The influence of nitrogen, phosphorus and potash fertilizer application on oat yield and quality

R. M. Mohr[1], C. A. Grant[1], W. E. May[2], and F. C. Stevenson[3]

[1]*Agriculture and Agri-Food Canada, Brandon Research Centre, Box 1000a, R.R. #3, Brandon, Manitoba, Canada R7A 5Y3 (e-mail: rmohr@agr.gc.ca);* [2]*Agriculture and Agri-Food Canada, Indian Head Research Farm, P.O. Box 760, Indian Head, Saskatchewan, Canada S0G 2K0; and* [3]*Statistical Consultant, 142 Rogers Rd., Saskatoon, Saskatchewan, Canada S7N 3T6.* *Received 3 November 2006, accepted 1 May 2007.*

Mohr, R. M., Grant, C. A., May, W. E. and Stevenson, F. C. 2007. **The influence of nitrogen, phosphorus and potash fertilizer application on oat yield and quality**. Can. J. Soil Sci. **87**: 459–468. Western Canada has become one of the key production areas for oat (*Avena sativa* L.) in North America. Limited information is available regarding fertilizer management strategies to optimize yield and quality in this environment. An experiment was conducted at two locations in southern Manitoba in 2000, 2001 and 2002 to assess the impact of factorial combinations of N (0, 40, 80, 120 kg N ha^{-1} as urea), P (0, 13, 26 kg P ha^{-1} as monoammonium phosphate), and KCl (0, 33 kg K ha^{-1}) on the growth, yield and quality of AC Assiniboia oat. Low to moderate N rates significantly increased yield, with optimum relative yield achieved with a plant-available N supply of approximately 100 kg N ha^{-1}. Increasing N rate also increased lodging and reduced test weight, kernel weight and kernel plumpness, suggesting that optimal N management must balance yield improvement against reductions in grain quality. Phosphorus application increased yield in 2 of 6 site-years, but had no overall effect on quality. Application of KCl resulted in small increases in yield (88 kg ha^{-1}), kernel weight and kernel plumpness on moderate to high K soils, which were not likely to provide a significant economic benefit. The lack of consistent interactions among N, P, and KCl suggests that these nutrients may be managed individually.

Key words: Oat, nitrogen, phosphorus, potassium chloride, yield, quality

Mohr, R. M., Grant, C. A., May, W. E. et Stevenson, F. C. 2007. **Incidence des applications d'azote, de phosphore et de potassium sur le rendement et la qualité de l'avoine**. Can. J. Soil Sci. **87**: 459–468. L'Ouest canadien est devenu une des grandes régions d'Amérique du Nord où l'on cultive l'avoine (*Avena sativa* L.). On manque néanmoins d'information sur les stratégies de gestion des engrais susceptibles d'optimiser le rendement et la qualité dans un tel environnement. Les auteurs ont entrepris une expérience à deux sites du sud du Manitoba en 2000, 2001 et 2002 afin de préciser l'impact d'une combinaison factorielle d'engrais N (0, 40, 80 ou 120 kg par hectare sous forme d'urée), d'engrais P (0, 13 ou 26 kg par hectare sous forme de phosphate d'ammonium diacide) et de KCl (0 ou 33 kg de K par hectare) sur la croissance, le rendement et la qualité de l'avoine AC Assiniboia. Une application faible ou moyenne d'engrais N augmente sensiblement le rendement, les meilleurs résultats étant obtenus avec un apport d'environ 100 kg par hectare de N assimilable par la plante. Augmenter le taux d'application de N accroît aussi la verse et diminue le poids spécifique, le poids d'amandes et la rondeur du grain, signe qu'une gestion optimale du N suppose un compromis entre la hausse du rendement et une perte au niveau de la qualité du grain. Les applications d'engrais phosphaté ont accru le rendement deux années-sites sur six, sans incidence sur la qualité. Celles de KCl engendrent une légère hausse du rendement (88 kg par hectare), du poids d'amandes et de la rondeur du grain sur les sols dont la teneur en K variait de moyenne à élevée, ce qui ne devrait pas aboutir à un véritable avantage économique. L'absence d'interactions conséquentes entre le N, le P et le KCl laisse croire qu'on peut gérer ces éléments nutritifs séparément.

Mots clés: Avoine, azote, phosphore, chlorure de potassium, rendement, qualité

Oat (*Avena sativa* L.) is widely grown in the eastern prairie region of western Canada for the milling, horse feed, and feed grain markets. In 2005/2006, an estimated 1.16 million ha of oats were harvested in western Canada (Canada Grains Council 2006). Despite the relative importance of oat in this region, limited information is available regarding optimal fertilization. Both yield and quality, and thus the economic value of oat, may be strongly influenced by fertilizer management. For example, oats meeting specific quality standards, such as a high test weight and a low percentage of thin kernels, may garner price premiums in specialized milling and horse feed markets.

Nitrogen may strongly affect both crop yield and quality and, as such, has been studied to the greatest extent. Nitrogen application has been shown to significantly increase oat grain yield (Frey 1959; Brinkman and Rho 1984; Jackson et al. 1994). In recent studies in western Canada, optimal grain yields were typically achieved with the application of moderate rates of N fertilizer (40 to 80 kg N ha^{-1}) for soils containing between 20 and 50 kg NO_3-N ha^{-1} in the top 60 cm of the soil profile (May et al. 2004b). Similar findings were reported under Manitoba conditions, where grain yield typically increased with the application of up to 80 kg N ha^{-1} on soils containing 36 kg NO_3-N ha^{-1} or less in the top 60 cm (Hamill 2002). Nitrogen fertilizer application, while often required to increase grain yield, may also reduce physical grain quality. Declines in test

Abbreviations: **MAP**, monoammonium phosphate weight, kernel weight and percent plump kernels, and increases in percent thin kernels have resulted from increasing N rates in several studies (Marshall et al. 1987; Jackson et al. 1994; May et al. 2004b). The relative effect of N fertilizer rate on oat may be influenced by various factors including soil N status, planting date and cultivar (Brinkman and Rho 1984; Anderson and McLean 1989; Hamill 2002; May et al. 2004b).

Compared with N, relatively little information has been published in western Canada about effects of P and K nutrition on oat, although the importance of early-season P supply to yield formation in field crops is well-documented (Grant et al. 2001). In recent field studies in Finland, application of a P-containing seed coating often increased biomass production and grain set for oat, but did not affect grain yield (Peltonen-Sainio et al. 2006). In that study, observed effects varied with experiment, location, cultivation method and cultivar. In contrast, field studies in Saskatchewan consistently demonstrated substantial increases in grain yield of oat with P fertilizer application regardless of cultivar (Mitchell et al. 1953), suggesting a significant P deficiency at experimental sites. Higher oat yields have been associated with greater plant tissue P concentration in P-deficient soils (Bolland and Brennan 2005). Various soil factors including soil P concentration, soil temperature, moisture, pH, texture and bulk density, and plant factors including root growth may affect the supply of P to the plant (Grant et al. 2001), and thus the potential for crop responses to P fertilizer application.

Application of K-containing fertilizers has also been shown to influence oat yield and quality in some cases. On high K soils in South Dakota, KCl application increased grain yield by 4% and increased kernel weight by 4 to 7% at two of four sites, but yield increases were considered too small to be profitable (Gaspar et al. 1994). No consistent cultivar × KCl rate interactions were evident for grain yield of the five oat cultivars included in the study, suggesting that oat cultivars responded similarly to KCl. In contrast, in a previous study on high K soils (≥ 427 kg NH_4OAc-extractable K ha^{-1}) in South Dakota, KCl application had no significant effect on grain yield of the oat cultivars Lancer and Moore (Fixen et al. 1986). Given the high K content of the soils used in these studies, observed responses might be due, at least in part, to the Cl^- component of the fertilizer. While crop yield responses to Cl^- application have been attributed to various mechanisms including disease suppression, advanced crop development, and improved plant water relationships (Fixen 1993), Gaspar et al. (1994) reported no effects of KCl on crown rust, relative water content or stomatal conductance for oat.

Fertilizer N, P and K are often applied in various combinations and at various rates in order to meet crop nutrient needs, and thus may either act alone or interact to influence crop growth (Olson and Kurtz 1982; Dibb and Thompson 1985). In greenhouse studies, Miller and Ashton (1960) found that N applied in a band with P fertilizer significantly increased fertilizer P absorption, and that N increased the oven-dry weight of oat grain plus straw. In contrast, Smith (1980) reported no significant N × K interactive effects for dry matter yield or plant height of silage oat in pot studies with soil containing low levels of N and K.

A better understanding of the impact of N, P and KCl fertilizers on oat yield and quality is required in order to develop fertilizer management strategies that optimize oat yield and quality, and thereby enhance returns to producers while meeting market standards for high-quality oats. Whereas the specific set of quality parameters required to achieve a high-quality oat varies depending upon the market (e.g., whether for human consumption or horse feed), higher test weights and kernel plumpness are two factors that may garner price premiums (May et al. 2004a). The objective of this study was to determine the effect of various rates and combinations of N, P and KCl fertilizers on the yield and quality of oat grown in Manitoba.

MATERIALS AND METHODS

Field experiments were conducted at two locations in southwestern Manitoba in 2000, 2001 and 2002 for a total of 6 site-years (Table 1). Soil samples were collected in the spring near the time of seeding. Two cores were collected to a depth of 120 cm in increments of 0–15, 15–30, 30–60, 60–90 and 90–120 cm, and combined to produce one sample for each depth increment per field replicate. Soil samples were air-dried immediately after collection and subsequently ground to pass a 2-mm sieve.

Soil NO_3-N, P and K were extracted with $NaHCO_3$, and the concentration of the nutrients determined by hydrazine reduction, molybdate/ascorbic acid and atomic absorption procedures, respectively (Hamm et al. 1970). Soil SO_4-S was extracted with $CaCl_2$ and determined by a methylthymol blue procedure (Hamm et al. 1973). Subsamples were also submitted to a second lab where soil P was extracted using a modified Kelowna method and P concentration was determined by automated molybdate colorimetry (Ashworth and Mrazek 1995).

Fertilizer treatments were arranged in a randomized complete block design with five replicates, except at Brandon–2000 where four replicates were established. At Brookdale in 2001, data from only four replicates were analyzed due to poor growth in one replicate. In all site-years, treatments consisted of a factorial combination of four N rates (0, 40, 80, 120 kg N ha^{-1} as side-banded urea), three P rates (0, 13, 26 kg P ha^{-1} as seed-placed monoammonium phosphate) and two KCl rates (0, 33 kg K ha^{-1} as side-banded KCl), for a total of 24 treatments. Monoammonium phosphate (MAP), the primary form of P fertilizer used in western Canada contains N so the rate of N applied in the form of urea was adjusted to account for N supplied in the form of MAP. Each treatment received the amount of N indicated by the N treatment plus 13 kg N ha^{-1}, regardless of the rate of MAP applied. (Treatments of 0, 13 and 26 kg P ha^{-1} as MAP supplied 0, 6.5 and 13 kg N ha^{-1}, and these amounts of N were adjusted to a total of 13 kg N ha^{-1} by applying 13, 6.5 and 0 kg N ha^{-1} as urea, respectively.) This adjustment was made so that MAP treatments were not confounded by differing levels of N. All fertilizer was applied at time of seeding through the seeder, with urea and potash applied in a single sideband. A control treatment receiving no fertilizer was also included. Plot dimensions were 3.65 m × 14 m.

Oats (*Avena sativa* L. 'AC Assiniboia') were direct-seeded in early- to mid-May, either directly into stubble or soil that had been tilled the previous fall, using a 3.65-m-wide ConservaPak® seeder equipped with hoe openers set on a 23-cm row spacing. The cultivar AC Assiniboia was selected because it was widely grown in western Canada at the time of the study, and had very good rust and lodging resistance. Weed control was achieved using recommended herbicides and rates based on the spectrum of weeds present (Manitoba Agriculture and Food 2002).

Plant density was determined at the three to four leaf stage by counting the number of plants in a 1-m length of row at two locations within each plot. Panicle density was determined after crop heading by counting the number of heads in a 1-m length of row at two locations within each plot. At harvest, crop lodging was rated on a scale of 0 to 9, with 9 denoting complete lodging.

Each plot was harvested with a small-scale commercial combine. Grain yield was calculated based on a cleaned subsample with moisture adjusted to 13%. Grain samples were cleaned using a Carter-Day dockage tester and subsequently assessed for test weight (Canadian Grain Commission 1998). The percentage by weight of plump kernels was calculated based on the mass of seed that stayed on top of a 2.18 × 19.05-mm slotted screen. The percentage by weight of thin kernels was calculated based on the mass of seed that passed through a 1.98 × 19.05-mm slotted screen. Thousand kernel weight was calculated based on the weight of two subsamples consisting of 250 kernels each.

Data were analyzed with the PROC MIXED procedure of SAS (Littel et al. 1996) with site-year (site by year combinations) and replicates considered to be random effects and the applied treatments considered to be fixed effects to determine the overall effect of fertilizer application on oat. In order to determine the frequency and magnitude of yield response to fertilizer application, data were analyzed separately for each site-year using the Proc GLM procedure in SAS (SAS Institute, Inc. 1999). Orthogonal polynomials were used to partition treatment effects into linear and quadratic components, as appropriate for each treatment. Treatment effects were considered significant at $P \le 0.05$. The Proc NLIN procedure was used to determine the relationship between relative grain yield and plant-available N supply (calculated as the sum of soil NO_3-N in kg ha^{-1} to a depth of 60 cm plus fertilizer N). For this analysis, relative yield for each treatment was calculated as a percentage of the highest-yielding treatment within each site-year and, from this, the mean relative yield for each N rate treatment was determined. To reflect common production practices, which would typically include P application, only treatments to which P fertilizer had been applied were included in this analysis. The Proc CORR procedure in SAS (SAS Institute, Inc. 1999) was used to identify correlations among lodging score, panicle density and plant height.

RESULTS AND DISCUSSION

Growing season rainfall and temperature in southwestern Manitoba were near-normal for the majority of site-years

Table 1. Characteristics of experimental sites in Manitoba, 2000 through 2002

Characteristic	Soil depth (cm)	2000		2001		2002	
		Brandon	Brookdale	Brandon	Brookdale	Brandon	Brookdale
Soil name		Newdale	Stockton	Newdale	Wellwood	Newdale	Wellwood
Legal location[z]		NW21-12-18W	SW13-11-17W	NW-21-12-18W	NW11-12-16W	NW21-12-18W	NW11-12-16W
Texture	0 to 15	Clay loam	Fine sandy loam	Clay loam	Clay loam	Clay loam	Clay loam
pH	0 to 15	7.7	6.0	7.5	6.2	7.6	6.7
EC in paste (dS m^{-1})	0 to 15	0.54	0.30	0.89	0.27	0.86	0.72
NO_3-N (kg ha^{-1})	0 to 60	50	49	33	61	34	38
NO_3-N (kg ha^{-1})	0 to 120	83	61	61	96	60	62
$NaHCO_3$-extr. P (kg ha^{-1})	0 to 15	13.5	19.7	9.4	31.4	8.0	18.2
extr. P, modified Kelowna (kg ha^{-1})	0 to 15	ND	ND	14.3	39.6	21.0	30.8
$NaHCO_3$-extr. K (kg ha^{-1})	0 to 15	297	227	374	493	409	439
S (kg ha^{-1})	0 to 60	30	35	134	25	1574[y]	38
Cl^- (kg ha^{-1})	0 to 60	112	156	134	195	ND	ND

[z]The Newdale site was located at 99°88′ W longitude and 50°03′ N latitude, the Stockton site at 99°68′ W longitude and 49°92′ N latitude, and the Wellwood site at 99°56′ W longitude and 50°00′ N latitude.

[y]Soil S content ranged among replicates from 42 to 5609 kg extr. S ha^{-1} to a depth of 60 cm.

based on general climatic data for the region. However, dry and cold conditions in spring 2002 delayed early-season growth at experimental sites (Table 2).

Plant Density

Fertilizer treatments did not have a statistically significant effect on early-season plant density in oat (Table 3), suggesting that the fertilization practices used did not result in measurable seedling damage under the conditions of this study. Although fertilizer treatment tended ($P < 0.10$) to influence plant density in some cases, the small numerical differences evident among treatments are not expected to be of agronomic significance given that the mean plant stand in this study exceeded the provincially recommended plant stand for oat of 194 to 248 plants m^{-2} (Table 4). In a previous study, May et al. (2004b) reported an average decrease in plant density of six plants per square meter with a side-band application of 120 kg N ha^{-1} in oat, but noted that decreases in plant density did not occur consistently in every site-year.

Crop Lodging

Increasing N rate resulted in a significant quadratic increase in both panicle density and plant height (Table 4), although crop responses to N differed among site-years as evidenced by a significant site × N interaction (Table 3). Oats that received the highest N rate (i.e., 120 kg N ha^{-1}) produced between 38 and 137 more panicles per square meter and, in 5 of 6 site-years, were 10 to 18 cm taller than oats in the 0 N treatment. Previous studies have similarly demonstrated increases in panicle density and plant height with N fertilizer application (Brinkman and Rho 1984; Hamill 2002; May et al. 2004b). While P application also increased panicle density and plant height, increases were comparatively smaller than those resulting from N application (Table 4), and tended to be influenced by N, as evidenced by a N × P interaction ($P < 0.10$) (Table 3). Where N had been applied, the highest P rate resulted in plants that produced 10 to 30 more panicles per square meter, and plants that were 3 to 4 cm taller than the 0 P treatment; however, these effects of P were not evident in the 0 N control treatment. The application of KCl also increased panicle density by an average of 11 panicles per square meter and tended ($P = 0.10$) to reduce plant height (Table 4).

Increasing N rate increased lodging (Tables 3 and 4) even though the cultivar grown was considered to have very good lodging resistance (Manitoba Agriculture, Food and Rural Initiatives 2006b). Previous studies have similarly reported increased lodging with increasing rates of N (Brinkman and Rho 1984; Hamill 2002; May et al. 2004b). Site-years differed in their relative response to N as illustrated by a significant site × N × P interaction. In some site-years, increases in lodging associated with increasing N rate were more pronounced where P had also been applied (Fig. 1). The application of KCl also increased lodging but only by 0.4 on a scale of 9 (Table 4). Effects of KCl were evident at low to moderate N rates, where KCl increased lodging score by 0.3 to 0.9 on a scale of 9, but not at the highest N rate (120 kg N ha^{-1}). Observed effects of KCl were relatively small compared with the effect of N application, and therefore not likely to be of agronomic significance. In previous field studies conducted in South Dakota on soils containing >391 kg NH_4OAC-extractable K ha^{-1}, KCl was found to have inconsistent effects on lodging for five oat cultivars (Gaspar et al. 1994).

Higher lodging scores under fertilized conditions were likely due, at least in part, to taller and/or denser plant stands, which may be more prone to lodging (Table 4). There was a significant correlation between lodging score and panicle density ($r = 0.69$; $P < 0.0001$) and between panicle density and plant height ($r = 0.40$; $P = 0.05$) when treatment means within site-years were considered; however, the correlation between lodging score and plant height was not statistically significant. Lodging is a concern in oat as it has the potential both to slow harvest of the crop, and to reduce yield and quality. Declines in oat quality parameters including kernel weight, test weight and groat yield have been associated with increased lodging, particularly with later-seeded oat crops (May et al. 2004a).

Grain Yield

Grain yields ranged from approximately 3200 to 4500 kg ha^{-1} across site-years, exceeding Manitoba's provincial average, which ranged from 2300 to 2900 kg ha^{-1} for the same period (Canada Grains Council 2006). When averaged across all site-years, N fertilizer significantly increased grain yield. Although a significant N × site interaction was evident (Table 3), in all site-years, the pattern of yield response was similar in that yield increased with fertilizer rates of 40 to 80 kg N ha^{-1} and leveled off or declined at higher N rates (Fig. 2). Low to moderate soil test NO_3-N levels at experimental sites (33 to 61 kg NO_3-N ha^{-1} to 60 cm) likely contributed to the consistent positive yield responses (Table 1). Similar results were obtained in a recent study in Manitoba. Hamill (2002) found that N applications of up to 80 kg N ha^{-1} increased grain yield on soils containing 36 kg NO_3-N ha^{-1} or less in the top 60 cm, but did not increase yield on soils containing more than 100 kg NO_3-N ha^{-1} to 60 cm.

Although yield varied considerably among site-years (Fig. 2), when all site-years were considered together, a reasonably close relationship ($R^2 = 0.76$) was evident between relative grain yield and plant-available N supply (calculated as the sum of spring soil test NO_3-N to 60 cm plus fertilizer N applied). Optimum relative yield was achieved with a plant-available N supply of 100 kg N ha^{-1} (Fig. 3) suggesting that higher rates of fertilizer N were not required to optimize grain yield under conditions of higher yield potential. In this study, all of the experimental sites had been commercially farmed and therefore had some history of fertilization and residue return, which may have contributed to the N mineralization potential of the soils.

Overall, P fertilizer did not result in a significant increase in grain yield (Table 3) even though most of the sites selected were considered to have low to moderate soil test P levels for cereal production (Manitoba Agriculture, Food and Rural Initiatives 2006a). When site-years were considered separately, however, P application was found to significant-

Table 2. Growing season temperature and precipitation at Brandon, Manitoba for 2000 through 2002

	Mean temperature (°C)						Total precipitation (mm)			
Month	2000	2001	2002	Normals[z]	SD[y]		2000	2001	2002	Normals[z]
April	4.1	4.5	1.7	4.0	2.6		4.1	17.2	16.4	29.3
May	11.1	12.8	7.9	11.8	2.2		53.6	56.2	7.8	52.6
June	13.5	15.2	17.6	16.6	1.8		61.0	122.0	75.0	75.7
July	18.8	19.6	20.2	18.9	1.4		118.0	38.0	51.0	72.5
August	17.7	19.2	17.3	18.0	1.8		59.0	22.0	101.0	69.2
September	11.5	12.9	12.2	11.9	1.5		44.2	23.8	38.0	48.3
Mean	12.8	14.0	12.8	13.5		Total	339.9	279.2	289.2	347.6

[z]As reported by Environment Canada (2004) for Brandon CDA located at 99°58′ W longitude and 49°52′ N latitude.
[y]standard deviation.

Table 3. Analysis of variance, with site-year and replicate as a random effect, for oats at six site-years in Manitoba from 2000 through 2002

Effect	Plant density	Panicle density	Plant height	Lodging	Grain yield	Thousand kernel weight	Test weight	Plump kernels	Thin kernels
					P value				
N fertilizer rate (N)	NS	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.007**
Linear (L)	NS	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**
Quadratic (Q)	0.08	**0.001**	**0.001**	**0.03**	**0.001**	NS	NS	NS	NS
P fertilizer rate (P)	0.09	**0.03**	**0.003**	**0.01**	NS	NS	NS	NS	NS
P × N	NS	0.09	0.08	NS	NS	NS	0.06	**0.002**	**0.02**
K fertilizer rate (K)	NS	**0.008**	0.10	**0.009**	**0.005**	**0.01**	NS	**0.001**	**0.003**
K × N	NS	NS	NS	**0.03**	NS	NS	**0.006**	NS	NS
K × P	NS	NS	NS	NS	NS	NS	**0.03**	NS	NS
K × P × N	NS	NS	NS	NS	NS	NS	NS	NS	NS
					Variance estimate[z]				
Site-year (S)	3553	255963	106	1.78	332496	1.82	45.8	3.11	0.0948
S × N	0	4716*	6**	0.48*	71635*	0.12	2.6*	0.20*	0.0016
S × P	0	1055	1	0.1	1055	0	1	0	0
S × P × N	0	451	1	0.47**	451	0.06	0.5	0	0
S × K	1	437	0	0	437	0.04	0.9	0	0
S × K × N	1	0	0	0	0	0.05	0	0	0.0028
S × K × P	0	359	0	0	359	0.04	0	0.04	0.0013
S × K × P × N	0	0	1	0	0	0	0	0	0.0012
					% total variance				
S	100	97	93	63	81	86	90	93	93
S × N	0	2	5	17	17	6	5	6	2
S × P	0	0	1	3	1	0	2	0	0
S × P × N	0	0	0	17	0	3	1	0	0
S × K	0	0	0	0	0	2	2	0	0
S × K × N	0	0	0	0	0	2	0	0	3
S × K × P	0	0	0	0	0	2	0	1	1
S × K × P × N	0	0	1	0	0	0	0	0	1

[z]The statistical significance of variance components are indicated as follows: * = 0.05 ≥ *P* value ≥ 0.01; and ** = *P* value < 0.01.

ly ($P < 0.05$) increase yield at both sites in 2002, with a significant linear effect at Brookdale and a significant quadratic effect at Brandon (Fig. 4). Soil test P alone did not appear to dictate whether a positive yield response would be obtained in that site-years with the lowest soil test P level did not always respond positively to P application. Based on an assessment of 74 small grain field experiments in South Dakota, Fixen and Carson (1978) found that the Olsen P test explained only 29% of the variability in yield increases from P fertilization, suggesting that soil test P alone may not be a strong predictor of crop response to P fertilizer. In our study, the positive yield responses observed in 2002 appeared to be, in part, a function of dry, cool conditions in spring 2002. Cold soils may create a set of conditions in which positive crop responses to banded P are more likely, including reduced availability of soil P, reduced root growth, greater availability of fertilizer P, and perhaps greater crop demand for P (Grant et al. 2001).

The application of 33 kg K ha^{-1} as KCl resulted in a small but statistically significant increase in grain yield of approximately 88 kg ha^{-1}, equivalent to a 2.2% increase in grain yield, averaged across all site-years (Table 3). Because K was applied only in the form of KCl, it is unclear whether the observed effect was due to the K and/or the Cl^- component of the fertilizer. The soil test K levels at most of the experimental sites were considered sufficient for cereal production in Manitoba. However, previous studies in the northern Great Plains have demonstrated yield responses to K application for cereals grown on soils testing high in K (Skogley and Haby 1981; Gaspar et al. 1994). Observed

Table 4. Effect of N, P and KCl fertilizer rate on plant density, panicle density, plant height and lodging score for oat (mean of 6 site-years)

N rate (kg N ha^{-1})	P rate (kg P ha^{-1})	KCl rate (kg K ha^{-1})	Plant density (plants m^{-2})	Panicle density (panicles m^{-2})	Plant height (cm)	Lodging score[z]
0			256	294	90.5	2.5
40			259	358	99.5	4.8
80			262	390	101.9	6.0
120			257	394	102.2	6.6
SE[y]			5	3	0.8	0.2
	0		255	350	96.9	4.4
	13		259	363	98.8	5.2
	26		261	363	99.9	5.4
	SE		4	3	0.7	0.1
		0	259	353	98.8	4.8
		33	258	364	98.3	5.2
		SE	3	2	0.6	0.1

[z]Lodging is rated on a scale of 0 to 9, with 9 denoting complete lodging.
[y]SE, standard error of the mean for the treatments indicated.

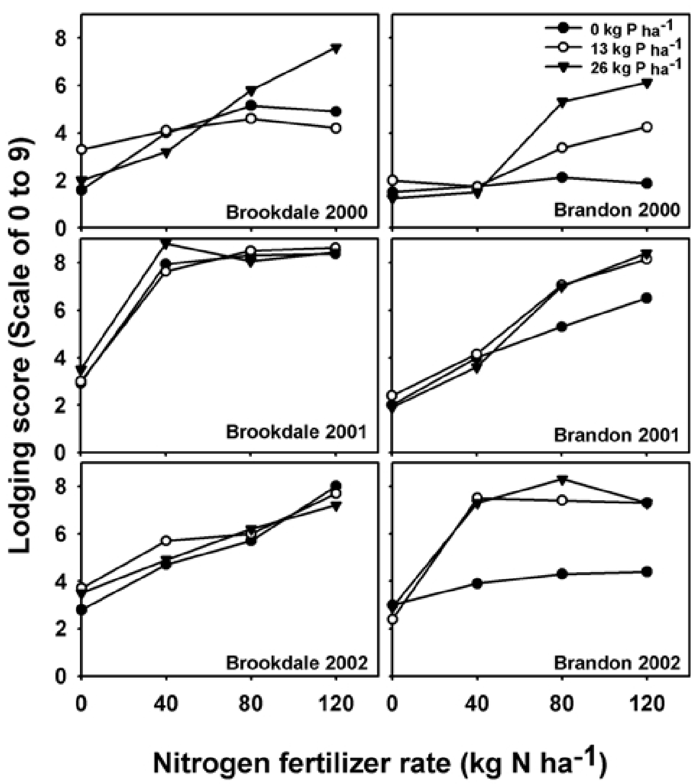

Fig. 1. Effect of N and P rate on lodging score of oat at harvest for 6 site-years in Manitoba

responses may be related to various factors including soil and climate (Skogley and Haby 1981; Schaff and Skogley 1982) and the Cl^- component of KCl fertilizer. In our study, soil Cl^- concentrations (measured only in 2000 and 2001) were substantially above the level at which maximum yield had been reported for wheat in South Dakota (Fixen et al. 1986). In the same South Dakota study, oats (cv. Lancer and Moore) were found to be less responsive than either wheat or barley, with no yield responses to KCl evident at five sites. Subsequent studies with five oat cultivars demonstrated a 4% increase in oat grain yield at two of four sites where KCl was applied to high K soils, but yield increases were deemed too small to be profitable (Gaspar et al. 1994). In the current study, when site-years were considered separately, KCl resulted in a significant yield increase of 4% in only 1 of 6 site-years (Fig. 4).

No significant interactions were evident among the fertilizers applied, suggesting that the pattern of yield response to

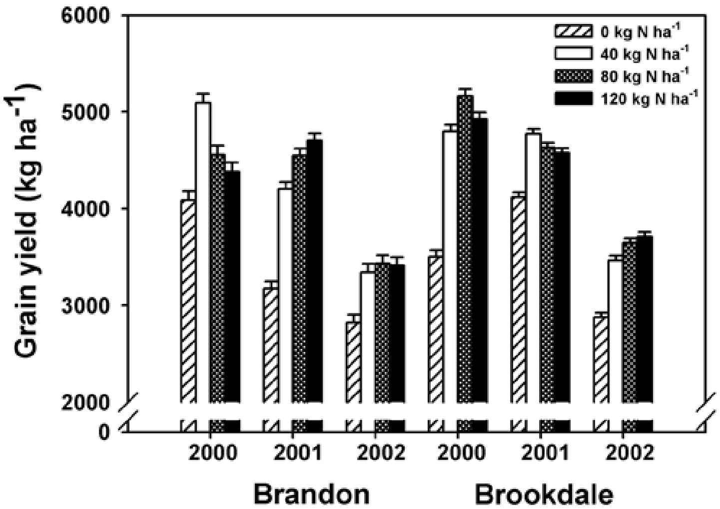

Fig. 2. Effect of N fertilizer rate on grain yield of oat for 6 site-years in Manitoba.

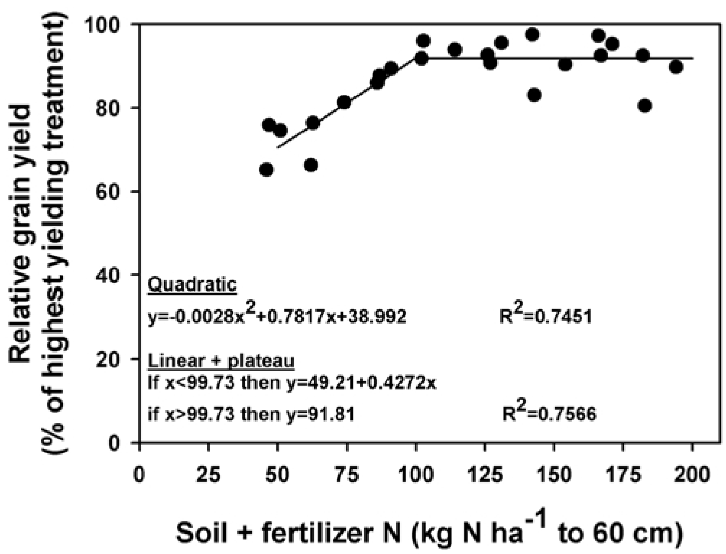

Fig. 3. Relationship between available N supply and relative grain yield of oat based on 6 site-years in Manitoba.

a given fertilizer was not influenced by the other fertilizers. The lack of interaction among fertilizers suggests that, while each of N, P and KCl may enhance yield, these nutrients may be managed individually.

Grain Quality

Increasing rates of N fertilizer resulted in a statistically significant linear decline in kernel weight, test weight and percent plump kernels, and a significant linear increase in percent thin kernels (Table 5). Although significant site × N interactions were evident for both test weight and percent plump kernels, similar trends were evident in all site-years, with each increasing increment of N fertilizer resulting in a progressive decline in both test weight and percent plump kernels; i.e., no cross-over interactions occurred among site-years (Fig. 5). Previous studies have similarly reported declines in test weight (Marshall et al. 1987; Jackson et al. 1994; May et al. 2004b) and percent plump kernels (Hamill 2002; May et al. 2004b) with increasing N rates.

The effect of N on both percent plump kernels and percent thin kernels appeared to be influenced by the rate of P fertilizer applied, as shown by a statistically significant N × P interaction (Table 3). For both quality factors, the effect of N became more pronounced with higher rates of P. While statistically significant, this effect is not likely to be of agronomic significance. In the case of percent plump kernels, for example, the difference between the control and the highest N rate was approximately 2% where no P was applied (95 vs. 93%), compared with 3% where the highest rate of P had been applied (95 vs. 92%). Percent thin kernels was ≤ 1% regardless of treatment; however, in the 0 P control, percent thin kernels was 0.73% where no N was applied, and ranged

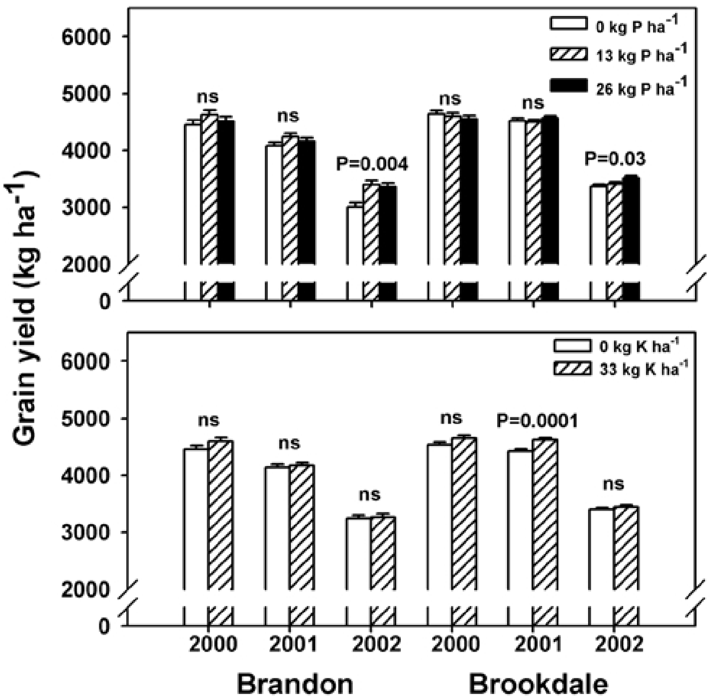

Fig. 4. Effect of P and KCl fertilizer on grain yield of oat for 6 site-years in Manitoba. (The ns indicates that fertilizer effects were not significant at $P \le 0.05$.)

Table 5. Effect of N, P and KCl fertilizer rate on physical quality of oat grain (mean of 6 site-years)

N rate (kg N ha^{-1})	P rate (kg P ha^{-1})	KCl rate (kg K ha^{-1})	Test weight (g 0.5L^{-1})	Kernel weight (g/1000 kernels)	Plump kernels (%)	Thin kernels (%)
0			229.4	37.2	95.3	0.75
40			226.3	36.3	94.2	0.83
80			223.1	35.6	93.4	0.88
120			220.4	35.1	92.6	0.93
SE[y]			0.6	0.1	0.2	0.03
	0		223.9	36.2	93.9	0.83
	13		225.1	36.1	93.9	0.86
	26		225.4	35.9	93.8	0.85
	SE		0.6	0.1	0.1	0.03
		0	224.9	35.8	93.7	0.89
		33	224.8	36.4	94.1	0.80
		SE	0.5	0.1	0.1	0.02

[y]SE, standard error of the mean for the treatments indicated.

from 0.84 to 0.88% when N had been applied. In contrast, in the high P treatment, percent thin kernels ranged from 0.74% where no N had been applied to 1.0% where the highest rate of N had been applied. A similar trend was evident for test weight, with more pronounced effects of N evident at higher rates of P, but the N × P interaction was not statistically significant ($P = 0.06$).

A significant N × KCl interaction was also evident for test weight, although test weight declined with increasing N rate regardless of KCl application. For low to moderate N rates, test weight ranged from 223.8 to 229.6 g 0.5L^{-1} in 0 K treatments compared with 222.5 to 229.2 g 0.5L^{-1} in treatments receiving KCl. At the highest N rate, however, the addition of KCl reduced the negative effect of N on test weight. In that treatment, test weight was 221.2 g 0.5L^{-1} where KCl had been added, versus 219.6 g 0.5L^{-1} in the 0 KCl control.

Phosphorus fertilizer rate did not have a significant effect on test weight, kernel weight, percent plump kernels or percent thin kernels when averaged across all site-years. Furthermore, there were no significant site × P fertilizer interactions, suggesting that P fertilizer did not influence physical grain quality factors over the range of soil test P levels and environmental conditions in the current study.

Averaged across site-years, KCl application increased 1000-kernel weight and percent plump kernels, decreased percent thin kernels, and had no effect on test weight (Table

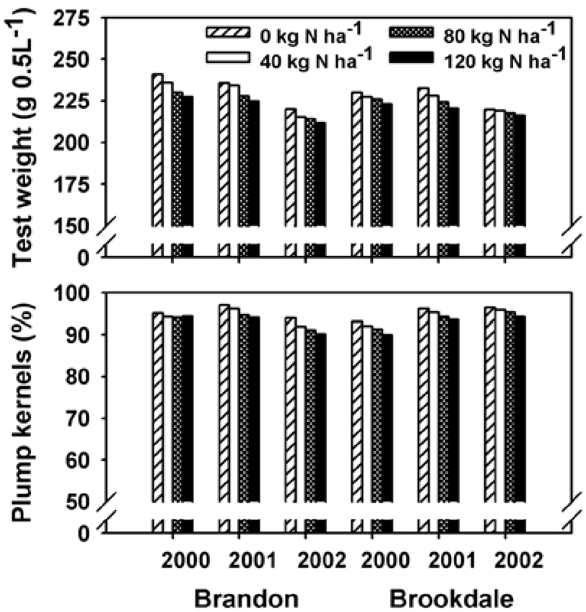

Fig. 5. Effect of N fertilizer rate on test weight and percent plump kernels in oat for 6 site-years in Manitoba.

5). In previous studies in South Dakota, KCl application on high K soils similarly increased the 1000-kernel weight of oat, but only at sites where a positive yield response to KCl had been measured (Gaspar et al. 1994). In our study, when site-years were analyzed separately, significant grain yield increases were observed only at Brookdale in 2001 (Fig. 4), whereas greater 1000-kernel weight occurred at Brandon in 2000 and 2001, and at Brookdale in 2001 and 2002 (data not presented). Like the current study, Gaspar et al. (1994) found no significant effect of KCl application on test weight for oat.

While fertilization may influence specific quality parameters, whether fertilizer management influences the acceptability of oats for a given market, or the value of oats, will depend on whether oats meet the quality standards set by a given buyer. For example, milling oats typically require less than 10% thin kernels and a minimum test weight of 235 g 0.5 L^{-1}, and may garner a price premium for test weights above 245 g 0.5 L^{-1}. In the current study, all site-years had less than 10% thin kernels regardless of treatment but, in 4 of 6 site-years, test weight was less than 235 g 0.5 L^{-1} for all N rates. In 2 site-years (Brandon in 2000 and 2001), however, test weight exceeded 235 g 0.5 L^{-1}, but only where lower rates of N had been applied (Fig. 5). A better understanding of the relative impacts of fertilizer management on oat quality parameters may assist growers in selecting those management practices that increase the probability of achieving oats that meet the quality standards required by the market.

SUMMARY AND CONCLUSIONS

Fertilizer N, P and KCl may influence both the yield and quality of oats grown in Manitoba. Results of the current study indicated that a plant-available N supply (fertilizer N + soil NO_3-N to 60 cm) of approximately 100 kg N ha^{-1} was sufficient to achieve optimum grain yield. Applying additional N above this level did not result in further yield increases, and may result in declines in physical grain quality and increases in lodging. Wheras oats were also responsive to P application, yield increases were observed in only one-third of the site-years at locations with dry, cool early-season conditions combined with low to moderate soil test P (8 to 18 kg $NaHCO_3$-extractable P ha^{-1}); no effects of P application rate on grain quality were evident. Small improvements in grain yield (88 kg ha^{-1}) and quality were also achieved with the application of 33 kg K ha^{-1} as KCl on soils with moderate to high soil test K levels. Given the small improvements observed, however, KCl application appears unlikely to provide significant economic benefits for most Manitoba soils which typically contain adequate K for cereal production.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Western Grains Research Foundation, the Potash and Phosphate Institute of Canada, and by Agriculture and Agri-Food Canada's Matching Investment Initiative.

Anderson, W. K. and McLean, R. 1989. Increased responsiveness of short oat cultivars to early sowing, nitrogen fertilizer and seed rate. Aust. J. Agric. Res. **40**: 729–744.

Ashworth, J. and Mrazek, K. 1995. Modified Kelowna test for available phosphorus and potassium in soil. Commun. Soil Sci. Plant Anal. **26**:731–739.

Bolland, M. D. A. and Brennan, R. F. 2005. Critical phosphorus concentrations for oats, barley, triticale and narrow-leaf lupin. Commun. Soil Sci. Plant Anal. **36**: 1177–1186.

Brinkman, M. A. and Rho, Y. D. 1984. Response of three oat cultivars to N fertilizer. Crop Sci. **24**: 973–977.

Canada Grains Council. 2006. Statistical handbook. [Online] Available: http://www.canadagrainscouncil.ca/subscriber/CGC Section/www_show_handbook [2006 Nov. 01].

Canadian Grain Commission. 1998. Official grain grading guide. Winnipeg, MB.

Dibb, D. W. and Thompson, W. R. 1985. Interaction of potassium with other nutrients. Pages 515–533 *in* Potassium in agriculture. R. D. Munson, ed. ASA-CSSA-SSSA. Madison, WI.

Environment Canada. 2004. Canadian climate normals 1971–2000. [Online] Available: http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html [2007 Apr. 04].

Fixen, P. E. 1993. Crop responses to chloride. Adv. Agron. **50**: 107–150.

Fixen, P. E. and Carson, P. L. 1978. Relationship between soil test and small grain response to P fertilization in field experiments. Agron. J. **70**: 838–844.

Fixen, P. E., Gelderman, R. H., Gerwing, J. and Cholick, F. A. 1986. Response of spring wheat, barley and oats to chloride in potassium chloride fertilizers. Agron. J. **78**: 664–668.

Frey, K. J. 1959. Yield components in oats. II. The effect of nitrogen fertilization. Agron. J. **51**: 605–608.

Gaspar, P. E., Reeves, D. L., Schumacher, T. E. and Fixen, P. E. 1994. Oat cultivars response to potassium chloride on soils testing high in potassium. Agron. J. **86**: 255–258.

Grant, C. A., Flaten, D. N., Tomasiewicz, D. J. and Sheppard, S. C. 2001. The importance of early season phosphorus nutrition.

Can. J. Plant Sci. **81**: 211–224.
Hamill, M. L. 2002. The effect of cultivar, seeding date, seeding rate and nitrogen fertility on oat (*Avena sativa* L.) yield and milling quality. M.Sc. thesis, University of Manitoba, Winnipeg, MB.
Hamm, J. W., Bettany, J. R. and Halstead, E. H. 1973. A soil test for sulphur and interpretative criteria for Saskatchewan. Commun. Soil Sci. Plant Anal. **4**: 219–231.
Hamm, J. W., Radford, F. G. and Halstead, E. H. 1970. The simultaneous determination of nitrogen, phosphorus and potassium in sodium bicarbonate extracts of soils. Pages 65–69 *in* Technicon International Congress, Advances in Automatic Analysis, Industrial Analysis, Vol. II.
Jackson, G. D., Berg, R. K., Kushnak, G. D., Blake, T. K. and Yarrow, G. I. 1994. Nitrogen effects on yield, beta-glucan content, and other quality factors of oat and waxy hulless barley. Commun. Soil Sci. Plant Anal. **25**: 3047–3055.
Littel, R. C., Milliken, G. A., Stroup, W. W. and Wolfinger, R. D. 1996. SAS system for mixed models. SAS Institute Inc., Cary, NC. 656 pp.
Manitoba Agriculture and Food. 2002. Guide to crop protection 2002.
Manitoba Agriculture, Food and Rural Initiatives. 2006a. Manitoba soil fertility guide. [Online] Available: http://www.gov.mb.ca/agriculture/soilwater/soilfert/fbd02s00.html [2006 Sep. 25].
Manitoba Agriculture, Food and Rural Initiatives. 2006b. Seed Manitoba 2006. [Online] Available: http://www.gov.mb.ca/agriculture/crops/cropproduction/pdf/seed2006/oats.pdf [2006 Sep. 25]
Marshall, H. G., Kolb, F. L. and Roth, G. W. 1987. Effects of nitrogen fertilizer rate, seeding rate and row spacing on semidwarf and conventional height spring oat. Crop Sci. **27**: 572–575.
May, W. E., Mohr, R. M., Lafond, G. P., Johnston, A. M. and Stevenson, F. C. 2004a. Early seeding dates improve oat yield and quality in the eastern prairies. Can. J. Plant Sci. **84**: 431–442.
May, W. E., Mohr, R. M., Lafond, G. P., Johnston, A. M. and Stevenson, F. C. 2004b. Effect of nitrogen, seeding date and cultivar on oat quality and yield in the eastern Canadian prairies. Can. J. Plant Sci. **84**: 1025–1036.
Miller, M. H. and Ashton, G. C. 1960. The influence of fertilizer placement and rate of nitrogen on fertilizer phosphorus utilization by oats as studied using a central composite design. Can. J. Soil Sci. **40**: 157–167.
Mitchell, J., Dion, H. G., Kristjanson, A. M. and Spinks, J. W. T. 1953. Crop and variety response to applied phosphate and uptake of phosphorus from soil and fertilizer. Agron. J. **45**: 6–11.
Olson, R. A. and Kurtz, L. T. 1982. Crop nitrogen requirements, utilization and fertilization. Pages 567–604 *in* F. J. Stevenson, ed. Nitrogen in agricultural soils. ASA-CSSA-SSSA. Madison, WI.
Peltonen-Sainio, P., Kontturi, M. and Peltonen, J. 2006. Phosphorus seed coating enhancement in early growth and yield components in oat. Agron. J. **98**: 206–211.
SAS Institute, Inc. 1999. SAS/STAT user's guide. [Online] Available: http://v8doc.sas.com/sashtml/ [2006 Sep. 25].
Schaff, B. E. and Skogley, E. O. 1982. Soil profile and site characteristics related to winter wheat response to potassium fertilizers. Soil Sci. Soc. Am. J. **46**: 1207–1211.
Skogley, E. O. and Haby, V. A. 1981. Predicting crop responses on high-potassium soils of frigid temperature and ustic moisture regimes. Soil Sci. Soc. Am. J. **45**: 533–536.
Smith, D. 1980. Vegetative responses of silage oats fertilized in the growth chamber with various levels of N and K. J. Plant Nutr. **2**: 547–555.