Effects of manure injection tool type and tool spacing on soil nutrient levels and spring barley performance

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Assefa, B., Chen, Y., Buckley, K. and Akinremi, W. 2006. **Effects of manure injection tool type and tool spacing on soil nutrient levels and spring barley performance**. Canadian Biosystems Engineering /Le génie des biosystèmes au Canada **48**: 2.45 - 2.54. A three-year field trial was conducted to study the effects of two manure injection tool types and three tool spacings on soil nutrient levels and crop response in a 2 x 3 factorial experiment. Liquid swine manure was injected using coulter and furrower injectors at 300- (S300), 600- (S600), and 900-mm (S900) tool spacings. Extractable soil NO$_3$-N, NH$_4$-N, P$_2$O$_5$, K, SO$_4$-S, pH, and electrical conductivity (EC), plant number of tillers, heads, and main stem length, plant biomass, grain and straw yields, total N and P in plant biomass, grain, and straw were measured. Application of manure with a furrower proved to be advantageous over a coulter in many ways. Use of a furrower resulted in 40 to 60% higher soil NO$_3$-N than a coulter at 0-300 mm soil depth at the time of rapid plant development in the second and third years of the experiment. Furthermore, use of a furrower resulted in 10% more plant biomass, 13, 3, and 16% higher total N in plant biomass, grain, and straw, respectively, and 2.5 and 13% higher total P in grain and straw, respectively, compared to use of a coulter in the first year of the experiment. Increased tool spacing decreased total N in plant biomass, grain, and straw. Soil nutrient levels also decreased with increase in tool spacing in one year of the study. In the other years, S300 resulted in higher soil NO$_3$-N and NH$_4$-N at 0-300 mm soil depth than S600. Plant number of tillers, heads, and main stem length in S300 were in some cases equivalent to and in other cases higher than those of S600 and S900. **Keywords:** manure, injection, tool, tool spacing, soil, nutrient, crop, yield.

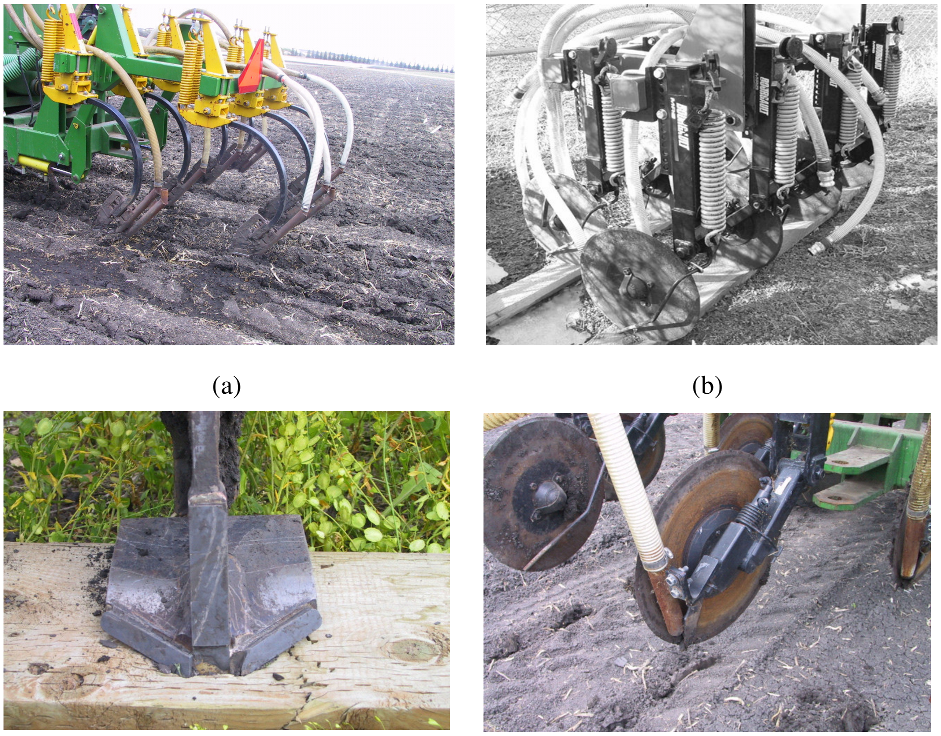
Une étude échelonnée sur trois ans a été entreprise pour examiner l'influence de l'espacement entre les outils pour deux types d'enfouisseurs de lisier sur le placement de nutriments et la production des cultures, par le biais d'un plan expérimental factoriel 2 X 3. Le lisier de porc était enfouis directement dans le sol avec soit des enfouisseurs du type`"coutre à disque" ou bien du type "soc patte d'oie" (profil en "V") espacés de 300- (S300), 600- (S600) ou 900-mm (S900). Les niveaux labiles de NO$_3$-N, NH$_4$-N, P$_2$O$_5$, K, SO$_4$-S, le pH et la conducitivité électrique (EC), la population de tiges, le nombre de gerbes, ainsi que la longueur de la tige principale, la biomasse totale, les rendements de grain et paille, les niveaux N et P totaux dans la biomasse récoltée ont tous été mesurés. L'enfouissement du lisier avec un soc est plus efficace qu'avec l'enfouisseur à disque à plusieurs égards. L'enfouissement avec un soc a favorisé des niveaux 40 à 60% plus élevés de NO$_3$-N que le coutre à disque pour les premiers 300 mm du sol au moment coïncidant à une croissance rapide de la culture durant la deuxième et troisième année de l'étude. L'enfouisseur à soc a résulté en une biomasse 10% plus élevée, des niveaux de N totale 13%, 3% et 16% plus élevés dans la biomasse, le grain et la paille, respectivement, ainsi que un P total 2.5% et 13% plus important dans le grain et la paille durant la première année de l'étude. La quantité de N totale mesurée dans la biomasse, grain et paille, décroît avec l'espacement plus grand entre les enfouisseurs. Les niveaux de nutriments dans le sol ont aussi décrût avec l'écartement plus grand entre les enfouisseurs pour une année de l'étude. Les autres années, S300 a permis des niveaux plus élevés de NO$_3$-N et NH$_4$-N dans les premiers 300 mm du sol que S600. Le nombre de tiges et gerbes, ainsi que la longueur de la tige principale avec S300 étaient soit équivalentes ou plus élevées que pour S600 et S900. **Mots clés :** lisier, injection, enfouissement, outils, espacement, sol, nutriment, culture, rendement.

INTRODUCTION

Land application of manure is considered the most economical management practice that enables recycling of the nutrients contained in manure. However, surface applications of liquid manure may lead to odour problems and nutrient losses due to surface runoff and ammonia volatilization. To maximize the returns from liquid manure and reduce environmental impact of applications, many livestock producers choose to inject the manure into the soil. Research findings also indicate that manure injection is preferable to surface application because it reduces odour, surface runoff, and loss of ammonia (Sutton 1994; Hoff et al. 1981), which eventually contributes to increased crop yields (Chen and Samson 2002; Mooleki et al. 2002).

Liquid manure injection involves selection of the right injection tool and tool spacing. Several types of injection tools, which include sweeps, discs, knives, chisels, and coulters, have been developed for injecting liquid manure below the soil surface. These tools are generally classified into two main groups: winged tools, such as furrowers and sweeps, and non-winged tools, such as discs, knives, and coulters. Winged tools place manure in wider bands and non-winged tools place manure in narrower bands (Rahman et al. 2004; Warner and Godwin 1988). Winged tools are more widely used compared to the non-winged ones because the former allow higher application rates and better soil-manure mixing (Chen and Tessier 2001).

Tool spacing determines the distance between manure bands. Narrow tool spacing may increase the capital cost of the


(a) (b)

(c) (d)

Fig. 1. Injection implement: (a) toolbar fitted with furrowers, (b) toolbar fitted with coulters, (c) close up of the furrower, (d) close up of the coulter.

injection equipment (more injection tools per unit working width of injector) and require more tractor power associated with the intensive soil cutting during the injection operations. Thus tool spacing should be selected in such a way that crops between manure bands can obtain manure nutrients to produce even crop response while at the same time, power requirement for field injection operations is reduced.

Wide tool spacing may contribute to inadequate crop nutrition (Warner and Godwin 1988). McCormick et al. (1983) sampled liquid swine manure injection bands and reported spatial differences in inorganic N concentrations in the injection zone. This observation was confirmed by Comfort et al. (1988) who suggested that due to the availability of C and NO_3-N in a reducing environment, rapid denitrification likely takes place in the manure injection zone. Warner and Godwin (1988) studied injection techniques for applying sewage and sludge to grassland. They found that large tool spacing caused uneven crop responses. Other studies have addressed soil and crop responses to varying swine manure application rates (Mooleki et al. 2002; Grevers and Schoenau 2001). However, there is little specific information regarding manure nutrients in soil and crop performance as affected by injection tool spacing under different injector types. This information is important to make practical recommendations for appropriate injection tool type and tool spacing as part of the best manure management practices.

The objective of this study was to examine effects of two injector types (furrower and coulter) and three tool spacings (300, 600, and 900 mm) on soil nutrient levels, plant development characteristics (plant number of tillers, heads, main stem length, biomass), and crop yield.

Table 1. Dimensions of the injection tools.

Tool type	Value
Furrower	
Width (mm)	120
Length (mm)	160
Sweep angle (°)	52
Rake angle (°)	11
Coulter	
Diameter (mm)	460
Gang angle (°)	14

MATERIALS and METHODS

Site description

The field experiment was conducted at the Brandon Research Centre, Brandon, Manitoba in the growing seasons of 2002, 2003, and 2004 on clay loam soils. The soil type at the 2002 field site was classified as an Orthic Black Chernozemic (Janick series) with clay loam surface texture developed on moderately to strongly calcareous silty clay to clay lacustrine deposits. In 2003 and 2004, the field trials were established on a Harding clay, Gleyed Black soil developed on moderately to strongly calcareous, silty clay to clay lacustrine deposits (Fitzmaurice et al. 1999). A broad-spectrum herbicide was applied to the 2002 field site before seedbed preparation. The site of the 2003 and 2004 field trials had very limited weed growth so only tillage was used to control weeds prior to seeding.

Field equipment

Liquid manure was applied to soil using an injection system equipped with a 4500-L manure tanker, a positive displacement pump, and a 2.1-m wide toolbar for mounting various injection tools in two gangs behind the tanker (Fig. 1a and 1b). The injection tools used (Fig. 1c and 1d) were named as coulter and furrower according to ASAE Standards (ASAE 2004). These two types of injection tools were selected because they create contrasting furrows during the injection process. A coulter creates narrow furrows whereas a furrower creates wide furrows. Dimensions of these injectors are summarized in Table 1. Manure was delivered from the tank to the injection tools via hoses of 48-mm diameter. A custom built seeder was used for seeding in 2002 and a 6200 IHC drill was used in 2003 and 2004. Both seeders had a 300-mm row spacing.

Experimental design

Manure injection treatments were arranged in a randomized complete block design. Twenty four plots (4.2 x 10 m) received manure injected using the aforementioned injection tools (coulter and furrower) at three tool spacings: 300 mm (S300), 600 mm (S600), and 900 mm (S900), with four replications. Each of the six treatment combinations was randomly assigned to a plot, forming four blocks.

Table 2. Dates of field operations and measurements.

Field activity	Year		
	2002	2003	2004
Manure injection	May 28	June 17	June 22
Seeding	June 4	June 20	June 25
First soil sampling	June 18	July 8	July 14
Second soil sampling	July 2	July 29	August 4
Third soil sampling	July 16	August 19	November 4
Fourth soil sampling	July 30	NA*	NA
Fifth soil sampling	August 13	NA	NA
Plant sampling	August 13	August 19	September 8
Yield harvesting	September 5, 11	September 3, 4	October 16

*NA = not applicable

Field operation procedure

Injection was performed after tillage with a heavy duty field cultivator and prior to seeding in the spring of each growing season. A custom built distributor delivered manure through flexible hoses to the injection tools. Manure was injected using seven, four, and three tools mounted on the toolbar for the S300, S600, and S900 tool spacing treatments, respectively. Manure was injected to a depth of 100 mm at an average rate of 34 m^3/ha for all plots and years. Manure flow rate from the tank was kept constant by maintaining a constant pumping rate during the entire manure injection operation. The travel speed of the injector was also kept constant. In all three years, plots were seeded to hulless spring barley (Cultivar: AC Bacon) a few days after manure injection. Dates for the field operations are given in Table 2.

Measurements

Soil and manure background Immediately prior to manure injection, soil samples were collected from five random plots across the entire field sites to determine the soil moisture content and bulk density. The sampling was done to a depth of 150 mm using 52-mm diameter core samplers. Soil moisture content and bulk density were determined by oven drying for 24 h at 105ºC. Manure samples were taken for analysis two weeks in advance of manure application. Electrical conductivity and pH measurements were performed on a 10:1 dilution of liquid manure with distilled water. Ammonia concentration in the diluted mixture was determined by an ion specific electrode against a certified standard. Moisture content was measured after oven drying to a constant weight at 105ºC. Total nitrogen was measured by standard Kjeldahl analysis (AOAC 1990). Total P, K, Ca, Na, Mg, and S were measured by total digestion of the sample in nitric/perchloric acid and analysed by inductively-coupled plasma spectrometry.

Soil nutrients Soil samples for nutrient analysis were collected along transects perpendicular to the travel direction of the injector. In each plot, three transects were identified in three random locations. Along the transects, samples were collected from positions located at 0, 150, 300, and 450-mm distances from the centre line of a manure band. Soil samples were collected five times to a depth of 300 mm in the growing season of 2002 and three times each growing season in 2003 and 2004 in two depth ranges (0-300 and 300-600 mm). The samples collected from the three locations per plot were mixed together depth-wise to form a composite sample of the respective position.

The soil samples were air dried and ground to less than 2-mm size prior to analyses. Samples collected in 2002 were analysed for extractable NO_3-N, NH_4-N, P_2O_5, K, SO_4-S, and pH and electrical conductivity (EC). In 2003 the soil samples were analysed for extractable NO_3-N, P_2O_5, and K. Soil samples collected in 2004 were analysed for extractable NO_3-N, NH_4-N, P_2O_5, and pH and EC. Methods used for analyses are presented in Table 3.

Plant tillers, heads, main stem length, and above ground biomass At the plants' soft dough stage, 20-40 plants were uprooted. The number of tillers and heads per plant were counted, and the main stem length of each plant was measured with a ruler. At the same time, a 500-mm wide plant strip was cut across each plot width to measure the amount of above ground biomass. The biomass samples were oven-dried at 60ºC for 72 h (ASAE 2004a) to determine the dry matter of the plant biomass. Total N and P in the biomass were determined on digested samples of ground plant biomass by the standard acid (H_2SO_4-H_2O_2) digestion method described in Thomas et al. (1967). A Technicon Autoanalyzer (Technicon Corporation, Terrytown, NY) was used to calorimetrically determine total N and P in the digest samples.

Grain and straw yield A plot combine was used to harvest the plots for yield measurements in 2002 and 2003. Entire plots were harvested and the harvest areas were calculated after adjustment for crop removal for the biomass measurement. In 2004, harvesting was done by hand, as wet soil and lodged crop did not allow for using the plot combine. Crop samples were collected by cutting a 1-m^2 area at three random locations from each plot. Samples were threshed in the lab. Grain and straw samples were separately weighed, oven dried at 60ºC for 72 h and weighed again to determine the dry matter of the grain and straw yields at 11% moisture content. Total N and P in the grain and straw were also determined the same way as for the ground biomass.

Statistical analyses

The data were analysed separately under each year using SAS software (SAS Institute Inc. 2001). Analysis of variance was carried out using the general linear model procedure to determine the means of each variable. Standard errors were used to determine differences among treatment means. All comparisons were made at a probability of 0.1 because of the inherent high variability of soil. The analyses results revealed that there were no interactions between the experimental factors (tool type and tool spacing). The main effects of the factors on soil nutrient levels and crop response are presented in the following sections.

Table 3. Methods used for soil analysis.

Soil property	Analytical method and reference		
	2002	2003	2004
NO_3-N	Cadmium reduction procedure (Maynard and Kalra 1993)	Sodium bicarbonate method (Olsen and Sommers 1982; Hamm et al. 1970)	Automated cadmium reduction method (Greenberg et al. 1992)
NH_4-N	Automated phenate method (Greenberg et al. 1992)	Not analysed	Automated phenate method (Greenberg et al. 1992)
P	Modified Kelowna soil test (Asworth and Mrazek 1995)	Sodium bicarbonate method (Olsen and Sommers 1982; Hamm et al. 1970)	Modified Kelowna soil test (Qian et al. 1994)
K	Automated flame photometry (Alberta Research Council 1996)	Sodium bicarbonate method (Olsen and Sommers 1982; Hamm et al. 1970)	Not analysed
SO_4-S	Automated methylthymol blue method (Clesceri et al. 1998)	Not analysed	Not analysed
pH	1:2 soil water extract (Hendershot et al. 1993)	Not determined	1:2 soil water extract (Hendershot et al. 1993)
EC	1:2 soil water extract (McKeague 1976)	Not determined	1:2 soil water extract (McKeague 1976)

Table 4. Growing season monthly air temperature and precipitation for the three years and averages of 16 years prior to 2002.

Growing season	Air temperature (°C)						Precipitation (mm)					
	April	May	June	July	August	Average	April	May	June	July	August	Total
2002	2	8	18	20	17	13	16	8	75	51	101	251
2003	5	12	16	20	22	15	45	42	65	5	28	185
2004	4	7	14	18	14	11	21	160	39	76	74	369
Average	4	12	17	19	18	14	24	60	71	77	58	291

Table 5. Soil (150 mm deep) bulk density and moisture content at the time of manure injection and composition of the manure applied (wet basis).

Term	Year		
	2002	2003	2004
Soil property			
Bulk density (Mg/m^3)	0.80	0.85	0.80
Gravimetric moisture content(%)	24	34	36
Manure characteristics			
Total N (kg/ML)	2.40	2.90	3.50
Organic N (kg/ML)	0.20	0.60	0.40
NH_4-N (kg/ML)	2.20	2.30	3.00
Nitrate and nitrite N (kg/ML)	0.10	0.10	0.10
Total P (kg/ML)	0.04	0.79	0.55
Total K (kg/ML)	1.32	1.51	1.84
Total S (kg/ML)	0.11	0.20	0.23
Solid content (%)	1.10	2.10	1.60
EC (dS/m)	15.85	18.10	19.80
pH	7.60	7.90	7.40

RESULTS and DISCUSSION

Weather conditions and soil and manure background

The monthly air temperature and precipitation data for the three growing seasons and averages of 16 years prior to 2002 are given in Table 4. The data were obtained from Brandon Research Centre weather station located within 1 km of the sites. The growing seasons of 2002 and 2003 were relatively dryer than the 16 year average whereas that of 2004 was the wettest and coldest of all.

Soil (150 mm deep) bulk density and moisture content and composition of the manure applied are presented in Table 5. At the time of manure application, the soils had low bulk densities as the measurement was done a few days after spring tillage. When averaged over three years, total N (2.9 kg /ML) and total P (0.6 kg /ML) in the manure were similar to and lower than the mean total N and mean total P in swine manure in Manitoba (Racz and Fitzgerald 2001), respectively. Approximately 90% of the total N existed in the form of NH_4-N. Total N, P, K, S, Ca, and Mg contents and EC in the manure used in 2003 and 2004 were higher than that used in 2002, whereas total Na and pH were similar.

Table 6. Levels of extractable NO_3-N (µg/g) in soil samples collected at different times and depths.

Year and factor*	Soil sampling time after injection and sampling depth					
2002	3 wk 0-300 mm	5 wk 0-300 mm	7 wk 0-300 mm	9 wk 0-300 mm	11 wk 0-300 mm	
Tool type						
Coulter	27.9a**	10.8a	6.6a	3.5a	1.6a	
Furrower	26.5a	13.1a	9.1a	2.9a	1.8a	
Tool spacing						
S300	32.3a	13.3a	9.3a	4.1a	2.2a	
S600	20.1b	8.4a	2.9b	1.9b	1.1b	
S900	29.4a	14.2a	11.1a	3.6a	1.8a	
2003	3 wk		6 wk		9 wk	
	0-300 mm	300-600 mm	0-300 mm	300-600 mm	0-300 mm	300-600 mm
Tool type						
Coulter	25.6a	14.0a	10.9b	11.0a	16.6b	9.3a
Furrower	28.4a	14.0a	17.5a	13.0a	20.9a	9.7a
Tool spacing						
S300	29.8a	13.1b	14.1ab	11.8a	18.3ab	10.0a
S600	25.8a	13.5b	11.8b	10.2a	16.7b	9.0a
S900	25.5a	15.5a	16.6a	14.0a	21.2a	9.5a
2004	3 wk		6 wk		19 wk (after harvest)	
	0-300 mm	300-600 mm	0-300 mm	300-600 mm	0-300 mm	300-600 mm
Tool type						
Coulter	19.4a	19.0a	11.3b	12.6a	4.8a	2.1a
Furrower	18.4a	17.5a	15.9a	14.2a	5.7a	2.7a
Tool spacing						
S300	21.7a	21.0a	13.1a	14.7a	5.5a	3.21
S600	20.7ab	18.7ab	14.4a	13.6ab	4.7a	1.8a
S900	14.2b	15.0b	13.5a	11.9b	5.6a	2.2a

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different ($P > 0.1$).

Extractable soil nutrient levels

Soil nitrate nitrogen (NO_3-N) Soil NO_3-N tended to be higher in plots where manure was applied using the furrower than in plots where manure was applied using the coulter (Table 6). However, there were no statistically significant differences observed at the 300-600 mm depth for all three years. At the 0-300 mm depth, use of the furrower rather than the coulter tended to result in higher levels of soil NO_3-N; this difference was significant in two out of three samplings in 2003 and in one out of three samplings in 2004. This is in agreement with results observed from dairy and swine studies conducted by Schmitt et al. (1995). They reported that, in Minnesota, levels of soil NO_3-N resulting from the use of winged tools were consistently higher than those from non-winged tools over the growing season. Similarly, Sawyer et al. (1990) reported increases in soil NO_3-N when using winged tools rather than non-winged tools for applying liquid beef manure in Illinois. Schmitt et al. (1995) suggested a twofold explanation for this observation. First, use of winged tools does not promote the levels of denitrification associated with using non-winged tools. Secondly, spatial distribution of manure might expedite mineralization of organic N as a result of shallower manure placement and increased contact between manure and soil.

Tool spacing also significantly affected the soil NO_3-N. However, mixed results were observed among years perhaps due to differences in weather conditions. In 2002, levels of soil NO_3-N for S300 and S900 were similar and higher by 77 and 74% (on average) than that for S600, respectively (Table 6). The reason why S600 resulted in lower NO_3-N than both S300 and S900 is unknown. In 2003, soil NO_3-N levels of S300 tended to be higher than those of S600 in both depth ranges, although they were not statistically significant (Table 6). Again, the significantly higher soil NO_3-N levels for S900 were not explainable.

Table 7. Levels of extractable NH_4-N (μg/g) in soil samples collected at different times and depths.

Year and factor*	Soil sampling time after injection and sampling depth			
2002	3 wk 0-300 mm	5 wk 0-300 mm	7 wk 0-300 mm	
Tool type				
Coulter	0.47a**	1.12a	0.56a	
Furrower	0.48a	1.26a	0.54a	
Tool spacing				
S300	0.45a	1.44a	0.51a	
S600	0.52a	0.90b	0.57a	
S900	0.46a	1.23a	0.57a	
2004	3 wk		6 wk	
	0-300 mm	300-600 mm	0-300 mm	300-600 mm
Tool type				
Coulter	17.3a	8.4a	10.8a	10.4a
Furrower	15.1a	8.5a	10.6a	10.6a
Tool spacing				
S300	13.4b	8.5a	11.7a	11.6a
S600	14.6b	8.2a	10.7a	9.9b
S900	20.6a	8.6a	9.7a	10.0b

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively. Data were not collected in 2003.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different ($P > 0.1$).

In 2004, the level of soil NO_3-N in S300 was similar to that of S600, and the same was true between S600 and S900 at both depth ranges (Table 6). However, S300 had significantly higher soil NO_3-N than S900 in one and two out of three sampling times at the 0-300 and 300-600 mm depths, respectively. This may be attributed to a possible greater denitrification loss in the S900 plots than in the S300 and S600 plots, favoured by a combination of large manure volume per manure band and the wetter soil condition in 2004.

With progress in the growing seasons, decreases in the overall soil NO_3-N were observed due to uptake by plants. At the last sampling, levels of soil NO_3-N were reduced by up to 95, 40, and 75% (maximum) of that at the first sampling following manure injection in 2002, 2003, and 2004, respectively, in the 0-300 mm soil depth.

Soil ammonium nitrogen (NH_4-N) Analyses were not done for soil NH_4-N on samples collected in 2003 due to a budget constraint. In comparison to 2002, more of the inorganic soil nitrogen was present in the form of NH_4-N in 2004 (Table 7). In the dry year (2002), most of the manure NH_4-N was possibly transformed to NO_3-N but in the wet year (2004) that did not occur. Probably the cooler temperature and wetter condition in 2004 reduced nitrification.

The type of injection tool did not affect the level of soil NH_4-N in 2002 and 2004 as indicated by the similar NH_4-N levels under both tools (Table 7). No particular trends were observed for spacing effects on the soil NH_4-N levels. Three and seven weeks after injection, there were no significant differences in the levels of soil NH_4-N between the tool spacing treatments in 2002. Five weeks after injection, soil NH_4-N of S300 and S900 were higher by 60 and 37% than that of S600, respectively. In 2004, three weeks after injection, soil NH_4-N increased with increasing tool spacing at the 0-300 mm depth; however it was not affected by the tool spacing at 300-600 mm depth. Six weeks after injection, soil NH_4-N decreased with the tool spacing at the 300-600 mm depth.

Over the growing season in 2002, soil NH_4-N during second sampling increased by more than 70% as compared to the first sampling, which may be due to net mineralization. At the third sampling, levels of soil NH_4-N were back to their values at the time of first sampling. Similarly, in 2004 levels of soil NH_4-N fluctuated over time. Again, this might be due to the combined effects of net mineralization and plant uptake.

Soil phosphate (P_2O_5) Significantly higher soil P_2O_5 levels were observed for the furrower than for the coulter in 17 observations over the three years (Table 8). Tool spacing also significantly influenced the level of soil P_2O_5. In 2002, S900 resulted in a higher soil P_2O_5 than S300 and S600 by 36 and 83%, respectively. This could be due to sampling errors. Eleven weeks after injection, S600 resulted in significantly lower level of P_2O_5 than S300 and S900. This isolated observation was also difficult to explain. In 2003, higher soil P_2O_5 was observed in the S900 plots than in the S300 plots in both ranges of soil depth six weeks after manure injection. Over the growing season of 2004, soil P_2O_5 of S300 was higher than those of S600 and S900. After harvest, however, levels of soil P_2O_5 in the S300 and S900 plots were not significantly different.

Potassium (K), sulphur (SO_4-S), pH, and EC Neither tool type nor the tool spacing affected levels of soil K, SO_4-S, pH, and EC. Therefore, no detailed data are presented. Instead values of these variables averaged over the growing season of each year are summarized in Table 9.

Crop performance

Plant tillers, heads, main stem length, and above ground biomass No significant differences were detected in plant number of tillers, heads, and main stem length between the furrower and the coulter in any of the three years. The furrower resulted in approximately 10% more plant biomass than the coulter in 2002 (Table 10); however, in 2003 and 2004, both tools yielded similar amounts of plant biomass.

In 2002, plant number of tillers, heads, main stem length, and above ground biomass followed a decreasing trend with increasing tool spacing (Table 10). This trend was significant for the biomass data among three tool spacing treatments. In 2003, there were no significant differences in any of the plant number of tillers, heads, main stem length, and biomass caused

Table 8. Levels of extractable P_2O_5 (µg/g) in soil samples collected at different times and depths.

Year and factor*	Soil sampling time after injection and sampling depth					
2002	3 wk 0-300 mm	5 wk 0-300 mm	7 wk 0-300 mm	9 wk 0-300 mm	11 wk 0-300 mm	
Tool type						
Coulter	101.1a**	84.5a	139.3a	83.0a	83.0a	
Furrower	106.1a	91.0a	126.2a	82.0a	90.5a	
Tool spacing						
S300	101.1a	84.5a	128.7b	81.0a	88.0a	
S600	101.6a	87.0a	95.5b	73.4a	81.5b	
S900	107.6a	91.5a	174.5a	93.5a	90.5a	
2003	3 wk		6 wk		9 wk	
	0-300 mm	300-600 mm	0-300 mm	300-600 mm	0-300 mm	300-600 mm
Tool type						
Coulter	12.9a	4.7b	10.5a	4.6a	13.5a	5.6a
Furrower	13.0a	5.7a	11.6a	4.8a	12.9a	4.7a
Tool spacing						
S300	13.1a	5.1a	10.0b	4.1b	12.9a	4.8a
S600	13.1a	5.2a	11.4ab	5.0a	12.7a	5.6a
S900	12.7a	5.1a	11.8a	5.1a	14.1a	5.2a
2004	3 wk		6 wk		19 wk (after harvest)	
	0-300 mm	300-600 mm	0-300 mm	300-600 mm	0-300 mm	300-600 mm
Tool type						
Coulter	77.7a	53.6a	59.4a	57.8a	65.3a	54.0a
Furrower	73.7a	54.7a	61.1a	54.3a	63.2a	51.4a
Tool spacing						
S300	76.0a	64.3a	69.3a	68.4a	70.9a	64.0a
S600	72.3a	51.5b	55.9b	48.5a	55.9b	44.7a
S900	78.9a	46.7b	55.6b	51.2a	665.9a	49.4a

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different ($P > 0.1$).

Table 9. Average values of extractable soil K (µg/g), SO_4-S (µg/g), pH, and EC (dS/m) in different years at different sampling depths.

Factor*	K			SO_4-S	pH			EC		
	2002	2003		2002	2002	2004		2002	2004	
	0-300 mm	0-300 mm	300-600 mm	0-300 mm	0-300 mm	0-300 mm	300-600 mm	0-300 mm	0-300 mm	300-600 mm
Tool type										
Coulter	482	269	224	8	7.68	7.54	8.06	0.63	0.59	0.70
Furrower	479	279	229	10	7.70	7.47	7.93	0.61	0.56	0.81
Tool spacing										
S300	484	267	221	9	7.71	7.53	7.97	0.66	0.60	0.74
S600	463	275	231	9	7.71	7.50	8.04	0.58	0.55	0.65
S900	495	279	228	10	7.64	7.48	7.97	0.62	0.57	0.87

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

Table 10. Plant number of tillers, heads, main stem length, and above ground biomass.

Year and factor*	No. of tillers	No. of heads	Main stem length (mm)	Biomass (kg/ha)
2002				
Tool type				
Coulter	2.8a**	2.5a	582a	6702b
Furrower	3.1a	2.8a	572a	7339a
Tool spacing				
S300	3.1a	2.7a	587a	7545a
S600	3.0a	2.7a	573a	6853b
S900	2.8a	2.5a	571a	6663b
2003				
Tool type				
Coulter	2.2a	1.8a	510a	4445a
Furrower	2.3a	1.9a	512a	4390a
Tool spacing				
S300	2.3a	1.9a	500a	4322a
S600	2.3a	1.9a	516a	4446a
S900	2.1a	1.7a	517a	4484a
2004				
Tool type				
Coulter	7.2a	6.2a	959a	8471a
Furrower	7.2a	6.6a	972a	8355a
Tool spacing				
S300	7.9a	7.2a	978a	8473a
S600	6.6b	5.9b	949b	8306a
S900	7.1ab	6.1b	969a	8459a

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different (P > 0.1).

by the tool spacing. In 2004, S300 resulted in higher plant number of tillers and heads and longer main stem than S600 and S900. There were no differences in above ground biomass between the spacing treatments in that year.

Grain and straw yields It is obvious that grain yields were dictated by the weather conditions. Both grain and straw yields were the lowest in the driest growing season of 2003 and they were highest in the wettest growing season (2004) (Table 11). The low yield in 2003 may be explained by the fact that the plant nutrient uptake was undermined by dry weather conditions (Table 11).

No significant differences were detected in grain yield between the furrower and the coulter (Table 11). Tool spacing did not significantly affect grain and straw yields in any of the growing seasons. Differences in grain yield due to injection tool type and spacing may have been masked due to the effect of late seeding on grain yield. Sawyer et al. (1991) reported inconsistent results in grain yield among tool types. Schmitt et al. (1995) observed higher grain yield when using winged tools than non-winged tools.

Warner and Godwin (1988) examined grass response to injected sewage sludge at various injector tool spacings and found that a 650-mm tool spacing resulted in higher grass yield than 500 and 850-mm tool spacings. Eghball and Sander (1989) studied band spacing effects of dual-placed N and P fertilizers on corn. Their observation was similar to the results of this study in that band spacing did not affect corn yield unless either N or P deficiency dominated the total input of the dual placed band. Results of this study agree with findings of Maxwell et al. (1984) who reported that 250 and 380-mm spacings resulted in more uniform plant growth and dry matter production early in the growing season, but the effects on yield were not significant, when compared to 500-mm spacing.

Total N and P in plant biomass, grain, and straw In 2002, as compared with the coulter, the furrower resulted in higher levels of total N in the plant biomass, and total N and P in grain and straw (Table 12). In 2003 and 2004, the amounts of total N and P in plant biomass, grain, and straw were similar when manure was applied using either the coulter or the furrower. One exception was that, in 2004, 10% higher total N and 21% lower P in straw were measured when using the furrower rather than the coulter.

Tool spacing did not significantly affect total N and total P in plant materials in 2002 (Table 12). In 2003 and 2004, S300 had higher plant nutrient values than S600 and S900. Statistically significant differences were observed for total N and total P in grain in 2003 and for total N in biomass in 2004.

CONCLUSIONS

Compared to the coulter-type, the furrower-type injection tool offered a slight advantage in terms of increased soil nitrate, plant biomass production, total N concentration in biomass, grain and straw, and total P in grain and straw. Among the tool spacings of 300, 600, and 900 mm, the 300-mm spacing resulted in higher levels of soil nitrate. Although the narrowest injection tool spacing did not offer any advantage over the other tool spacings in terms of yield response, better plant development and higher plant biomass production were observed for the 300-mm tool spacing, which is important with regard to nutrient cycling in agricultural systems. Considering the resultant higher levels of soil nitrate and better crop performance, the furrower-type tool spaced 300-mm apart was the best choice for liquid manure injection in spring barley production. It would be of particular interest to perform similar experiments on different soil types, and under varying climatic conditions, to confirm the observed trends since this experiment was carried out on heavy clay-loam lacustrine soils under less than optimum growing conditions.

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Table 11. Grain and straw yields for different treatments in three years.

Factor*	Grain yield (kg/ha)			Straw yield (kg/ha)		
	2002	2003	2004	2002	2003	2004
Tool type						
Coulter	2959a**	1229a	3744a	1776a	1194a	4702b
Furrower	2850a	1286a	3612a	1712a	1207a	5089a
Tool spacing						
S300	2896a	1276a	3522a	1713a	1271a	4962a
S600	2893a	1306a	3837a	1773a	1181a	4977a
S900	2924a	1190a	3674a	1745a	1150a	4748a

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different (P > 0.1).

Table 12. Total N (TN) and P (TP) in plant biomass, grain, and straw.

Year and factor*	Biomass		Grain		Straw	
	TN (%)	TP (%)	TN (%)	TP (%)	TN (%)	TP (%)
2002						
Tool type						
Coulter	1.32b**	0.18a	1.91b	0.40b	0.93b	0.15b
Furrower	1.50a	0.17a	1.97a	0.41a	1.08a	0.17a
Tool spacing						
S300	1.40a	0.17a	1.96a	0.40a	1.03a	0.16a
S600	1.47a	0.18a	1.93a	0.40a	1.00a	0.15a
S900	1.37a	0.18a	1.93a	0.41a	0.97a	0.16a
2003						
Tool type						
Coulter	1.84a	0.11a	2.30a	0.32a	1.41a	0.05a
Furrower	1.90a	0.12a	2.25a	0.32a	1.40a	0.05a
Tool spacing						
S300	1.95a	0.12a	2.35a	0.34a	1.46a	0.06a
S600	1.83a	0.12a	2.22b	0.31b	1.41a	0.05a
S900	1.82a	0.11a	2.25b	0.32ab	1.36a	0.05a
2004						
Tool type						
Coulter	2.5a	0.14a	2.0a	0.29a	1.37b	0.14a
Furrower	2.5a	0.14a	2.0a	0.31a	1.50a	0.11b
Tool spacing						
S300	2.6a	0.14a	2.1a	0.31a	1.47a	0.13a
S600	2.5ab	0.15a	2.0a	0.30a	1.40a	0.13a
S900	2.4b	0.14a	2.0a	0.30a	1.44a	0.12a

* S300, S600, and S900 refer to 300-, 600-, and 900-mm tool spacing treatments, respectively.

** Mean values for each factor within a year and a column followed by the same letter are not significantly different (P > 0.1).

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