Improving nitrogen and phosphorus response of corn (*Zea mays* L.) to dairy slurry by precision injection: benefits and risks

Derek Hunt[1], Shabtai Bittman[1], Coby Hoogendoorn[2] and Hongjie Zhang[1]

[1] Agriculture and Agri-Food Canada, Box 1000, Agassiz, BC, Canada, V0M 1A0, derek.hunt@agr.gc.ca
[2] Independent Researcher, 15 Beattie St, Feilding, New Zealand, 4772

Abstract
We evaluated the benefits and risks of precision planting corn near dairy slurry injection furrows (DS-I) in terms of crop performance and environmental impact relative to mineral fertilizer (MF) and broadcast/ incorporated (DS-B) slurry. The study was conducted in 2010-2014 on silty loam in a cool maritime climate in south coastal BC, Canada. Injected manure improved N and P uptake and yield relative to broadcast manure at all application rates. Phosphorous (P) uptake was comparable or better than fertilizer but nitrogen (N) uptake was lower. Apparent N uptake (% of applied N adjusted for control), depending on application rates, was 53-79% for MF, 41-53% for DS-I, 36-42% for DS-B. Crop response to DS-I plus starter (i.e. DS-I+S) approached MF for most variables and for P uptake it was higher. DS-I had about two times higher emissions of nitrous oxide (N_2O) than DS-B due to greater emission peaks within a month of nutrient application; N_2O emissions were slightly higher than IPCC factors for DS-I but substantially lower for DS-B. Movement of nitrate below the root zone had modest peaks after application and after summer drought but unlike N_2O continued through the cool rainy season. The study showed that precision injection improves corn performance compared to conventional methods but to reach maximum yield either starter fertilizer or relatively high N manure rates are required.

Key Words
Dairy slurry, Nitrogen, Phosphorus, Corn, Nitrous oxide, Nitrate

Introduction
Slurry manure is an important source of plant nutrients for corn (*Zea mays* L.) on many dairy farms in Canada (Sheppard et al. 2011) but effective use of slurry manure as a nutrient source is constrained by nitrogen (N) losses (e.g. ammonia volatilization) and nutrient (N and phosphorous (P)) imbalances (low N:P ratios). Corn yield and N uptake from dairy slurry manure (DS) can be improved by injection while precision-injecting liquid manure near corn rows may increase crop responses to both N and P (Bittman et al 2006; Bittman et al 2012; Schröder et al. 2015). The injected manure poses low risk of ammonia loss because of limited exposure to the atmosphere but concentrating N in wet, anaerobic conditions poses risk of pollution swapping, namely, increased nitrous oxide (N_2O) emissions and nitrate (NO_3) leaching (Cameron et al 1996, Dell et al 2011).

The objectives of this study were to 1) assess the efficacy of N and P from repeated applications of DS precision injected in corn relative to conventional broadcast application of DS or mineral fertilizer (MF); 2) assess the effect of precision injection of DS on emissions of N_2O and leaching of NO_3^-.

Methods
The study was conducted in 2010-2014 on silty loam soil in a moist, maritime climate. The DS (dry matter, 6.0%; total N, 2.54 mg/g; ammonium (NH_4^+)-N, 1.45 mg/g; P, 0.41 mg/g; pH, 7.2) was obtained from typical high-producing dairy farms that use sawdust bedding.

Our study was arranged in a Randomized Complete Block design and the main treatments were structured as a 3 (nominal total-N rates) x 4 (nutrient practices) factorial plus a control (Table 1). The nominal application rates of total-N were 80, 160 and 240 kg/ha with P doses (for DS) averaging about 16% of N. Some plots also received starter MF at 20 and 32 kg/ha of N and P, respectively. The nutrient practices were: 1, conventional MF (starter + broadcast NH_4^+ nitrate); 2, DS applied by broadcasting and rapid incorporation (DS-B); 3, DS applied by precision injection near the corn rows (DS-I); and 4, DS injected near the corn rows (as in 3) plus starter MF (DS-I + S) to establish maximum crop response at each manure application rate. There was also a zero nutrient control (reported here) and additional treatments that served as controls that are not reported here. The DS was injected 12-15 cm deep using double disk openers at 75 cm (corn row) spacing between May 7-19. Corn was planted in 7 m long, 4-row plots within 2- 8 days following manure application. The corn rows were carefully placed within 10 cm of the injection furrows (Bittman et al. 2012) using a John Deere corn planter fitted with no-till openers. Starter fertilizer was side-banded with the planter at 5 cm to side and 5 cm below the seed. The DS-B treatments were roto-tilled to 15 cm to incorporate the manure within 2 h of manure application. Nitrogen fertilizer (MF treatment) was applied by broadcasting immediately after corn planting and other nutrients (potassium , sulfur, Zinc) and lime were applied according to soil test.

Corn was sampled at 6 leaves (early July) and at harvest (late Sept. to early Oct.); samples were dried at 60 °C until constant weight (± 0.5 g) and grounded. Subsamples were analyzed for N using Dumas method (Leco, FP 428) and for P by digestion and spectrophotometer. Selected treatments were sampled for N_2O according to Hunt et al. (2016) except that 3 chambers (15 x 30 cm by 15 cm high) were used on most plots to account for spatial variability; 2 chambers were placed across the injection furrow and one placed mid-way between the corn rows. Emissions were calculated based on chamber placements. Annual emissions were determined by linear interpolation. Soil water samples for NO_3^- analysis were collected at 45 cm depths (below most corn roots) and mid-way between injection furrows with ceramic cup suction lysimeters generally 1-2 times per week when there was extractable water. Water samples were tested for both NH_4^+ and NO_3^- using a flow injection auto-analyzer. Apparent N recovery was calculated as $(N_{treatment} - N_{control})/N_{applied}$.

Results were analyzed by PROC MIXED (SAS Institute, 2011) with blocks as random effects and years and treatments as fixed effects.

Table 1. Nutrient application rates and methods for 3 x 4 factorial experiment to evaluate precision injection of dairy slurry (DS) compared to mineral fertilizer (MF) in a coastal temperate climate.

Nutrient	Symbol	Method	Rate	Starter	Application rates (kg/ha/yr) Total N	NH_4^+-N	P
Control	CTR	-	-	-	0	0	0
Fertilizer	MF	Broadcast	Low	+	81	81	32.0
Fertilizer	MF	Broadcast	Med	+	163	163	32.0
Fertilizer	MF	Broadcast	High	+	244	244	32.0
DS	DS-B	Broadcast	Low	-	81	45	12.8
DS	DS-B	Broadcast	Med	-	163	90	25.8
DS	DS-B	Broadcast	High	-	244	134	38.7
DS	DS-I	Inject	Low	-	81	45	12.8
DS	DS-I	Inject	Med	-	163	90	25.8
DS	DS-I	Inject	High	-	244	134	38.7
DS	DS-I + S	Inject	Low	+	105	69	44.8
DS	DS-I + S	Inject	Med	+	187	114	57.8
DS	DS-I + S	Inject	High	+	268	158	70.7

Results and Discussion

Year effects and treatment x year interactions were significant ($P < 0.05$) but as no clear temporal trend emerged only over-years results were presented. There were significant ($P < 0.05$) effects of rates, methods and rate x methods interactions for yield, N and P uptake at corn harvest, but there was no significant interaction for harvest index and for P uptake at the critical 6-leaf stage when P deficiency in corn was frequently observed (Table 2). Precision injected slurry (DS-I) performed better than broadcast slurry (DS-B) across N rates for all variables. Response to DS-I was less than MF and less than DS-I + S except for P uptake showing that precision injection slurry is an effective source of P.

Table 2. Statistical significance (P values) of nutrient rate, nutrient method and interaction of several response factors (yield, harvest index and N and P uptake) at corn maturity and of P-uptake also at 6-leaf stage.

	Yield	Harvest Index	N uptake	P uptake	P Uptake (6 leaves)
Nutrient Rate	< 0.001	< 0.001	< 0.001	<0.001	<0.001
Nutrient Method	< 0.001	0.012	< 0.001	<0.001	<0.001
Mineral fertilizer	A[1]	AB	A	AB	C
Dairy slurry-broadcast	C	B	D	C	D

Dairy slurry-injected	B	A	C	B	B
Dairy slurry-injected +starter	A	A	B	A	A
Nutrient Rate x Nutrient Method	<0.001	NS	<0.001	<0.002	NS

[1]nutrient methods for each response variable not followed by the same letter are significantly different at P<0.05

The interaction of rates and methods is shown for yield in Fig. 1. Yield with DS-I is consistently higher than with DS-B at all rates. Yield of DS-I approaches that of MF at over 200 kg N/ha (approx. 120 kg of available NH_4-N). Similar yield was achieved at about 120 kg NH_4^+-N/ha from DS-I as 160 kg N/ha from MF suggesting that about 30-40 kg N/ha were mineralized from the current and historical applications of DS-I (about 35% of organic N fraction). The data indicate that apparent N recovery from DS-I is about 41-53%. In contrast, apparent recovery from DS-B is only 36-42% likely due in part to volatilization after broadcasting. Relatively poor apparent N recovery in DS-B may also be attributed to substantially lower P recovery than DS-I, especially at the critical 6-leaf stage when P deficiency in corn is often noted (Fig. 2). At the low N application rate, yield from DS-I + S was similar to that from MF despite about 35 kg less available N in the former (Fig. 1). However, the DS-I + S treatment received considerably more precision-placed P (from mineral and DS sources) and had much higher early P uptake (Fig. 2). These results show the importance of considering both the N and P from the current and previous applications when assessing crop responses to various nutrient sources.

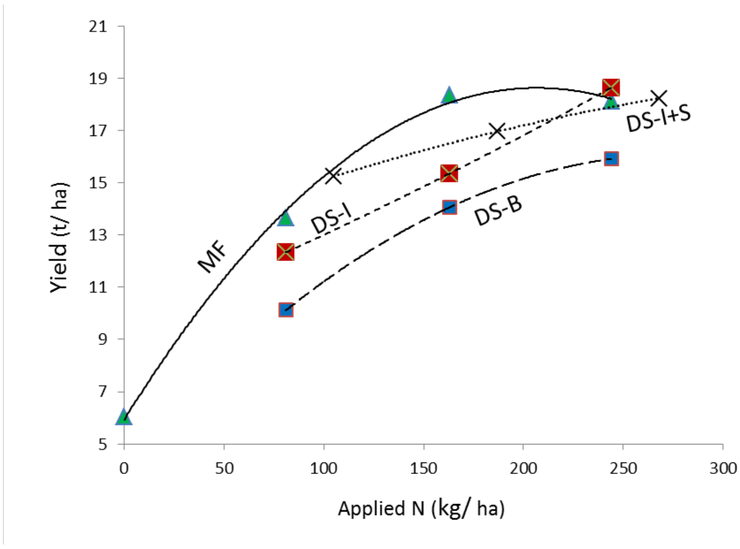

Figure 1. Yield (2010-14) of corn at mature harvest as affected by mineral fertilizer (MF) and dairy slurry (DS) applied by broadcasting (DS-B), injection (DS-I) and injection plus starter (DS-I + S) at different rates of total N.

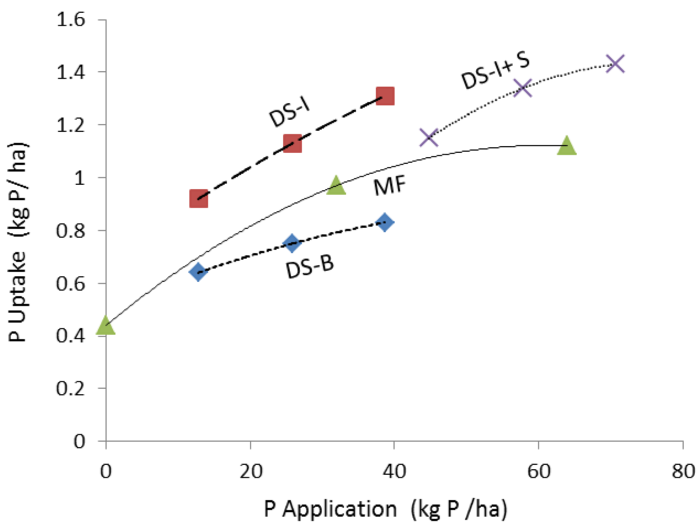

Figure 2. P-uptake (2010-14) by corn at 6-leaf stage as affected by mineral fertilizer (MF) and dairy slurry (DS) applied by broadcasting (DS-B), injection (DS-I) and injection plus starter (DS-I+ S) at different rates of P.

There was relatively little difference in N_2O emissions from MF and DS-B but injecting DS resulted in significantly higher emission rates (Fig. 3). This was expected due to the concentration of N in wet anaerobic injection furrows (Wulf et al 2002). The emission peaks lasted about a month after nutrient application probably because the manure band has become drier and very little emissions occurred at other times, even during freeze-thaw cycles. Overall emission factors were less than 0.5% for DS-B, just over 0.5% for MF compared to about 1.4% for the equivalent N rate applied as DS-I.

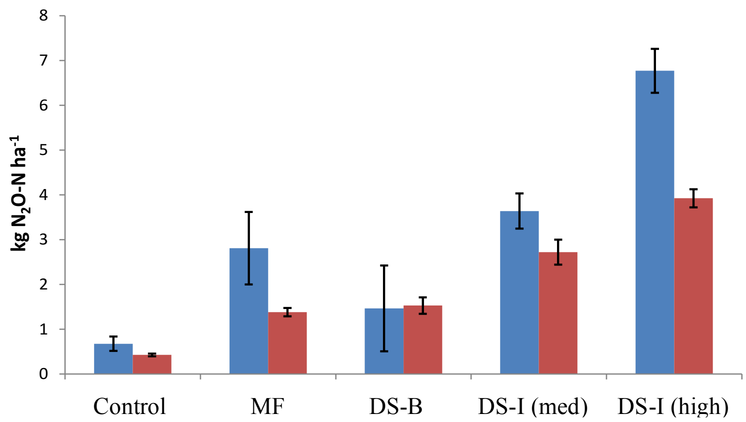

Figure 3. Annual emissions of nitrous oxide (kg N_2O-N/ ha) in 2011 (blue) and 2012 (red) as affected by applications of mineral fertilizer (MF) and dairy slurry (DS) applied by broadcasting (DS-B) and injection (DS-I) at medium and high N rates (vertical bars are standard errors).

Preliminary analysis of the lysimeter water data showed the highest NO_3^- concentrations after nutrient application and after summer drought. Unlike N_2O emissions, NO_3^- was measured well after nutrient application including early summer, fall and winter. This suggests that soil remains active and releases N for much of the year and that low N_2O emissions may be due to NO_3^- leaching and complete denitrification to N_2 during the wettest periods.

Conclusions

This study showed that precision injection of dairy slurry can provide sufficient P for crop production but yield will be somewhat restricted due to lower N availability from current and historical applications. The apparent N availability from multi-year applications was 53-79% for MF compared to 41-53% for DS-I and 36-42% for DS-B. Injection increased N_2O emissions losses and perhaps also N_2, and there was increased concentrations of NO_3^- especially under the injection furrows, although NO_3^--N rarely exceeded the drinking standard of 10 mg Nkg^{-1}. Further work is being conducted to mitigate N losses from injected DS.

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