4	**	NS
Grain yield (T ha^{-1})						
2003	2.27	2.36	2.37	2.38	NS	NS
2004	4.79	4.84	4.60	4.48	**	NS
2005	5.37	5.64	5.78	5.53	NS	**

Note: *, **, and *** significant at 5%, 1%, and 0.1% levels, respectively; NS, not significant.

Table 5. The effect of seeding rate and wild oat on panicle density, grain yield, biomass, dockage, and maturity of tame oat.

	Seeding rate (seeds m^{-2})				Contrasts	
	150	250	350	450	Linear	Quadratic
Panicles m^{-2}						
No	296	329	389	452	***	*
Yes	262	331	386	460	***	NS
Panicles plant^{-1}						
No	2.12	1.50	1.36	1.36	***	***
Yes	1.86	1.53	1.39	1.36	***	**
Grain yield (T ha^{-1})						
No	4.47	4.52	4.51	4.28	*	*
Yes	3.81	4.03	3.99	3.98	*	*
Tame oat biomass (kg ha^{-1})						
No	8264	8293	8771	8815	**	NS
Yes	6876	7751	7996	8216	***	*
Dockage (%)						
No	2.4	2.2	2.1	2.2	NS	NS
Yes	4.0	3.0	3.0	2.8	***	***
Crop maturity (d)						
No	98	97	96	96	***	**
Yes	97	96	96	95	***	NS

Note: *, **, and *** significant at 5%, 1%, and 0.1% levels, respectively; NS, not significant.

also found that P had no effect on the kernel weight of oat. There was a linear decrease in kernel weight as the seeding rate increased in 2004 and 2005 but not in 2003 (Table 4). Interestingly, kernel weight was greater in 2005 than in 2003 or 2004 (LSD = 1.5).

The biomass of the oat crop was affected by seeding rate, P, and the seeding rate × year and wild oat × seeding rate interactions. There was a linear increase of 7.6% in oat biomass as the rate of P increased (Table 6). The increase in biomass should help to increase the competitiveness of the oat crop with wild oat. The biomass continued to increase to the high rate of 30 kg ha^{-1}. This increase in biomass from P fertilizer is supported by Berkenkamp et al. (1984), who reported that P fertilizer increased biomass at 9 out of 15 site years and the optimum rate was between 20 and 30 kg ha^{-1}. The lack of interaction between P and wild oat for tame oat biomass indicates that the wild oat did not deter the uptake of the banded P.

In addition, the biomass of the oat crop was affected by seeding rate, and the seeding rate × year and wild oat × seeding rate interactions. The wild oat depressed the biomass of tame oat at the low seeding rate. As the seeding rate increased in the wild oat treatment, the oat biomass increased by 19%, while in the no wild oat treatment, increasing the seeding rate resulted in a 6.7% increase in tame oat biomass (Table 5). The larger increase in oat biomass when wild oat was present indicates that increasing the seeding rate increased the competitiveness of the tame oat relative to the wild oat. The fact that at the highest seeding rate, the tame oat biomass was lower in the high density wild oat treatment than in the wild oat free treatment indicates that the wild oat is still competitive enough to impact the development of the tame oat even at a high seeding rate. The increase in oat biomass as the seeding rate increased also differed among the 3 yr, with a linear increase in the oat biomass of 17% in 2003 and 14% in 2005 and a curvilinear increase of 14% in 2004 (Table 8).

Grain yield was affected by all the main effects including seeding rate, P, wild oat, and year plus several interactions: wild oat × seeding rate, year × seeding rate, and year × wild oat (Table 2). There was a 3.4% linear increase in grain yield as the P rate increased (Table 6). If more than three rates had been used, especially rates above 30 kg P ha^{-1}, a curvilinear response would have likely been detected as most of the yield increase was brought about by the first 15 kg of P applied. It is interesting to note that the only one yield component, seed density, contributed to this grain yield increase and an increased oat biomass. In this study, we cannot determine if P had a direct impact on the ability of the crop to set and retain more seed or indirectly through the increased biomass. The possible theories for the effect of a P deficiency on grain yield were well elucidated by Grant et al. (2001). Mohr et al. (2007) could not find a grain yield response when six site–years of data were combined; however, separate individual site analysis found that the grain yield of oat increased with the addition of P fertilizer at two out of six sites. In a preliminary study with one site–year, Holzapfel (2015) found that there was a 4% increase in the grain yield of oat as the applied P fertilizer increased from 0 to 20 kg ha^{-1}. The fact that, in our study, P did not interact with the seeding rate of tame oat indicates that the effects of P on grain yield were independent of the effects of wild oat and seeding rate. Interestingly, the lack of a P × wild oat interaction indicates that the wild oat did not interfere with the uptake of P, as observed by Blackshaw and Molnar (2009) in wheat, even when the P was seed-placed or banded away from the seed. They found that the presence of wild oat reduced the benefit of P fertilizer towards increasing the seed yield of wheat.

Wild oat decreased grain yield by 23% in 2003, 4.4% in 2004, and 11% in 2005 (Table 7). The largest yield decrease occurred in 2003, which also had the lowest grain yield and plant density. There were significant linear and quadratic responses to seeding rate both with and without wild oats (Table 5). The difference is that when wild oat was present there was a 5% increase in grain yield as the seeding rate increased above 150 seeds m^{-2}, whereas in the treatment with no wild oat, the grain yield was negatively affected by the highest seeding rate, 450 seeds m^{-2}. May et al. (2009), using the oat cultivar Pinnacle, found that the grain yield of oat increased as the seeding rate increased in both the low and high wild oat density treatments. The yield increase from seeding

Table 6. The effect of phosphorus on the seed density, grain yield, and biomass of tame oat and percentage of wild oat in the harvested grain.

Phosphorous fertilizer rate (kg ha^{-1} of P_2O_5)	Seed density (seeds m^{-2})	Grain yield (T ha^{-1})	Oat biomass (kg ha^{-1})	Wild oat in harvested grain (%)
0	10 000	4.11	7759	1.26
15	10 400	4.25	8261	1.48
30	10 450	4.24	8349	0.76
Contrasts				
Linear	0.002	0.011	0.001	0.027
Quadratic	0.150	0.099	0.071	0.458

Table 7. The effect of year and wild oat on the seed density, yield, maturity, and dockage of tame oat.

	Wild oat		
Year	No	Yes	Statistical significance
Seed density (seeds m^{-2})			
2003	6756	5209	**
2004	12 100	11 740	NS
2005	13 610	12 280	*
Grain yield (T ha^{-1})			
2003	2.64	2.04	**
2004	4.78	4.57	*
2005	5.91	5.25	**
Crop maturity (d)			
2003	89.9	89.2	*
2004	—	—	—
2005	103.1	102.9	*
Dockage (%)			
2003	3.65	4.61	**
2004	0.72	1.09	*
2005	2.26	3.94	***

Note: *, **, and *** significant at 5%, 1%, and 0.1% levels, respectively; NS, not significant; —, no value.

Table 8. The effect of seeding rate and year on the test weight, groat yield, and biomass of tame oat and the panicle density and biomass of wild oat and the percentage of wild oat seed in the harvested sample.

	Seeding rate (seeds m^{-2})				Contrasts	
Year	150	250	350	450	Linear	Quadratic
Test weight (g 0.5 L^{-1})						
2003	248.9	251.3	251.7	253.8	**	NS
2004	220.1	219.8	218.3	215.6	*	NS
2005	243.2	243.8	242.4	240.8	NS	NS
Groat yield (%)						
2003	69.3	69.7	69.8	70.5	*	NS
2004	68.0	64.0	62.2	64.1	*	*
2005	75.1	75.0	75.0	75.2	NS	NS
Wild oat in harvested grain						
2003	1.37	1.30	1.39	1.04	NS	NS
2004	3.08	1.71	1.38	0.66	***	NS
2005	1.40	0.80	0.57	0.52	***	*
Tame oat biomass (kg ha^{-1})						
2003	4274	4776	4765	4987	*	NS
2004	9459	10 045	10 779	10 314	***	*
2005	8976	9245	9607	10 244	***	NS
Wild oat biomass (kg ha^{-1})						
2003	953	857	867	809	NS	NS
2004	1501	1063	694	585	***	NS
2005	1379	887	903	668	***	NS
Wild oat panicles (panicles m^{-2})						
2003	58	55	63	58	NS	NS
2004	72	58	44	37	***	NS
2005	98	66	73	58	***	NS

Note: *, **, and *** significant at 5%, 1%, and 0.1% levels, respectively; NS, not significant.

rate was higher in the high wild oat density treatment. The fact that the study by May et al. (2009) and this current study had a similar response to seeding rate using different cultivars from different breeding programs indicates that we can expect that most if not all cultivars will have their competitiveness with wild oat increase as their seeding rate is increased.

Both height and lodging were affected by seeding rate and the year × seeding rate interaction and not by P (Table 2). There was a linear decrease in the height by 4% in 2003, 11% in 2004, and 5% in 2005 as the seeding rate increased (data not shown). As the seeding rate increased, there was a curvilinear increase in lodging from 1.0 to 3.8 in 2004 and 3.3 to 5.8 in 2005. There was very little lodging in 2003. May et al. (2009) found a 4.5% decrease in height and an increase in lodging as the seeding rate increased, supporting the results of this study. Although P was not significant in the analysis of variance (Table 2), the linear contrast was significant ($p < 0.023$), with the height increasing from 95.5 cm at 0 kg ha^{-1} P to 96.7 cm at 30 kg ha^{-1}. Mohr et al. (2007) found that plant height increased as the P rate increased and two studies (Mohr et al. 2007; Holzapfel 2015) both found that lodging increased as P increased. In this study, P did not have an effect on lodging.

Test weight was affected by year and year × seeding rate but not P (Table 2); however, the trend was not

Table 9. The effect of year, seeding rate, and wild oat on dockage.

	Without wild oat						With wild oat					
	Seeding rate (seeds m^{-2})						Seeding rate (seeds m^{-2})					
Year	150	250	350	450	Linear	Quadratic	150	250	350	450	Linear	Quadratic
2003	4.0	3.5	3.4	3.6	NS	*	5.0	4.5	4.8	4.3	**	NS
2004	0.9	0.5	0.8	0.7	NS	NS	1.6	0.9	1.0	0.8	*	NS
2005	2.2	2.6	2.0	2.1	NS	NS	5.4	3.7	3.2	3.5	***	***

Note: *, **, and *** significant at 5%, 1%, and 0.1% levels, respectively; NS, not significant.

consistent for the year × seeding rate interaction with a linear increase in test weight as the seeding rate increased in 2003, followed by a linear decrease in test weight in 2004 (Table 8).

Both plump seed and thin seed were affected by seeding rate and year but not P (Table 3). Plump seed showed a linear increase from 92.8% to 94.1% and thin seed had a linear decrease from 2.0% to 1.7% as the seeding rate increased. Both changes do not appear to be of biological or economic significance. May et al. (2009) observed a similar response in plump and thin seed that was larger than the response observed in this study. Phosphate did not impact plump or thin seed in this study or the studies conducted by both Mohr et al. (2007) and Holzapfel (2015).

Groat yield was affected by year and the year × seeding rate interaction but not P (Table 3). No clear trend could be observed, with groat yield increasing in 2003 and decreasing in 2004 (Table 8).

Dockage was affected by all four main effects and the interactions of wild oat × seeding rate, year × WO, and year × wild oat × seeding rate (Table 3). The presence of wild oat increased dockage in the harvested samples in all 3 yr (Table 7). In addition, as the seeding rate increased, dockage decreased when wild oat was present in the plots (Table 9).

Wild oat seed in the harvested grain was affected by P, seeding rate, and year × seeding rate (Table 3). There was a linear decrease in wild oat seed as the P rate increased from 1.26% to 0.76% in the harvested grain or from 52 to 32 kg ha^{-1} of wild oat seed (Table 6). It should also be remembered that a large portion of the wild oat seed will have shattered and be on the soil surface when the plots were combined. Therefore, increasing the P rate increased the competiveness of tame oat with wild oat, reducing the fecundity of wild oat by 38%. This improved competitiveness that reduced wild oat seed production may have been due to the increase in tame oat biomass as the P rate increased. In addition, there was a linear decrease from 3.08% to 0.66% in 2004 (142–29 kg wild oat seed ha^{-1}) and a curvilinear decrease from 1.40% to 0.52% (68–28 kg wild oat seed ha^{-1}) in 2005 as the seeding rate of the tame oat increased (Table 8). Therefore, increasing the seeding rate reduced wild oat fecundity by 80% in 2004 and 59% in 2005. The lack of effect by seeding rate in 2003 is probably due to the low seeding rate and only a slight increase in plant density as the seeding rate increased. These results indicate that increasing the P rate and seeding rate probably reduce the number of wild oat seeds being added to the seed bank in the soil.

Wild oat plant density varied among the 3 yr and was not affected by seeding rate or P rate (Table 3). In the plots that were seeded with wild oat, the wild oat plant density when averaged across P rate and seeding rate was 58 plants m^{-2} in 2003 and 48 plants m^{-2} in 2004, and both where higher than the wild oat plant density in 2005, 24 plants m^{-2} (LSD = 0.19 log transformation).

Wild oat panicle density and wild oat biomass were both affected by seeding rate and year × seeding rate but not P (Table 3). There was a linear decrease in both wild oat panicles and wild oat biomass as the seeding rate increased in 2004 and 2005 but not in 2003 (Table 8). Therefore, increasing the seeding rate increased the competitiveness of the tame oat, reducing wild oat biomass by 61% in 2004 and 52% in 2005. Again, the lack of effect of seeding rate in 2003 is probably due to the low plant density of the tame oat and the small increase in tame oat plant density as the seeding rate increased in 2003 (Table 4).

The impact of tame oat seeding rate and P fertilizer improving the competitiveness of tame oat and improving the management of wild oat in tame oat have been investigated in this study. The next step to improving our ability to manage wild oat in tame oat crops is to investigate the effects of nitrogen fertility and distance between seed rows in interaction with seeding rate and P fertilizer on the competitiveness of tame oat.

Conclusions

Four major conclusions can be drawn from this research. Firstly, the effect of seeding rate on wild oat is strongly influenced by the environmental conditions during the growing season. Secondly, wild oat did not interfere with the uptake of side-banded P by tame oat. Thirdly, P fertilizer increased the competitive ability of oat by increasing oat biomass and the grain yield of oat and reducing the fecundity of wild oat by 38%. Fourthly, these results indicate that P rate and seeding rate are agronomic practices that can be managed independently of each other to increase the competiveness of an oat crop and improve the control of wild oats in an oat crop. Therefore, producers need to use P fertilization and higher seeding rates to improve the management of wild oat in tame oat.

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