MEASURING AND MODELING NITRATE-NITROGEN MOVEMENT IN SOILS FOLLOWING MANURE INJECTION

A thesis submitted to the
Faculty of Graduate Studies of the University of Manitoba
in partial fulfillment of the requirements for the

Degree

of

Doctor of Philosophy

by

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FACULTY OF GRADUATE STUDIES

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ABSTRACT

Injection spacing and lateral movement of manure nutrients in the soil following manure injection are important characteristics to determine proper liquid manure placement in soil. A three-year manure injection field experiment was conducted in Manitoba, Canada in the growing seasons of 2002, 2003, and 2004 on clay soils. Liquid swine manure was injected into soils in spring using coulter and furrower injectors at 0.3-, 0.6-, and 0.9-m tool spacings which correspond to three manure application rates: 1.02, 2.04, and 3.06 litters per meter of manure band. Effects of the two manure injection tool types and three tool spacings on the overall soil nutrient levels and crop response and soil nutrient distribution and crop response at different lateral positions relative to injected manure bands were investigated. Measured soil variables include: extractable soil NO_3-N, NH_4-N, P_2O_5, K, SO_4-S, pH, and electrical conductivity (EC). Soil variables were measured on soil samples collected at 0, 0.15, 0.30, and 0.45 m lateral distances from the centre lines of manure bands. Measured plant variables include number of tillers, heads, and main stem length, plant biomass, grain and straw yields, total N and P in plant biomass, grain, and straw.

Injection of manure with furrower proved to be advantageous over coulter in many ways. Use of furrower resulted in 40 to 60% higher soil NO_3-N than coulter at 0-0.3 m soil depth at the time of rapid plant development in the second and third years of the experiment. Furthermore use of furrower resulted in 10% more plant biomass, 13, 3, and 16% higher total N in plant biomass, grain, and straw, 2.5 and 13% higher total P in grain and straw, respectively, compared to the use of coulter in the first year of the experiment. Among tool

spacings, the 0.3 m tool spacing resulted in the best plant performance and the most elevated nutrients in plant parts as compared to the 0.6 and 0.9 m spacings.

The soil NO_3-N, NH_4-N, and P_2O_5 concentrations and soil EC were significantly lower at a farther position from the centerlines of manure bands, especially at the highest manure application rate. Plants in the crop row further from a manure band had 25% fewer tillers, 20% fewer seed heads, 10% shorter stem length, 60% less plant biomass, and 25% lower total N in the plant biomass, compared to those in the crop row close to the band.

A soil sampling protocol that enables accounting for banding effects of manure injection was developed based on soil nutrients data from the field study. A *directed paired-sampling* approach (sampling at two positions along a transect perpendicular to the injector travel direction) was suggested to obtain more accurate estimates of average soil NO_3-N and P concentrations than the traditional random sampling method.

A model for simulating NO_3-N movement in cropped soils following manure injection was developed. The domain for modeling NO_3-N movement was a cross sectional area defined by two hypothetical lines, each mid way between centerlines of two consecutive manure bands in the vertical plane. Hydrus-2D software package was used to calibrate and validate the model. The model was validated using a separate set of data collected from field experiments (different from those used to calibrate the model). The model predicted soil NO_3-N concentrations satisfactorily over the growing season and laterally at 0.0, 0.15, 0.30, and 0.45 m distances from center line of manure band. Model predictions at the abovementioned lateral distances from manure band revealed that manure nitrate nitrogen does not move laterally beyond 0.15 m from the manure band. The model predictions were consistent with the experimental data.

Keywords: manure, injection, tool, tool spacing, soil, nutrient, crop, yield, position, sampling protocol, modeling, nitrate movement

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NOTATIONS USED IN CHAPTER 6

Symbol	Description
a	Constant
$a(h)$	Prescribed function of soil pressure head
α	Retention curve-fitting parameter
a_v	Air content
β	Empirical coefficient
b	Vector of optimized parameters
c	Solute concentration in soil solution
c_{im}	Solute concentration in mobile region
c_r	Solute concentration of in flow sink term
D	Diffusion-dispersion coefficient of solute
D_h	Dispersion coefficient of solute
D_L	Longitudinal dispersivity
D_s	Diffusion coefficient of solute
D_T	Transversal dispersivity
D^w	Dispersion coefficient in the liquid phase
E	Maximum potential infiltration rate or evaporation
F	Coefficient
f	Fraction of exchange sites
G	Coefficient
g	Gaseous phase
γ_g	Zero-order rate constants for the gas phases
γ_s	Zero-order rate constants for the solid phases
γ_w	Zero-order rate constants for the liquid phases
h	Pressure head
h_A	Minimum pressure head under prevailing soil conditions
h_s	Maximum pressure head under prevailing soil conditions
J_c	Solute flux
J_d	Diffusive solute flux
J_h	Dispersive solute flux
k	Empirical coefficient
K	Hydraulic conductivity of soil
K^{A}	Anisotropy tensor
$K(h)$	Unsaturated hydraulic conductivity

K_r	Relative hydraulic conductivity
K_s	Saturated hydraulic conductivity
l	Retention curve-fitting parameter
m	Retention curve-fitting parameter
m	Retention curve-fitting parameter
μ_g	First-order rate constants for solutes in gaseous phase
μ_g'	First-order rate constants for individual chain species in gaseous phase
μ_s	First-order rate constants for solutes in solid phase
μ_s'	First-order rate constants for individual chain species in solid phase
μ_w	First-order rate constants for solutes in liquid phase
μ_w'	First-order rate constants for individual chain species in liquid phase
n	Retention curve-fitting parameter
η	Empirical coefficient
n^*	Number of observations
NU	NO_3-N uptake by plant roots
ω	Mass transfer coefficient for solute
q	Volumetric flux density
$q(x,z,t_i)$	Specific measurements
$q(x,z,t_i,b)$	Corresponding model predictions
R	Retardation factor
ρ	Soil bulk density
R_s	Sink or source term in transport equation
S	Sink term in water flow equation
s	Solid phase
S_e	Relative saturation
$S_{\max}$	Potential water uptake rate
t	Time
θ	Volumetric water content
θ_m	Mobile volumetric water content
θ_r	Residual volumetric water content
θ_s	Saturated volumetric water content
v	Velocity of soil solution
$\bar{v}$	Average velocity of soil solution
v_j	Weights associated with particular measurement set
w	Liquid phase
w_{ij}	Weights associated with a particular point

x	Lateral coordinate
z	Vertical coordinate

CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Current environmental concern due to agricultural activities is a commonplace issue. Specialized farming activity, particularly livestock production, has become a global concern in terms of nutrient cycling. While the specialized farming brought about reduction in the total number of farms, at the same time, it resulted in intensified and expanded individual livestock operations. The shift is not only in terms of farm number and size but also in species type. Swine production has an accelerating growth whereas that of cattle is decelerating. For example, in Canada, compared to 1991, cattle production increased by 14.8 and 19.9% in contrast to swine production increase by 8.1 and 36.6% in 1996 and 2001, respectively (Statistics Canada 2001).

The increase in the amount of manure produced due to the expanding livestock production, particularly swine, is obvious. Consequently improved manure management is one of the recommended actions for nutrient recycling. Recognizing the value of manure is the basis for proper treatment of manure with consideration from economical and environmental standpoints (Schroder 2005). This is contrary to biased social and cultural perceptions that regard manure as a waste.

Manure has been a major source of nutrients for crop production. Salter and Scholenberger (1938) reported that, owing to its nutrient and humus content, manure's value in maintaining and improving soil productivity had been recognized since earliest times. Use of manure as a primary source of crop nutrient was disrupted by the appearance of commercial nutrients in early 1950's and was ignored up until 1970's (Nowak et al. 1998). Once again, it has been recognized as an alternative resource that can be used in place of fertilizers to supply the nutrients required in crop production. However, it has not gained its original status yet and this may remain so for years to come. Nowak et al. (1998) pointed out how, in the last century, manure underwent transition from a situation where it was perceived as the means to agronomic, economic, and spiritual viability to a situation today where it is viewed as a waste. They also emphasized the negative implications of calling manure a waste as opposed to an on-farm nutrient source, which makes it unattractive for farmers to invest time, money, and effort into managing manure. "Public research dollars are invested in this topic under the rubric of waste management, public committees and groups debate programs to manage this waste, and farmers largely treat it as a waste" (Nowak et al. 1998).

The challenges of manure management are manifold such as nutrient variability in manure both in terms of forms and amount, soil nutrient variability, and engineering problems leading to non-uniform application rates (Karlen et al. 2004; O'Dell et al. 1995). Though achieving optimum manure management is a not a simple task, Karlen et al. (2004) suggested that it would be possible to use liquid swine manure as a resource while sustaining the balance between agronomy, environment, and economy.

Manure management systems consist of five main components namely: collection, storage, treatment, transfer, and use/disposal (Stonehouse et al. 2002; MAF 2001), use of manure being the most important component. In Manitoba regulations require that manure be applied to agricultural land. If properly managed, it will enable effective utilization of the nutrients contained in manure without posing environmental impact. Liquid swine manure may be surface applied or injected into the soil. As compared to injection, surface application is less costly; however, it has many disadvantages such as potential for odor emissions, surface runoff, and loss of ammonia via volatilization (Meisinger and Jokela 2000; Schmitt et al. 1995; Sutton et al. 1982).

Injection of liquid swine manure is a superior method to surface application in terms of reducing odor, runoff, and loss of ammonia (Misselbrook et al. 1996; Pain et al. 1991), which eventually contributes to increasing crop yields (Chen and Samson 2002; Mooleki et al. 2002). Swine manure is commonly handled in the liquid form perhaps due to ease of mechanization and low labor requirement (Zhang and Westerman 1997). The superiority of injection method coupled with preference (due lack of choice) to handle swine manure in liquid form make injection the recommended method of liquid manure application.

A large body of research on manure exist that spans from science to social issues (AAFRD 2004). In an effort to fine tune land application in general and injection in particular a great deal of research has been accomplished with significant contribution to making land application of manure a sustainable way of utilizing/managing manure. Such studies include: design and selection of injection tools (Godwin et al. 1976; McKyes et al. 1977; Warner and Godwin 1988; Chen 2002; Chen and Tessier 2001; Chen and Ren 2002), injection tool effects on soil-manure mix zone (Rahman et al. 2004), injection tool working depth and speed (Rahman and Chen 2001; Rahman et al. 2001; Rahman et al. 2005a), effects of injected manure on crop and soil properties (Mooleki et al. 2002, Assefa et al. 2004), development of low disturbance liquid manure injection systems by the Prairie Agricultural Machinery Institute (PAMI 2002). Yet there is limited research that attempted to establish a relationship between injection tool spacing and lateral soil nutrient distribution and crop performance. Addressing this issue will complement previous findings in the area of liquid manure injection bringing it a step forward to being whole. This was the purpose of this study. Injected manure band was used as an important point of reference in the overall study. A manure band may be defined as the manure that has been placed into a slot in the soil formed by an injection tool along the direction of travel. Any effect arising from such placement of manure is considered as a banding effect.

1.2 Objectives

The general objective of this study was to identify the best injection tool type and spacing that will give optimal nutrient movement and crop performance without compromising soil quality. The specific objectives were:

1. to examine the effects of selected injector tool types and spacings on soil nutrient levels, plant development characteristics, and crop yield,
2. to investigate soil nutrient levels and crop performance at different lateral positions relative to the centerline of injected manure band, under different rates and different injector types,
3. to develop a soil sampling protocol that accounts for banding effect of manure injection,
4. to develop and validate a model to simulate manure NO_3-N movement in the soil over a growing season following manure injection.

1.3 Thesis structure

This thesis has been structured in paper format. General introduction and literature review are presented in chapters 1 and 2. Chapters 3, 4, 5, and 6 are parts of the thesis written in paper formats geared to publication in selected scientific journals. Chapters 3 and 5 have been published in the Canadian Biosystems Engineering Journal. Chapter 4 has been submitted to Agricultural Engineering International: CIGR Journal. Chapter 6 has been submitted to Canadian Biosystems Engineering Journal. General conclusions and recommendations are outlined in chapter 7.

The general introduction covers livestock and manure issues as related to socio-economic and environmental concerns, challenging issues, and gaps to fill. The literature review explores information on research conducted to date on various aspects of manure on a wider scale. Chapters 3 and 4 report on a three-year field experiment that examined the effects of two injection tool types and three injection spacings on soil nutrient levels and distribution as well as crop performance. Chapter 5 describes a soil sampling protocol that was developed to account for banding effects of manure injection using soil nutrients data from the field trials. Chapter 6 demonstrates model development and validation to simulate lateral manure NO_3-N distribution in the soil using data collected from field experiments. Finally, chapter 7 outlines the overall conclusions and recommendations.

1.4 References

AAFRD, Alberta Agriculture, Food and Rural Development. 2004. Manure research findings and technologies: from science to social issues. Edmonton, AB, Canada.

Assefa, B.A., J.J. Schoenau and M.C.J. Grevers. 2004. Effects of four annual applications of manure on Black Chernozemic soils. *Canadian Biosystems Engineering* 46: 6.39-6.46.

Chen, Y. 2002. A liquid manure injection tool adapted to different soil conditions. *Transactions of the ASAE* 45(6): 1729-1736.

Chen, Y. and R. Samson. 2002. Integration of liquid manure into conservation tillage corn systems. *Transactions of the ASAE* 45(3): 629-638.

Chen, Y. and S. Tessier. 2001. Criterion for design and selection of injection tools to minimize liquid manure on the soil surface. *Transactions of the ASAE* 44(6): 1421-1428.

Chen, Y. and X. Ren. 2002. High performance tool for liquid manure injection. *Soil & Tillage Research* 67(1): 75-83.

Godwin, R.J., E. McKyes, S. Negi, G.V. Eades, J.R. Ogilvie and C. Lovegrove. 1976. Engineering design criteria for slurry injectors. In *Land as a Waste Management Alternative: Proceedings of the 1976 Cornell Agriculture Waste Management Confernce,* 657-671. Ann Arbor, MI.

Karlen, D.L., C.A. Cambardella and R.S. Kanwar. 2004. Challenges of managing liquid swine manure. *Applied Engineering in Agriculture* 20(5): 693-699.

MAF, Manitoba Agriculture and Food. 2001. Components of a manure handling system for livestock production. http://www.gov.mb.ca/agriculture/livestock/pork/swine/bah00s01.html (2006/07/21).

McKyes, E., S. Negi, R.J. Godwin and J.R. Oglivie. 1977. Design of a tool for injecting organic waste slurries in soil. *Journal of Terramechanics* 14(3): 127-136.

Meisinger, J.J. and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. In *Proceedings from Managing Nutrients and Pathogens from Animal Agriculture*, pp 334-354. PA: Camp Hill.

Misselbrook, T.H., J.A. Laws and B.F. Pain. 1996. Surface application and shallow injection of cattle slurry on grassland: nitrogen losses, herbage yield and nitrogen recoveries. *Grass and Forage Science* 51(3): 270-277.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen and J.L. Charles. 2002. Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. *Canadian Journal of Soil Science* 82(4): 457-467.

Nowak, P., R. Shepard and F. Madison. 1998. Farmers and manure management: a critical analysis. In *Animal Waste Utilization: Effective Use of Manure as a Soil Resource*, eds. J.L. Hatfield and B.A. Stewart,1-32. Chelsea, MI: Sleeping Bear Press.

O'Dell, J.D., M.E. Essington and D.D. Howard. 1995. Surface application of liquid swine manure: chemical variability. *Communications in Soil Science and Plant Analysis* 26(19&20): 3113-3120.

Pain, B.F., C.R. Clarkson, V.R. Phillips, J.B. Klarenbeek, T.H. Misselbrook and M.Bruins. 1991. Odor emission arising from application of slurries on land: Measurements following spreading using a micrometeorological technique and olfactometry. *Journal of Agricultural Engineering Research* 48(2): 101-110.

PAMI, Prairie Agricultural Machinery Institute. 2002. Sustainable manure management: demonstration of manure injection technology. Report 754. Humboldt, SK: PAMI.

Rahman S. and Y. Chen. 2001. Laboratory investigation of cutting forces and soil disturbance resulting from different manure incorporation tools in a loamy sand soil. *Soil & Tillage Research* 58(1-2): 19-20.

Rahman, S., Y. Chen and D. Lobb. 2005a. Soil movement resulting from sweep type liquid manure injection tools. *Biosystems Engineering* 91(3): 379-392.

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

Rahman, S., Y. Chen, Q. Zhang, S. Tessier and S. Baidoo. 2001. Performance of a liquid manure injector in a soil bin and on established forages. *Canadian Biosystems Engineering* 43: 2.33 -2.40.

Salter, R. and C. Scholenberger. 1938. Farm manure. In *Soils and Men: USDA Yearbook of Agriculture*, Government printing office, 445-461. Washington: DC.

Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8:186-189.

Schroder, J. 2005. Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. *Bioresources Technology* 96(2): 253-261.

Statistics Canada. 2001. Census of agriculture. http://www.statcan.ca/english/freepub/95F0301XIE/index.htm (2007/04/17).

Stonehouse, D.P., G.W. de Vos and A. Weersink. 2002. Livestock manure systems for swine finishing enterprises. *Agricultural Systems* 73(3): 279-296.

Sutton, A.L., D.W. Nelson, J.D. Hoff and V.B. Mayrose. 1982. Effects of injection and surface application of liquid swine manure on corn yield and soil composition. *Journal of Environmental Quality* 11(3): 468-472.

Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39(4): 287-300.

Zhang, R.H. and P.W. Westerman. 1997. Solid-liquid separation of animal manure for odor control and nutrient management. *Applied Engineering in Agriculture* 13(5): 657-664.

CHAPTER 2: LITERATURE REVIEW

2.1 Manure composition

Manure is an inevitable natural by-product of livestock production that needs continual management so long as a given livestock production is operational. While it primarily consists of excreted feces and urine, it may also contain bedding materials, spilled feed, water, soil, milking center wastewater, contaminated milk, hair, feathers, and other debris (ASAE Standards 2004). Manure exhibits physical, chemical, and biological characteristics in high degree of variability.

Physically, manure may be classified into four categories (liquid, slurry, semi-solid, and solid) based on solids and moisture content without sharply defined transitions between categories. The ASAE Standards (2004) describes swine manure as liquid, slurry, semi-solid, and solid when the solids content of the manure is in the ranges 0-5, 5-15, 15-25, and greater than 25%, respectively, on wet basis. Chemically, manure contains organic and inorganic forms of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), chlorine (Cl), zinc (Zn), manganese (Mn), and copper (Cu) (ASAE Standards 2005). Biologically, manure contains various microorganisms such as bacteria, including many types of pathogens (Gagliardi and Karns 2000). A review of microbiology in swine manure odor control by Zhu (2000) enlisted nearly ten types of bacteria in swine manure.

2.2 Types of manure

Manure may broadly be categorized into solid and liquid manure types. Owing to their difference in physical form these types of manure differ in several aspects. For example, liquid manure is characterized by more water and urine, higher concentration of NH_4^+-N, and less bedding material than solid manure. They also differ in mechanisms responsible for emissions of ammonia from them (Dewes 1999).

2.3 Manure related issues

As it is the case with commercial fertilizers, poorly managed manure utilization in crop production can bring about pollution. Research has been underway for several decades dealing with different facets of manure management issues.

2.3.1 Social perception

Among manure related issues, the social perception towards manure is an important aspect. It is so important that in the last decade manure management research efforts concentrated on changing people's perception towards swine manure from a waste needing disposal to a resource that can be utilized in an environmentally sound and economically profitable manner (Karlen et al. 2004). Public concerns for environmental problems such as odor and water pollution stem out of increased number of concentrated animal feeding operations replacing small to medium sized operations. This brought about the increased demand for environmentally sound manure management practices (Karlen et al. 2004; Stonehouse et al. 2002; Jackson et al. 2000; Zhu 2000; Schmitt et al. 1999; Honeyman 1996).

2.3.2 Ammonia and odor emissions

Ammonia and odor emissions from animal manure are of significant concern. Buijsman et al. (1987) reported that ammonia emissions from livestock operations accounted for 81% of the total ammonia emissions in Europe. More recent studies by Pain et al. (1998) and McCrory and Hobbs (2001) indicated that the contribution of ammonia emissions from livestock production in Europe remained the same. Land spreading of the manure has been identified as the major source of the ammonia emission in the U.K followed by animal housing and then manure storage (Pain et al. 1998; Misselbrook et al. 2000). Similarly Jackson et al. (2000) reported approximately up to 90% ammonia volatilization from swine manure stored in lagoons and then applied by spraying on land in north-central Iowa. By comparison this emission was reduced to 34% when the manure was stored in earthen basins and then injected to the soil. However, odor and ammonia emissions may still occur if injected manure is not covered with soil immediately following injection (Moseley et al. 1998; Chen et al. 2001; Rahman et al. 2005b). In the USA, ammonia emission from livestock production accounts for approximately 80% of the total emissions (Battye 1994). According to Kurvits and Marta (1998) 72% of the total ammonia emission in Canada was attributed to the livestock production sector. When calculated globally, the livestock production accounted for approximately 50% of the total ammonia emission (Oliver et al. 1998).

2.3.3. Nutrient availability and loading

Addition of soil nutrient sources is based on a supply-demand relationship. The supply comes from soils, manure, and commercial fertilizers which supplement the requirement that may not have been met by available nutrients in the soil and the added manure. The demand for nutrients is driven by relative requirements of crops for the nutrients with the expectation of obtaining some average target yield. Several researchers reported that, when using manure as the major source of nutrients, matching and keeping the balance between the supply and demand for nutrients in crop production is not easy. Research also indicates that shortage of available cropland to apply the large volumes of manure produced in intensive livestock operations is a problem shared among many swine farms (Stonehouse et al. 2002; Jackson et al. 2000).

Due to the bulky nature and low nutrient content of manure, hauling and applications cost is considered as a problem associated with using animal manure (Araji et al. 2001). Atia and Mallarino (2002) indicated that the relatively variable N to P ratio in manure could lead to P accumulation in soils when swine manure is applied at rates recommended to meet cereal crops' N requirement. Chen and Samson (2002) observed accumulation of soil P due to continuous application of liquid swine manure within the top 0-0.15 m depth of soil. For example a study showed that P application was nearly double that recommended for optimum crop production even when manure application followed suggested manure management plans for the region (Jackson et al. 2000). Such P loading could result from manure application practices based on targeting to supply plant N requirements. The issue is more complicated by the variability in P nutritional physiology, P contents of feedstuffs, and differing mineral P supplements (Atia and Mallarino 2002) fed to animals. This leads to wide variations in the forms (organic vs. inorganic) and contents in manure P thereby affecting estimates of available P for crops. However, the problem is not unique to P. For example, estimated N available for crop production in nine out of ten confined feeding operations was 33% less than research based estimates from the same operations (Jackson et al. 2000).

2.4 Methods of application

Liquid manure application may broadly be categorized into two methods, surface application and injection. As the names imply, manure is applied on the soil surface with the method of surface application whereas it is applied under the soil surface by the method of injection. Surface application is further classified into broadcasting, surface banding, surface incorporation, and infiltration enhancement (Chen et al. 2001).

As discussed by Chen et al. 2001, broadcasting is the application of manure on the soil surface using a tank wagon, sprayer boom or irrigation gun whereby the manure is applied through a single or multiple deflectors or splash plate system. Surface banding is the application of manure on the soil surface in separate bands using such tools as dribble bar. Surface incorporation is the application of manure on the soil surface by the method of broadcasting or surface banding and then followed by tillage operation to incorporate the manure in the soil. Infiltration enhancement is broadcasting of manure on perforated soil surface using an aerator whereby some of the applied manure infiltrates into the ground via the perforations. Injection is the direct placement of the manure under the soil surface using tillage tools such as coulter, disk, or sweep that make openings for the manure placement and then cover it with soil.

Methods of manure application affect odor and ammonia emissions. According to an evaluation, Chen et al. (2001) concluded that broadcasting, in which the applied manure covers the whole surface of the application area, is expected to result in the highest potential for odor emission as compared to the other methods. When used on grassland, surface banding reduces grass contamination and ammonia volatilization as compared to broadcasting (Chen et al. 2001). For example, Thomson et al. (1990) reported 50 and 17%

reduction in total ammonia volatilization over two hours and five days, respectively, with surface banding method instead of broadcasting. Apart from being an odorous nuisance in the environment, ammonia volatilization may mean reduced nitrogen availability for crops (Schmitt et al. 1995). Methods of manure application also have influence on availability of applied manure nutrients. Schmitt et al. (1995) reported 17% more N in the top 0.6 m soil when manure was injected than when it was broadcasted. The difference was attributed to loss of N via volatilization of ammonium-N in the broadcast application.

2.5 Liquid manure injection

Injection of liquid manure is preferable to all surface application methods provided that it is done properly. Reasons for injection to be a preferred method of liquid manure application include: reducing odor problems, minimizing ammonia volatilization, and maximizing returns from the applied manure (Sawyer et al. 1991; Comfort et al. 1988). For example, when compared to surface application, manure injection reduced odor emission by 80% (Pain et al. 1991) and ammonia emission by 79% (Misselbrook et al. 1996). According to Warner and Godwin (1988) injection reduces the risk of crop contamination and pathogenic activities.

Liquid manure handling systems evolved with time and currently they are more commonly used than the conventional solid manure handling systems, particularly in hog operations. This change from solid to liquid manure handling systems, driven by the need for reduced labor requirements for livestock operations, efficient confinement operations, conserving manure nutrients, and more application options (Comfort et al. 1988; Schmitt and Hoeft 1986), lends itself to injection as being an alternative method of manure application. Thus, injection of liquid manure has gained popularity (Sawyer et al. 1991) and there has been much research on injection (Rahman et al. 2005a; Rahman et al. 2004; Petersen et al. 2003; Chen and Ren 2002; Chen 2002; Chen and Tessier 2001; Rahman et al. 2001; Rahman and Chen 2001; Chen et al. 1999; Schmitt et al. 1995; Comfort et al. 1988).

2.5.1 Types of manure injection tools

Manure injection tools can broadly be divided into two categories, winged and non-winged. The winged tools include such tools as sweep and furrower whereas the non-winged tools include knife, disc, and opener. Compared to non-winged tools, winged tools distribute manure in wider bands and result in better soil manure mixing (Moseley et al. 1998; Godwin et al. 1976). Chen and Tessier (2001) have shown that winged tools are more suitable for high rate manure injection than non-winged tools because they create a larger soil cavity that can hold a larger volume of manure.

An experiment carried out in Minnesota compared effects of knife (non-winged tool) and sweep (winged tool) injections of liquid manure on soil inorganic N concentrations and yields (Schmitt et al. 1995). Their results showed that as compared to knifes, the sweeps resulted in 7% yield increase. In the top 0.6 m depth sweep injection elevated soil nitrate-N by 21% as compared to knife injection. Results of the study also revealed that the superiority of sweep injection in yielding higher soil nitrate-N concentrations as compared to knife injection was consistent. Similarly Sawyer et al. (1990) reported increases in soil nitrate-N concentrations associated with sweep injection method. Winged tools have also been reported to enable the placement of manure at shallower depths and in wider bands as compared to non-winged tools at similar application rates (Warner and Godwin 1988;

Hultgreen and Stock 1999). Compared to non-winged tools, winged tools require more draft force when working at the same depth (Rahman and Chen 2001). While shallow (0.05 m) manure injection is commonly practiced in Europe, deeper (0.1 to 0.2 m) injection is more common in Canada (Danesh et al. 1999).

Sawyer et al. (1991) conducted field studies in northwestern Illinois that examined the effects of application methods and manure placement relative to plant rows on corn grain yield and N concentrations in the grain. Liquid beef manure was injected using knife, sweep, and broadcast followed by incorporation methods. The report indicated that sweep and knife resulted in contrasting manure distribution patterns in the soil. While injection using sweep produced a 0.6 m wide horizontal manure distribution in a soil depth range of 0.05-0.10 m, injection using knife produced a circular or vertical manure distribution in a soil depth range of 0.15-0.20 m.

Sawyer et al. (1991) indicated that in two (first and third years) out of four years, no significant differences were observed in grain yield among the three injection methods. In one (second year) out of four years knife injection produced similar yield to sweep injection but lesser than broadcast which could not be well explained. In the last year, knife injection at 1.5 m shank spacing produced higher yield than both sweep and broadcast methods at 0.76 m shank spacing. This was attributed to N loss following manure application due to improper injection/incorporation. They summarized that sweep injection would result in more uniform N uptake and grain yield as it distributes manure in a thin and wider band than knife thus suggesting sweep injection to be a practical alternative to knife injection.

2.5.2 Injection tool versus manure application rate

Nutrient losses into the environment, resulting from unacceptable ammonia emissions following liquid manure injection, have led to evaluation of capacity of injection tools. Minimizing exposed manure on the soil surface can significantly reduce both volatilization and odor emissions (Chen 2002; Chen et al. 2001; Thomson et al. 1990). Chen and Tessier (2001) pointed out two potential sources for manure exposure following injection, both contributing to ammonia and odor emissions. One is overflow manure, which occurs due to high rates of manure injection beyond the capacity of the injection tools and thus resulting in overflow. The other one is in-furrow manure, which occurs due to lack of manure coverage by soil. They defined tool capacity as "the maximum amount of manure that can be injected into the soil by the tool without occurrences of overflow manure".

Studies indicate that in-furrow manure is likely to occur when manure is injected using non-winged injection tools (Chen et al. 2001; Rahman and Chen 2001). Warner et al. (1991) demonstrated a more efficient slot closure using additional furrow closing tools when manure is applied with the above tools. Similarly, while recognizing in-furrow manure could also be minimized using winged tools such as sweep, Chen and Tessier (2001) agreed with Rahman et al. (2001) that it is difficult to attain complete coverage of furrows. Instead, Chen and Tessier (2001) suggested a "no overflow manure" condition as a more realistic selection criterion for injection tool. Accordingly they concluded that greater tool capacity than the volume of manure to be injected should be the main criterion in the selection of injection tools as it enables effective prevention of manure overflow.

2.5.3 Injection tool spacing versus soil nutrient distribution

There is little research that looked into injection of liquid manure at variable tool spacing and the effect on soil nutrient availability and crop performance. A four-year study conducted by Mooleki et al. (2002) included two treatments of liquid swine manure injection performed in the preceding fall of each growing season using sweep at 0.3 and 0.6 m spacings. Their results indicated that in one out of two sites and in one out of four years, pre-seeding available soil N was lower when liquid swine manure was applied at 0.6 m spacing than at 0.3 m and similar the rest of the time. After harvest, in contrast, the 0.6 m spacing resulted in elevated available soil N than the 0.3 m spacing treatment in one of two field sites in two years of the four-year experiment. Also a higher wheat grain yield with sweep injection at 0.6 m spacing than at 0.3 m spacing was reported.

Maxwell et al. (1984) reported uneven plant growth and reduced plant P concentration following preplant banding of N and P fertilizer in wheat production due to knife spacing greater than 0.2 m. Sawyer et al. (1991) cited Gasser (1971), Whitear (1971), and Sim (1971) who injected anhydrous NH_3 for production of ryegrass and barley using knife at varying spacings and reported similar results as Maxwell et al. (1984). The study carried out by Maxwell et al. (1984) included a greenhouse and a field experiments. Results from the greenhouse study suggested that early season P uptake by plants was greater when the pre-plant band of P was closer to wheat seedlings. Plants at 0 and 0.1 m distances from the pre-plant bands accumulated more fertilizer P than those at 0.2 and 0.3 m early in the growing season. However, towards the end of the season (44 days after seeding) no differences in plant P uptake were reported when the distances between the fertilizer bands and plants were 0, 0.1 and 0.2 m. According to their field tests, spacings of 0.38 and 0.25 m between deep-placed (0.15-0.2 m) pre-plant bands of N and P fertilizer resulted in more uniform plant growth and dry matter yield than 0.5 m spacing, early in the growing season. However, the smaller spacings did not excel the largest spacing in terms of grain yield and thus no greater than 0.5 m spacing was concluded to be adequate spacing for fertilizer banding in wheat production.

Eghball and Sander (1989) conducted a four-year field experiment that evaluated the effects of band spacing of dual-placed N and P fertilizers on corn grain yield and P uptake. The banding spaces used in the study were 0.30, 0.45, 0.60, and 0.75 m to depths of 0.075 and 0.15 m at three rates of P and three rates of N. Their results revealed that with increase in band spacing the effectiveness of N increased while that of P decreased in terms of grain yield. However, compared to low N rate, at high N rate the widest band spacing (0.75 m) resulted in poor grain yield, which was attributed to N loss during application. Overall their experiment showed no difference in grain yield between plants grown atop the dual-placed band and those away from the band irrespective of the band spacing. They concluded that it would be difficult to determine the optimum band spacing for dual application of N and P fertilizer, as the optimum band spacing for N may be different from that of P.

Positional relationship between manure band and crop rows may also influence nutrient availability to crops. Determination of plant N concentration and grain yield in plants grown at 0, 0.25, 0.50, and 0.75 m distances from the centre of knife injection zone revealed highest N concentration and greatest yield in plants grown over the knife injection zone (Sawyer et al. 1991). Reductions in yield when knife-injecting manure was mainly attributed to the positional relationship and thus reduced manure N availability to plants.

2.5.4 Manure application rate and injection depth

Manure application rates are mostly determined based on N requirements of crops and sometimes based on P requirements. Generally, field soils have different levels of nutrients. Thus, the amount of manure to be added to meet a given crop's requirement is a function of the crop itself and the initial amount of nutrient levels in the soil prior to the planting operation. Because of this, determination of application rates usually involves determination of soil nutrient levels prior to manure injection. This is normally done by collecting soil samples. Commonly, samples are collected in depth ranges of 0-0.3 and 0.3-0.6 m combined or separated for the determination of soil NO_3-N, and for the determination of P and K usually the top 0-0.15 m soil depth is sampled (Chen and Samson 2002). The sampling may be carried out in the fall or in the spring to determine residual nutrient levels in the soil after the previous growing season or before the preceding growing season.

Owing to variations in soil and manure nutrient contents and crop nutrient requirements, manure application rates vary greatly. Sawyer et al. (1991) used application rates in the range of 28 to 42 m^3 ha^{-1} in northwestern Illinois to study the effect of liquid beef manure on corn production. They injected the liquid manure to a depth of 0.15 - 0.20 m before seeding in the spring of each of a four-year experiment. Schmitt et al. (1995) also used similar rates (28 to 37 m^3 ha^{-1}) of manure application in field experiments they conducted at seven locations in Minnesota for two consecutive years. The rates were chosen so as to provide less available N than required for optimum grain yields based on a premise that "relatively small differences in N availability among treatments would result in grain yield differences".

In Manitoba, Chen (2002) used application rates of 28 and 56 m^3 ha^{-1} to inject liquid swine manure at four target injection depths: 0.08, 0.10, 0.12, and 0.14 m. The author reported that those application rates were commonly used by agricultural producers in the province. In a four-year field experiment in east-central Saskatchewan, Mooleki et al. (2002) applied liquid swine manure at three variable rates of 31, 62, and 124 m^3 ha^{-1} representing low, medium, and high rates, respectively. These rates were determined based on the assumption that 50-90% of the manure N would be available in the year of application. The injection was performed to a depth of 0.1 m in the preceding fall of each growing season with one exception when manure had to be applied in the spring due to early fall freezing. The aforementioned rates were referred as macro-rate (manure volume applied by an injection unit per unit of area, m^3 ha^{-1}) by Rahman et al. (2004). They introduced a more interesting term, micro-rate, which was defined as the "volume of slurry applied by one injection tool within a unit distance (m^3 m^{-1} $tool^{-1}$)". They suggested that micro-rate better reflects characteristics of manure soil mix zone (manure band injected) than the traditional rate (macro-rate).

2.5.5 Disadvantages of injection

Injection of liquid manure has not yet been proven to be perfect in providing a means of achieving the desired agronomic efficiency to the fullest potential. Schmitt and Hoeft (1986) reported erratic crop growth and nutrient deficiency following liquid manure injection. Comfort et al. (1988) concluded that liquid manure injection created favorable conditions for denitrification when an abundant supply of nitrate and readily oxidizable C were combined with high soil moisture content.

There are some common problems associated with injection tools. For example, according to Chen and Ren (2002), "most existing injection tools require considerable draft force and cause high soil surface disturbance, associated with their soil cutting action during injection operation". Sideways movement of soil associated with some injection tools (Rahman and Chen 2001; McKyes et al. 1977) reduces manure coverage with soil following injection. The banding effect of manure placement some times results in uneven crop response and denitrification process (Chen and Ren 2002; Sawyer et al. 1991; Schmitt et al. 1995).

Shallow injection has several advantages over deep injection. The advantages include: enhancing plant nutrient uptake (McKyes et al. 1977), minimizing the risk of nitrate leaching, and favoring aerobic stabilization thereby increasing mineralization but decreasing denitrification (Jokela and Côté 1994). Another advantage of shallower placement of manure is reducing the power requirement (Huijsmans et al. 1998). Chen and Tessier (2001) and Sawyer et al. (1991) emphasized the importance of manure injection as shallow as possible but at the same time deep enough to achieve proper coverage of the manure placed in the soil.

2.6 Soil sampling

Soils are characterized by different levels of variability that should inevitably be dealt within the process of measurement of soil attributes (Vanes 2002) and taken into consideration when planning for any soil analysis. Petersen and Calvin (1998) and Vanes (2002) emphasized the importance of awareness of spatial and temporal soil attribute variability for proper selection of experimental design, sampling protocols, measurement techniques, and parameterization methods.

Tan (2005) criticized soil sampling to have been performed without due consideration given to proper procedures despite the information (guidelines) made available by Cline (1944, 1945), Reed and Rigney (1947), and Petersen and Calvin (1986). However, there are four types of sampling protocols: namely, random sampling, systematic sampling, stratified sampling, and compositing, offering various levels of cost-effectiveness and precision. According to Tan (2005), the random sampling plan is the simplest method. In this method selection of the sample totally depends on chance regardless of variation in soil. It is considered satisfactory in a highly homogeneous field. In systematic sampling samples are collected systematically such as at a predefined interval in a field. It yields more accurate results than random sampling due to more evenly distributed samples over the population. Stratified sampling, a method more suitably used in heterogeneous population, is done by dividing fields into a number of strata and drawing samples independently from each stratum. Compositing, mixing of several samples to form a larger single sample, is performed to obtain an estimate of the mean with increased accuracy with an underlying assumption that each of the sampling units contributes to the composite.

2.7 Nutrient movement in soil

Injection of liquid manure for crop production places solutes (manure nutrients) within the root zone. Immediately following injection the nutrients start moving within the soil carried by the water filling into the opening created in the soil and into the pore spaces in the soil. Even after the soil water stops moving within the soil, nutrients can still move driven by concentration differences. There will be transformation (for example, mineralization, immobilization) between different forms (organic/inorganic) of the nutrients through chemical interactions. Plants will also make use of the nutrients as the crop develops over the growing season. Apart from being taken by plants, movement of the nutrients in the soil is effected by the general mechanism of solute transport in the soil as discussed in the section below.

One of the ways in which nutrient movement through soils is evidenced is by the consequential effect of groundwater contamination. For example, this may occur as a result of nitrate leaching following land application of inorganic fertilizers. Nitrate is a mobile nutrient that gets transported with flowing water in the soil. This not only leads to environmental concern but it may also translate into inefficient use of nitrogen fertilizers. Due to concern for the impact on the environment and/or inefficient use of inorganic fertilizers or manure in crop production, several studies addressed NO_3-N movement in the soil (Yang et al. 2006; Rajput and Patel 2006; Clay et al. 2004). As land application of manure is becoming more common several studies were conducted on NO_3-N movement in the soil following manure application (Redding et al. 2007; Israel et al. 2005).

Nitrate movement in the soil is commonly estimated from measured movement of tracers, usually $Br^-$and $^{15}NO_3$-N (Ottman et al. 2000; Ressler et al. 1998; Schuh et al. 1997; Kessavalou et al. 1996). According to these authors the difference between soil applied tracer and the amount recovered is considered as the amount of nitrate moving. Based on leaching experiments in undisturbed soil columns Clay et al. (2004) suggested that the use of Br^- to estimate NO_3-N leaching leads to overestimation by approximately 25%. This makes use of tracer for estimating NO_3-N movement questionable. More recently, Israel et al. (2005) characterized nitrate movement from swine-lagoon effluent application fields by using the measurements of $\delta^{18}O$ and $\delta^{15}N$ enrichment.

2.8 Mechanism of solute transport in the soil

Solute transport in the soil-air-water system takes place in three different ways: convection, molecular diffusion, and hydrodynamic dispersion (Warrick 2002; Hillel 1998). Convection, also known as advection or mass flow, is the movement of solute with flowing water through the soil. Diffusion is the movement of solute within the soil solution due to the random thermal motion of the molecules in the solution. Hydrodynamic dispersion is the movement of solute in the soil that occurs as a result of microscopic non-uniformity of flow velocity in the soil's conducting pores. Brief explanation of these solute transport mechanisms, equations used to describe each process, and the laws they are based on are presented below.

2.8.1 Convection

In this process dissolved solutes in soil water are carried with the water while flowing through the soil. Such convective flow of solutes in the soil is based on Darcy's law whereby the convective flux of solutes is given by the equation:

$$J_c = cq \qquad \textbf{(2. 1)}$$

where J_c is solute flux expressed as the mass of the solute passing through a unit cross-sectional area of the soil per unit time, c is concentration of the solute expressed as the mass of the solute per unit volume of solution, and q is water flux expressed as the volume of water flowing through a unit cross-sectional area of the soil per unit time.

The water flux q is given by the following equation known as Darcy's law.

$$q = -Kdh/dx \qquad \textbf{(2. 2)}$$

where K is hydraulic conductivity of the soil, and dh/dx is the hydraulic gradient, the driving force of convective flow.

2.8.2 Diffusion

Solutes can also move within the soil irrespective of the state of soil water (flowing or stationary) by the simultaneous processes of diffusion and hydrodynamic dispersion (Warrick 2002; Hillel 1998). Diffusion is a process whereby solutes move within the solution in response to concentration gradient from region of higher to lower concentration. The diffusive flux of solutes is based on Fick's law and is given by:

$$J_d = -D_s(\theta)dc/dx \qquad \textbf{(2. 3)}$$

where J_d is the diffusive flux, D_s is the diffusion coefficient of a solute in the soil, θ is the fractional water volume, and dc/dx is the solute's effective concentration gradient, the driving force of diffusive flux.

2.8.3 Dispersion

Dispersion is a phenomenon of mixing that occurs due to local variations in water flow velocity in the soil (Warrick 2002; Hillel 1998). For example, water moves faster in large pores than in small pores, and in each pore, it moves faster at the centre than near the walls of soil pores. Such a motion causes some portions of the solution to move ahead leaving other portions behind. This brings about mixing of an incoming solution with resident solution. Similar to the diffusive flux, dispersive flux of solute is described by Fick's law as follows:

$$J_h = -D_h(\theta)dc/dx \qquad \textbf{(2. 4)}$$

where J_h is the dispersive solute flux and D_h is the coefficient of dispersion of the solute, which is given by:

$$D_h = a\overline{v} \qquad \textbf{(2. 5)}$$

where a is a constant and $\overline{v}$ is the average velocity of the soil solution.

Diffusion and dispersion are different in mechanism. However, since their net effect is similar (i.e. to overcome concentration differences) the two processes are usually lumped together. The combined diffusion-dispersion coefficient, D is a function of θ and $\overline{v}$ given by:

$$D(\theta,\overline{v}) = D_s(\theta) + D_h(\overline{v}) \qquad \textbf{(2. 6)}$$

2.8.4 Convection-dispersion Equation (CDE)

The above equations are based on the first laws of Darcy and Fick that apply to steady state transport of solute through porous media. In field soils world solute movement is much more complicated and does not occur separately as discussed in the above processes. Description of the more practical movement of solute in the soil evolved with the advancement in soil physics and soil chemistry. That is, development of Darcy's and Fick's second laws by application of the continuity equation (the law of conservation of mass) to their respective first laws. Moreover, it has been discovered that solutes may also go into chemical interaction such as mineralization, immobilization, sorption, nitrification, and denitrification. The concept of the chemical interaction introduced the chemical term, R_s which could be considered as sink or source. Putting all these facts together, a combined solute transport equation has been developed (Eq. 2.7) and it can be applied in one, two, or three-dimensional flows.

The convection-dispersion equation (CDE) is given as (Warrick 2002):

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x} + R_s \qquad \textbf{(2. 7)}$$

where c is the concentration of the solute in the soil solution, t is time, D is the diffusion-dispersion coefficient, x is position, v is the solution velocity, and R_s is the sink or source term.

By incorporating concepts of two-site sorption and two-region solute transport to allow for non-equilibrium adsorption-desorption reactions and physical non-equilibrium transport, respectively, Simunek et al. (1999) have developed a variant CDE describing the transport of mutually independent solutes as follows:

$$\frac{\partial \theta R c}{\partial t} = \frac{\partial}{\partial x}\left(\theta D^w \frac{\partial c}{\partial c}\right) - \frac{\partial q c}{\partial x} + Fc + G \qquad \textbf{(2. 8)}$$

where θ is volumetric water content ($L^3\ L^{-3}$), R is retardation factor as given below, c is solute concentration in the liquid phase ($M\ L^{-3}$), t is time (T), x is a spatial coordinate (L), D^w is the dispersion coefficient in the liquid phase ($L^2\ T^{-1}$), q is the volumetric flux density ($L\ T^{-1}$), and F and G are coefficients as given below.

The retardation factor R is given by:

$$R(c) = 1 + \frac{\rho}{\theta}\frac{f k_s \beta\, c^{\beta-1}}{(1+\eta\, c^{\beta})^2} + \frac{a_v k_g}{\theta} \qquad \textbf{(2. 9)}$$

where ρ is soil bulk density (M L^{-3}), f is the fraction of exchange sites assumed to be in equilibrium with the solution phase, k (L^3 M^{-1}), β, and η (L^3 M^{-1}) are empirical coefficients, a_v is the air content (L^3 L^{-3}). The coefficient F is given by the following equation:

$$F(c) = -(\mu_w + \mu'_w)\theta_m - (\mu_s + \mu'_s)\rho\, f \frac{k_s c^{\beta-1}}{1+\eta\, c^{\beta}} - (\mu_g + \mu'_g)a_v k_g - \omega \qquad \textbf{(2. 10)}$$

where μ_w, μ_s, and μ_g (T^{-1}) are first-order rate constants for solutes in the liquid, solid, and gaseous phases, respectively; $\mu'_{w,}$ $\mu'_{s,}$ and μ'_g are similar first-order rate constants providing connections between individual chain species; θ_m is the mobile volumetric water content (L^3 L^{-3}); ω is the mass transfer coefficient for the solute. The subscripts s, w, and g refer to the solid, liquid, and gaseous phases.

The coefficient G is given by the equation below:

$$G(c) = \gamma_w \theta_m + \gamma_s f\rho + \gamma_g a_v - Sc_r + \omega\, c_{im} - \rho\, f\, g(c) \qquad \textbf{(2. 11)}$$

where γ_w (M L^{-3} T^{-1}), γ_s (T^{-1}), and γ_g (M L^{-3} T^{-1}) are zero-order rate constants for the liquid, solid, and gas phases, respectively; S is the sink term in the water flow equation; c_r is the concentration of the sink term (M L^{-3}); c_{im} is the concentration in the mobile region (M L^{-3}).

Numerical solutions of equation 2.8 and its variations are commonly used to characterize transport of solute in the soil. The numerical solutions are obtained using a variety of methods such as finite element and finite difference built into computer programs. Among others, Hydrus-2D is a software package that is used to numerically solve solute transport equations such as equation 2.8 to study solute transport in the soil. For example, using Hydrus-2D to numerically solve the transport equation, Abbasi et al. (2004) studied the transport of Bromide in furrow irrigation experiments, Gardenas et al. (2005) estimated nitrate leaching in relation to fertigation experiments, and Coquet et al. (2005) studied Bromide transport as affected by tillage operations.

Hydrus-2D is used to simulate two-dimensional movement of water and solutes in variably saturated porous media (Simunek et al. 1999) and for inverse optimization of soil hydraulic and transport parameters. It uses the Galerikin-type linear finite elements to numerically solve governing flow and transport equations and the Levernberg-Marquardt algorithm to optimize the hydraulic and transport parameters.

2.9 References

Abbasi, F., J. Feyen and M.Th. van Genuchten. 2004. Two dimensional simulation of water flow and solute transport below furrows: model calibration and validation. *Journal of Hydrology* 290(1-2): 63-79.

Araji, A.A., Z.O. Abdo and P. Joyce. 2001. Efficient use of animal manure on crop land-economic analysis. *Bioresource Technology* 79(2): 179-191.

ASAE Standards. 2004. Uniform terminology for rural waste management. 44th ed. ASAE S292.5 FEB04. 657-659. St. Joseph, MI: ASAE.

ASAE Standards. 2005. Manure production and characteristics. ASAE D384.2 MAR2005. 1-19. St. Joseph, MI: ASAE.

Atia, A.M. and A.P. Mallarino. 2002. Agronomic and environmental soil phosphorous testing in soils receiving liquid swine manure. *Soil Science Society of America Journal* 66(4): 1696-1705.

Battye, R., W. Battye, C. Overcash and S. Fudge. 1994. Development and selection of ammonia emission factors. Environmental Protection Agency, Washington, DC.

Buijsman, E., H.F.M. Mass and W.A.H. Asman. 1987. Anthropogenic NH3 emissions in Europe. *Atmospheric Environment* 21(5): 1009-1022.

Chen, Y. 2002. A liquid manure injection tool adapted to different soil conditions. *Transactions of the ASAE* 45(6): 1729-1736.

Chen, Y. and R. Samson. 2002. Integration of liquid manure into conservation tillage corn systems. *Transactions of the ASAE* 45(3): 629-638.

Chen, Y. and S. Tessier. 2001. Criterion for design and selection of injection tools to minimize liquid manure on the soil surface. *Transactions of the ASAE* 44(6): 1421-1428.

Chen, Y. and X. Ren. 2002. High performance tool for liquid manure injection. *Soil & Tillage Research* 67(1): 75-83.

Chen, Y., Q. Zhang and D. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. *Applied Engineering in Agriculture* 17(4): 489-496.

Chen, Y., S. Rahman and X. Ren. 1999. Criteria for selecting injection depth and evaluation on existing liquid manure injection tools. ASAE Paper No. 991112. St. Joseph, MI: ASAE.

Clay, D.E., Z. Zheng, Z. Liu, S.A. Clay and T.P. Trooien. 2004. Bromide and nitrate movement through undisturbed soil columns. *Environmental Quality* 33(1): 338-342.

Cline, M.G. 1944. Principles of soil sampling. *Soil Science* 58: 275-288.

Cline, M.G. 1945. Methods of collecting and preparing soil samples. *Soil Science* 59: 3-5.

Comfort, S.D., K.A. Kelling, D.R. Keeney and J.C. Converse. 1988. The fate of nitrogen from injected liquid manure in a silt loam soil. *Journal of Environmental Quality* 17: 317-322.

Coquet, Y., J. Simunek, C. Coutadeur, M.Th. van Genutchten, V. Pot and J. Roger-Estrade. 2005. Water and solute transport in cultivated silt loam soil: 2. Numerical analysis. *Vadose Zone Journal* 4(3): 587-601.

Danesh, S., D.G. Hodgkinson and D. Small. 1999. Hog production: Environmental problems and waste management strategies. In *Proceedings of Tri-Provincial Conference on Manure Management,* 117-132. Saskatoon, SK. June 22-25.

Dewes, T. 1999. Ammonia emissions during the initial phase of microbial degradation of solid and liquid cattle manure. *Bioresource Technology* 70(3): 245-248.

Eghball, B. and D.H. Sander. 1989. Band spacing effects of dual-placed nitrogen and phosphorus fertilizers on corn. *Agronomy Journal* 81(2): 178-184.

Gagliardi, J.V. and J.S. Karns. 2000. Leaching of *Escherichia coli* O157:H7 in diverse soils under various agricultural management practices. *Applied and Environmental Microbiology* 66(3): 877-883.

Gardenas, A.I., J.W. Hopmans, B.R. Hanson and J. Simunek. 2005. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water Management* 74(3): 219-242.

Gasser, J.K.R. 1971. Some biological effects of ammonia injected into soil. In *Proc. Sympo. on Aspects of Anhydrous Ammonia Technology and Use as a Fertilizer*, eds. J.K.R. Gassser et al, 30-38. Nat. Coll. Agric. Eng., Silsoe, Bedford. 15-17 Dec. 1970. IPC Business Press, London, England.

Godwin, R.J., E. McKyes, S. Negi, G.V. Eades, J.R. Ogilvie and C. Lovegrove. 1976. Engineering design criteria for slurry injectors. In *Land as a Waste Management Alternative: Proceedings of the 1976 Cornell Agriculture Waste Management Confernce,* 657-671. Ann Arbor, MI.

Hillel, D. 1998. Environmental Soil Physics. San Diego, CA: Academic Press.

Honeyman, M.S. 1996. Sustainability issues of U.S. swine production. *Journal of Animal Science* 74(6):1410-1417.

Huijsmans, J.F.M., J.G. L. Hendriks and G.D. Vermeulen. 1998. Draught requirement of trailing-foot and shallow injection equipment for applying slurry to grassland. *Journal of Agricultural Engineering Research* 71(4): 347-356.

Hultgreen, G. and W. Stock. 1999. Injecting swine manure with minimum disturbance. In *Proceedings of Tri-Provincial Conference on Manure Management*, 52-65. Saskatoon, SK: June 22-25.

Israel, D.W., W.J. Showers, M. Fountain and J. Fountain. 2005. Nitrate movement in shallow ground water from swine-lagoon effluent spray fields managed under current application regulations. *Environmental Quality* 34(5): -1842.

Jackson, L.L., D.R. Keeney and E. Gilbert. 2000. Swine manure management plans in North-Central Iowa: Nutrient loading and policy implications. *Journal of Soil and Water Conservation* 55(2): 205-212.

Jokela, W. and D. Côté. 1994. Options for direct incorporation of liquid manure. In *Proceedings of the Liquid Manure Application System Conference*, 201-215. Ithaca, NY: Northeast Regional Agricultural Engineering Service, Cooperative Extension.

Karlen, D.L., C.A. Cambardella and R.S. Kanwar. 2004. Challenges of managing liquid swine manure. *Applied Engineering in Agriculture* 20(5): 693-699.

Kessavalou, A., J.W. Doran, W.L. Powers, T.A. Kettler and J.H. Qian. 1996. Bromide and nitrate-15 tracers of nitrate leaching under irrigated corn in central Nebraska. *Journal of Environmental Quality* 25:1008–1014.

Kurvits, T. and T. Marta. 1998. Agricultural NH_3 and NO_x emissions in Canada. *Environmental Pollution* 102(S1): 187-194.

Maxwell, T.M., D.E. Kissel, M.G. Wagger, D.A. Whitney, M.L. Cabrera and H.C. Moser.1984. Optimum spacing of preplant bands of N and P fertilizer for winter wheat.

McCrory, D.F. and P.J. Hobbs. 2001. Additives to reduce ammonia and odor emissions from livestock wastes: a review. *Journal of Environmental Quality* 30(2): 345-355.

McKyes, E., S. Negi, R.J. Godwin and J.R. Oglivie. 1977. Design of a tool for injecting organic waste slurries in soil. *Journal of Terramechanics* 14(3): 127-136.

Misselbrook, T.H., J.A. Laws and B.F. Pain. 1996. Surface application and shallow injection of cattle slurry on grassland: nitrogen losses, herbage yield and nitrogen recoveries. *Grass and Forage Science* 51(3): 270-277.

Misselbrook, T.H., T.J. Van Der Weerden, B.F. Pain, S.C. Jarvis, B.J. Chambers, K.A. Smith, V.R. Phillips and T.G.M. Demmers. 2000. Ammonia emission factors for UK agriculture. *Atmospheric Environment* 34(6): 871-880.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen and J.L. Charles. 2002. Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. *Canadian Journal of Soil Science* 82(4): 457-467.

Moseley, P.J., T.H. Misselbrook, B.F. Pain, R. Earl and R.J. Godwin. 1998. The effect of injector tine design on odor and ammonia emission following injection of bio-solids into arable cropping. *Journal of Agricultural Engineering Research* 71(4): 385-394.

Oliver, J.G.J., A.F. Bouwmana, K.W. Van der Hock and J.J.M. Berdowskib. 1998. Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990. *Environmental Pollution* 102(S1): 135-148.

Ottman, M.J., B.R. Tickes and S.H. Husman. 2000. Nitrogen-15 and bromide tracers of nitrogen fertilizer movement in irrigated wheat production. *Journal of Environmental Quality* 29: 1500–1508.

Pain, B.F., C.R. Clarkson, V.R. Phillips, J.B. Klarenbeek, T.H. Misselbrook and M.Bruins. 1991. Odor emission arising from application of slurries on land: Measurements following spreading using a micrometeorological technique and olfactometry. *Journal of Agricultural Engineering Research* 48(2): 101-110.

Pain, B.F., T.J. Van Der Weerden, B.J. Chambers and V.R. Phillips. 1998. A new inventory for ammonia emissions from U.K. *Atmospheric Environment* 32(3): 309-313.

Petersen, R.G. and L.D. Calvin. 1986. Sampling. In *Methods of Soil Analysis, Part 1-Physical and Mineralogical Methods, Agronomy Series No. 9*, ed. A. Klute, 33-51. Madison, WI: American Society of Agronomy, Inc., Soil Science Society of America, Inc.

Petersen, R.G. and L.D. Calvin. 1998. Sampling. In *Methods of Soil Analysis. Part 1-Physical and Mineralogical Methods. Soil Science Society of America Book Series: 5*, ed. A. Klute, 33-51. Madison, WI: American Society of Agronomy, Inc., Soil Science Society of America, Inc.

Petersen, S. O., H.H. Nissen, I. Lund and P. Ambus. 2003. Redistribution of slurry components as influenced by injection method, soil, and slurry properties. *Journal of Environmental Quality* 32: 2399-2409.

Rahman, S. and Y. Chen. 2001. Laboratory investigation of cutting forces and soil disturbance resulting from different manure incorporation tools in a loamy sand soil. *Soil & Tillage Research* 58(1-2): 19-20.

Rahman, S., Y. Chen and D. Lobb. 2005a. Soil movement resulting from sweep type liquid manure injection tools. *Biosystems Engineering* 91(3): 379-392.

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

Rahman, S., Y. Chen, Q. Zhang and D. Lobb. 2005b. Evaluation methods on manure exposure from liquid manure injection tools. *Canadian Biosystems Engineering* 47: 6.9-6.16.

Rahman, S., Y. Chen, Q. Zhang, S. Tessier and S. Baidoo. 2001. Performance of a liquid manure injector in a soil bin and on established forages. *Canadian Biosystems Engineering* 43: 2.33 -2.40.

Rahman, S., Y.Chen, Q. Zhang and D. Lobb. 2005b. Evaluation methods on manure exposure from liquid manure injection tools. *Canadian Biosystems Engineering* 47: 6.9-6.16.

Rajput, T.B.S and N. Patel. 2006. Water and nitrate movement in drip-irrigated onion under fertigation and irrigation treatments. *Agricultural Water Management* 79 (3): 293-311.

Redding, M.R., A. Skerman, J. Ritchie and K.D. Casey. 2007. How effective are broad-scale nutrient mass balances for determining the sustainability of lot-feed manure application? *Agriculture Ecosystems & Environment* 120 (2-4): 166-178.

Reed, J.F. and J.A. Rigney. 1947. Soil sampling from fields of uniform and non-uniform appearance and soil types. *Journal of American Society of Agronomy* 39: 26-40.

Ressler, D.E., R.Horton, T.C. Kaspar and J.L.Baker. 1998. Localized soil management in fertilizer injection zone to reduce nitrate leaching. *Agronomy Journal* 90:747–752.

Sawyer, J.A., M.A. Schmitt and R.G. Hoeft. 1990. Effect of injected liquid beef manure on soil chemical properties and corn root distribution. *Journal of Production Agriculture* 3: 50-55.

Sawyer, J.E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens and D.V. Vanderholm. 1991. Corn production associated with liquid beef manure application methods. *Journal of Production Agriculture* 4(3): 335-344.

Schmitt, M.A. and R.G. Hoeft. 1986. Manure injection can sometimes injure corn crop. *Crops and Soils Magazine* 38(8): 19-22.

Schmitt, M.A., M.P. Russelle, G.W. Randall and J.A Lory. 1999. Manure nitrogen crediting and management in the USA: survey of university faculty. *Journal of Production Agriculture* 12(3): 419-422.

Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8:186-189.

Schuh, W.M., D.L. Klinkebiel, J.C. Gardner and R.F. Meyer. 1997. Tracer and nitrate movement to groundwater in the northern Great Plains. *Journal of Environmental Quality* 26: 1335–1347.

Sim, L. 1971. The effects of varying the tine spacing and depth of injection ofanhydrous ammonia on the growth of spring barley. p. 78-83. In J.K.R. Gassser et al. (ed.) Proc. Sympo. on Aspects of Anhydrous Ammonia Technology and Use as a Fertilizer. Nat. Coll. Agric. Eng., Silsoe, Bedford. 15-17 Dec. 1970. IPC Business Press, London, England.

Simunek, J., M. Sejna and M. T. van Genuchten. 1999. The hydrous-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. Riverside, CA: U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture.

Stonehouse, D.P., G.W. de Vos and A. Weersink. 2002. Livestock manure systems for swine finishing enterprises. *Agricultural Systems* 73(3): 279-296.

Tan, K.H. 2005. *Soil Sampling, Preparation and Analysis*, 2nd edition. Boca Raton, FL: Taylor & Francis Group, LLC.

Thomson, R.B., B.F. Pain and Y.J. Rees. 1990. Ammonia volatilization from cattle slurry following surface application to grassland: I. Influence of application rate, wind speed, and applying slurry in narrow bands. *Plant and Soil* 125(2): 119-128.

Vanes, H.M. 2002. Soil variability. In *Methods of Soil Analysis. Part 4 - Physical Methods. Soil Science Society of America Book Series:5,* eds. J.H. Dane and G.C. Topp, 1-13. Madison, WI: Soil Science Society of America, Inc.

Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39(4): 287-300.

Warner, N.L., R.J. Godwin and M.J. Hann. 1991. Modifications to slurry injector tine to reduce surface disturbance and improve slot closure under dry grassland conditions. *Journal of Agricultural Engineering Research* 48(1): 195-207.

Warrick, A.W. 2002. *Soil Physics Companion.* Boca Raton, Fl. CRC Press.

Whitear, J.D. 1971. Levington experiments on anhydrous ammonia for grass and arable crops. p. 39-54. In J.K.R. Gassser et al. (ed.) Proc. Sympo. on Aspects of Anhydrous Ammonia Technology and Use as a Fertilizer. Nat. Coll. Agric. Eng., Silsoe, Bedford. 15-17 Dec. 1970. IPC Business Press, London, England.

Yang, C.C., S.O. Prasher, S. Wang, S.H. Kim, C.S. Tan, C. Drury and R.M. Patel. 2007. Simulation of nitrate movement in southern Ontario, Canada with DRAINMOD-N. *Agricultural Waste Management* 87(3): 299-306.

Zhu, J. 2000. A review of microbiology in swine manure odor control. *Agriculture, Ecosystems and Environment* 78(2): 93-106.

CHAPTER 3: EFFECTS OF MANURE INJECTION TOOL TYPE AND TOOL SPACING ON SOIL NUTRIENT LEVELS AND SPRING BARLEY PERFORMANCE*

3.1 Summary

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 0.3- (S300), 0.6- (S600), and 0.9-m (S900) tool spacings. Extractable soil NO_3-N, NH_4-N, P_2O_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 furrower proved to be advantageous over coulter in many ways. Use of furrower resulted in 40 to 60% higher soil NO_3-N than coulter at 0-0.3 m soil depth at the time of rapid plant development in the second and third years of the experiment. Furthermore use of furrower resulted in 10% more plant biomass, 13, 3, and 16% higher total N in plant biomass, grain, and straw, 2.5 and 13% higher total P in grain and straw, respectively, compared to use of 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 0-0.3 m soil depth than S600. Plant number of tillers, heads, and main stem length in S300 were in some cases equivalent to and in other

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cases higher than those of S600 and S900. ***Keywords:*** *manure, injection, tool, tool spacing, soil, nutrient, crop, yield.*

3.2 Introduction

Land application of manure is considered the most economical management practice that enables recycling of the nutrients contained in manure. To maximize the returns from liquid manure and to 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 odor, surface runoff, and loss of ammonia (Sutton 1994; Hoff et al. 1981), which eventually contributes to increasing 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 injection equipment (more injection tools per unit working width of injector) and consume 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 within the liquid swine manure injection bands and reported spatial differences in inorganic N concentrations. 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 wide 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 and 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 the effects of two injector types (furrower and coulter) and three tool spacings (0.3-, 0.6-, and 0.9-m) on soil nutrient levels, plant development characteristics (plant number of tillers, heads, main stem length, biomass), and crop yield.

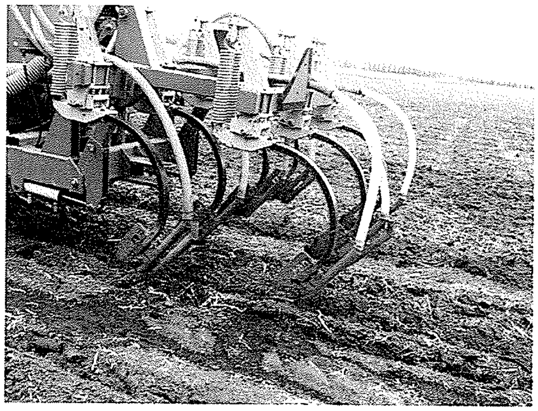
3.3 Materials and methods

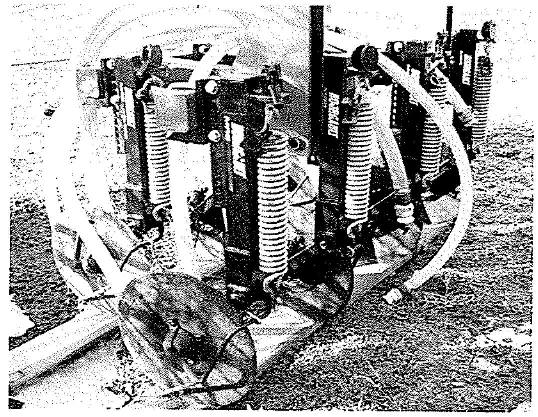
3.3.1 Site description

This field experiment was conducted at the Brandon Research Centre, Brandon, Manitoba, Canada in the growing seasons of 2002, 2003, and 2004 on predominantly clay 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 2003 and 2004 field trials had very limited weed growth so only tillage was used to control weeds prior to seeding.

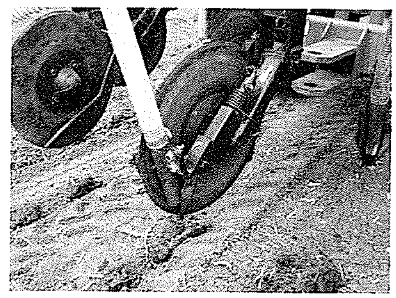
3.3.2 Field equipment

Liquid manure was applied to soil using an injection system equipped with a 4.5 m^3 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. 3.1 a and b). The injection tools used (Fig. 3.1 c and d) were named as coulter and furrower according to ASAE Standards (2004). These two types of injection tools were selected because they create contrasting furrows during injection process. The coulter creates narrow furrows whereas the furrower creates wide furrows. Dimensions of these injectors are summarized in Table 3.1. Manure was delivered from the tank to the injection tools via hoses of 48 mm inside 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 0.3 m row spacing.





(a) (b)



(c) (d)

Figure 3.1. Injection implement: (a) toolbar fitted with furrowers, (b) toolbar fitted with coulters, (c) close up of the furrower, (d) close up of the coulter.

Table 3.1. 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

3.3.3 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: 0.3-m (S300), 0.6-m (S600), and 0.9-m (S900), with four replications. Each of the six treatment combinations was randomly assigned to a plot, forming four blocks.

3.3.4 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 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 0.1 m at an average rate of 34 m^3 ha^{-1} 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 the 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 3.2.

Table 3.2. 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

3.3.5 Measurements

3.3.5.1 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 0.15 m using 52-mm diameter core samplers. Soil moisture content and bulk density were determined by oven drying for 24 h at 105°C. Manure samples were taken for analysis two weeks in advance of manure application. Electrical conductivity and pH measurements were taken on a 10:1 dilution of liquid manure with distilled water. Ammonia concentration in the diluted mixture was determined by ion specific electrode against a certified standard. Moisture content of manure was measured after oven drying to a constant weight at 105°C. 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.

3.3.5.2 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, 0.15, 0.30, and 0.45 m distances from the centre line of a manure band as illustrated in Figure 3.2. Soil samples were collected five times to a depth of 0.3 m in the growing season of 2002 and three times in each of the growing seasons of 2003 and 2004 at two depth ranges (0-0.3 and 0.3-0.6 m). 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, 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, pH, and EC. Methods used for analyses are presented in Table 3.3.

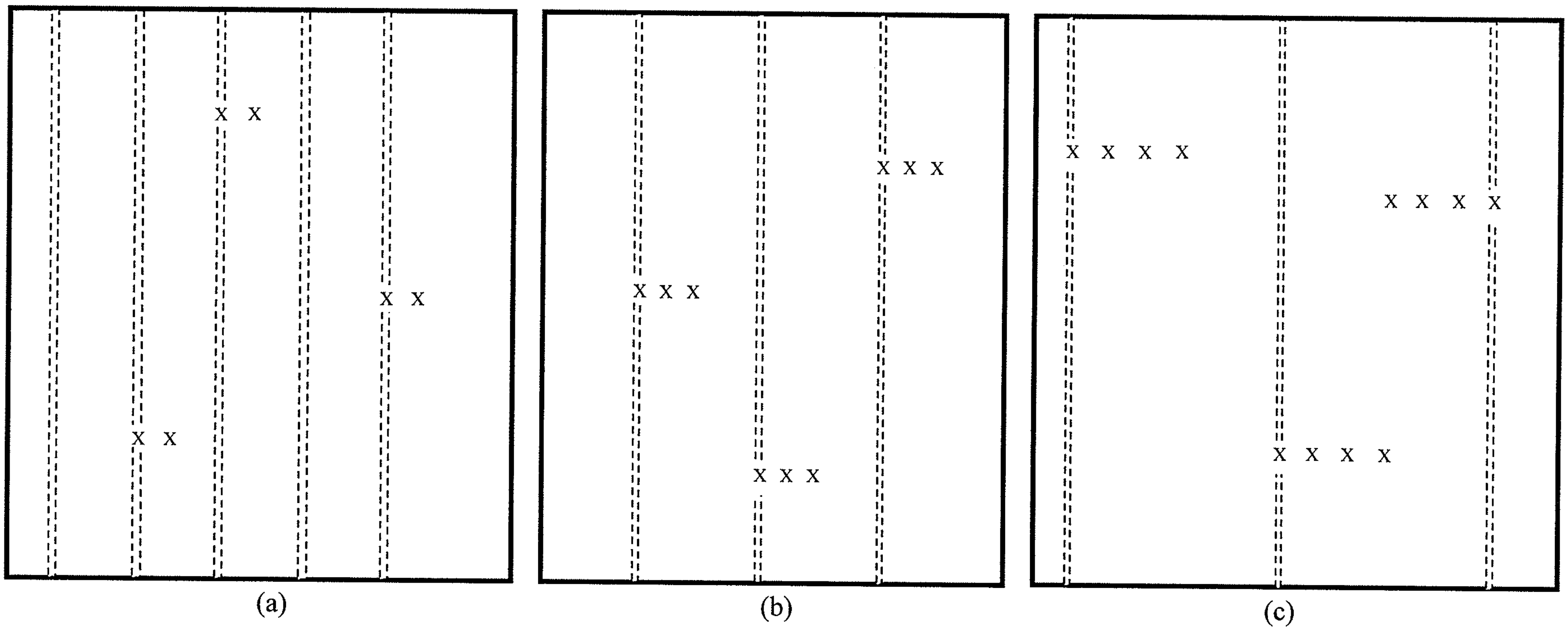


Figure 3.2. A Schematic diagram showing sampling locations within plots for (a) S300, (b) 600, and (c) S900 treatments. Double dashed lines represent manure bands. "X" refers to sampling locations. Each group of X's represents separate hypothetical horizontal transect.

Table 3.3. Methods used for soil analysis.

Soil property	Analytical method and reference		
	2002	2003	2004
NO_3-N	Cadmium reduction procedure (Maynard and Kalra 1993)	Simultaneous NPK method (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 (Ashworth 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)	Simultaneous NPK method (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)

3.3.5.3 Plant tillers, heads, main stem length, and above ground biomass

At the plants' soft dough stage, 20-40 plants were uprooted randomly along plant rows parallel to manure bands. 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 0.5-m wide plant strip was cut across each plot width to measure the amount of above ground biomass. The biomass samples were oven-dried at 60°C for 72 h (ASAE Standards 2002) to determine the dry matter of 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 was used to colorimetrically determine total N and P in the digested samples.

3.3.5.4 Grain and straw yield

A plot combine was used to harvest the plots for final yield measurements in 2002 and 2003. Entire plots were harvested and the harvested 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 the use of a 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 60°C 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 grain and straw were also determined the same way as in above ground biomass.

3.3.6 Statistical analyses

The data were analysed separately in 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 soils' inherent high variability. 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.

3.4 Results and discussion

3.4.1 Weather conditions and soil and manure baseline properties

The monthly air temperature and precipitation data for the three growing seasons and averages of 16 years prior to 2002 are given in Table 3.4. The data were obtained from the 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 6th wettest and 1st coldest of 19 years growing seasons.

Table 3.4. Growing season monthly mean 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

Soil (0.15 m deep) bulk density and moisture content and composition of the manure applied are presented in Table 3.5. 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, the total N (2.9 kg 1000 L^{-1}) in the manure used in this study was similar to the mean total N in swine manure in Manitoba (Racz 2001). On the other hand, the averag total P (0.6 kg 1000 L^{-1}) in the manure used in this study was lower than the mean total P in swine manure in Manitoba (Racz 2001). 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 3.5. Soil (0.15 m 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 1000 L^{-1})	2.40	2.90	3.50
Organic N (kg 1000 L^{-1})	0.20	0.60	0.40
NH_4-N (kg 1000L^{-1})	2.20	2.30	3.00
Nitrate and nitrite N (kg 1000 L^{-1})	0.10	0.10	0.10
Total P (kg 1000 L^{-1})	0.04	0.79	0.55
Total K (kg 1000 L^{-1})	1.32	1.51	1.84
Total S (kg 1000 L^{-1})	0.11	0.20	0.23
Solid content (%)	1.10	2.10	1.60
EC (dS m^{-1})	15.85	18.10	19.80
pH	7.60	7.90	7.40

3.4.2 Extractable soil nutrient levels

3.4.2.1 Soil nitrate nitrogen (NO_3-N)

Soil NO_3-N tended to be higher in plots where manure was applied using furrower than in plots where manure was applied using coulter (Table 3.6). However, there were no statistically significant differences observed at the 0.3-0.6 m depth for all three years. At the 0-0.3 m depth, the use of furrower rather than 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. Base upon their observation Schmitt et al. (1995) suggested that 1) use of winged tools does not promote the levels of denitrification associated with using non-winged tools and 2) 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 3.6). 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 3.6). At 0-0.3 m depth, there were no differences in the levels soil NO_3-N between the S300 and S900 treatments. At 0.3 - 0.6 m depth, levels of soil NO_3-N in the S900 treatment were higher than the S300 treatment two out of three times.

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 3.6). However, S300 had significantly higher soil NO_3-N than S900 in one out of three sampling times at the 0-0.3 depth and two out of three sampling times at the 0.3-0.6 m depth. This may be attributed to a possible denitrification loss in the S900 plots than in the S300 and S600 plots, favoured by combination of large manure volume per manure band and the wetter soil condition in 2004.

Table 3.6. Levels of extractable NO_3-N ($\mu g\ g^{-1}$) in soil samples collected at different times and depths.

Year and Factor* — Soil sampling time after injection and sampling depth

2002	3 wk	5 wk	7 wk	9 wk	11 wk
	0-0.3 m	0-0.3 m	0-0.3 m	0-0.3 m	0-0.3 m
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	
	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m
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)	
	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m
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	3.2a
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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

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

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 0-0.3 m soil depth.

3.4.2.2 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 3.7). 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 3.7). 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 0-0.3 m depth; however it was not affected by the tool spacing at 0.3-0.6 m depth. Six weeks after injection, soil NH_4-N decreased with the tool spacing at the 0.3-0.6 m depth.

During the growing season in 2002, soil NH_4-N at second sampling period 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.

Table 3.7. Levels of extractable NH_4-N ($\mu g\ g^{-1}$) in soil samples collected at different times and depths.

Year and Factor*	Soil sampling time after injection and sampling depth			
2002	3 wk 0-0.3 m	5 wk 0-0.3 m	7 wk 0-0.3 m	
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	
	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m
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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively. Data were not collected in 2003.

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

3.4.2.3 Soil phosphate (P_2O_5)

Significantly higher soil P_2O_5 levels were observed for furrower than for coulter in one out of seventeen observations over three years (Table 3.8). 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. 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.

Table 3.8. Levels of extractable P_2O_5 ($\mu g\ g^{-1}$) in soil samples collected at different times and depths.

Year and Factor*	Soil sampling time after injection and sampling depth				
2002	3 wk 0.3 m	5 wk 0.3 m	7 wk 0.3 m	9 wk 0.3 m	11 wk 0.3 m
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	
	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m
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)	
	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0.3-0.6 m
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	65.9a	49.4a

* S300, S600, and S900 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

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

3.4.2.4 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 3.9.

Table 3.9. Average values of extractable soil K (μg g^{-1}), SO_4-S (μg g^{-1}), pH, and EC (dS m^{-1}) in different years and at different sampling depths.

Factor*	K			SO_4-S	pH			EC		
	2002	2003		2002	2002	2004		2002	2004	
	0-0.3 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0-0.3 m	0-0.3 m	0.3-0.6 m	0-0.3 m	0-0.3 m	0.3-0.6 m
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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

** Mean values with in each experimental factor within a year and a column are not significantly different ($P > 0.1$).

3.4.3 Crop performance

3.4.3.1 Plant tillers, heads, main stem length, and above ground biomass

No significant differences were detected in the number of tillers, heads, and main stem length between furrower and coulter in any of the three years. Furrower resulted in approximately 10% more plant biomass than coulter in 2002 (Table 3.10); however, in 2003 and 2004, both tools yielded similar 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 3.10). 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 by the tool spacing. In 2004, S300 resulted in a significantly greater number of tillers and heads and longer main stem than S600. Also the S300 resulted in a significantly greater number heads than S900. There were no differences in above ground biomass between the spacing treatments in that year.

Table 3.10. Plant number of tillers, heads, main stem length, and above ground biomass at soft dough stage.

Year and Factor*	No. of tillers	No. of heads	Main stem length (mm)	Biomass (kg ha^{-1})
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	510.3a	4445a
Furrower	2.3a	1.9a	512.1a	4390a
Tool spacing				
S300	2.3a	1.9a	500.2a	4322a
S600	2.3a	1.9a	516.3a	4446a
S900	2.1a	1.7a	517.1a	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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

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

3.4.3.2 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 greatest in the wettest growing season (2004) (Table 3.11). The low yield in 2003 may be explained by the fact that the plant nutrient and water uptake was undermined by dry weather conditions (Table 3.1).

Table 3.11. Grain and straw yields at harvest for different treatments in three years.

Factor*	Grain yield (kg ha^{-1})			Straw yield (kg ha^{-1})		
	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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

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

No significant differences were detected in grain yield between furrower and coulter (Table 3.11). 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 0.65 m tool spacing resulted in higher grass yield than 0.5 and 0.85 m tool spacing spacings. Eghball and Sander (1989) studied band spacing effects of dual-placed N and P fertilizers on corn. Their observation is 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 0.25 and 0.38 m 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 0.5 m spacing.

3.4.3.3 Total N and P in plant biomass, grain, and straw

In 2002, as compared with coulter, furrower resulted in higher levels of total N in plant biomass, total N and P in grain and straw (Table 3.12). 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 coulter or furrower. One exception was that, in 2004, 10% higher total N and 21% lower P in straw were measured when using furrower rather than coulter.

Table 3.12. 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 = 0.3-, 0.6-, and 0.9-m tool spacing treatments, respectively.

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

Tool spacing did not significantly affect total N and total P in plant materials in 2002 (Table 3.12). 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.

3.5 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. Mixed results were observed among years regarding the effect of spacing on levels of soil nitrate nitrogen. Although the narrowest injection tool spacing did not offer any advantage over the other tool spacings in terms of yield response, the best plant development and highest plant biomass production were observed for the 0.3-m tool spacing, which is important with regard to nutrient cycling in agricultural systems. Based upon the above, the furrower-type tool spaced 0.3-m apart is suggested as the best choice for liquid manure injection. It would be of particular interest to perform similar experiments on different soil types, under varying climatic conditions, to confirm the observed trends since this experiment was carried out on heavy clay lacustrine soils under less than optimum growing conditions.

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3.7 References

Alberta Research Council. 1996. Methods manual for chemical analysis of water and wastes. Method 19103 565, Potassium, dissolved, automated photometry method. Edmonton, AB.

AOAC, Association of Official Analytical Chemists International. 1990. *Official Methods of Analysis of AOAC*, 15th ed. Arlington, VA: AOAC.

ASAE Standards. 2002. ASAE S358.2 Moisture measurement-Forages. St. Joseph, MI: ASAE.

ASAE Standards. 2004. ASAE S414.1 FEB04. Terminology and definitions for agricultural tillage implements. St Joseph, MI: ASAE.

Ashworth, J. and Mrazek K. 1995. "Modified Kelowna" test for available phosphorus and potassium in soil. *Communications in Soil Science and Plant Analysis* 26(5&6): 731-739.

Chen, Y. and R. Samson. 2002. Integration of liquid manure into conservation tillage corn systems. *Transactions of the ASAE* 45(3): 629-638.

Chen, Y. and S. Tessier. 2001. Criterion for design and selection of injection tools to minimize liquid manure on the soil surface. *Transactions of the ASAE* 44(6): 1421-1428.

Clesceri, L.S., A.E. Greenbert, A.D. Eaton and M.A.H. Franson. 1998. *Standard Methods for the Examination of Water and Wastewater*. 20th ed. Washington, DC. American Public Health Association.

Comfort, S.D., K.A. Kelling, D.R. Keeney and J.C. Converse. 1988. The fate of nitrogen from injected liquid manure in a silt loam soil. *Journal of Environmental Quality*. 17: 317-322.

Eghball, B. and D.H. Sander. 1989. Band spacing effects of dual-placed nitrogen and phosphorus fertilizers on corn. *Agronomy Journal* 81(2): 178-184.

Fitzmaurice, J., E.S. Jacques, A. Waddell and R. Eilers. 1999. Soils of the Brandon Research Centre – updated from Hopkins and St. Jacques, 1985. Special Report Series 99-2, Land Resource Unit, Brandon Research Centre, Agriculture & Agri-Food Canada.

Greenbeg, A.E., L.S. Clesceri and A.D. Eaton. 1992. Standard Methods for Examination of Water and Wastewater. 18th ed. Washington, DC: American Public Health Association.

Grevers, M. and J. Schoenau. 2001. Swine manure - a dilute fertilizer with extra's. In *Proceedings of the 2001 Soils & Crops Workshop*, 452-456. Saskatoon, SK: University of Saskatchewan.

Hamm, J.W., F.G. Radford and E.H. Halstead. 1970. The simultaneous determination of nitrogen, phosphorus and potassium in sodium bicarbonate extracts of soils. In *Advances in Automatic Analysis Vol. 2 Industrial Analysis Technicon International Congress*: pp. 65-69. Mt. Kisco, NY.

Hendershot, W.H., H. Lalande and M. Duquette. 1993. Soil reaction and exchangeable acidity. In *Soil sampling and methods of soil analysis* ed. M.R. Carter, 25-38 Boca Raton, Florida.

Hoff, J.D., D.W. Nelson and A.L. Sutton. 1981. Ammonia volatilization from liquid swine manure applied to cropland. *Journal of Environmental Quality* 10(1): 90-95.

Maxwell, T.M., D.E. Kissel, M.G. Wagger, D.A. Whitney, M.L. Cabrera and H.C. Moser. 1984. Optimum spacing of preplant bands of N and P fertilizer for winter wheat. *Agronomy Journal* 76(2): 243-247.

Maynard, D.G. and Y.P. Kalra. 1993. Nitrate and exchangeable ammonium nitrogen. In *Soil sampling and methods of soil analysis* ed. M.R. Carter, 25-38 Boca Raton, Florida.

McCormick, R.A., D.W. Nelson, A.L. Sutton and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformation in soil treated with liquid swine manure. *Agronomy Journal* 75(6): 947-950.

McKeague, J.A. 1976. Soluble salts. Manual on soil sampling and methods of analysis. Subcommittee of Canada Soil Survey Committee. Ottawa, ON.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen and J.L. Charles. 2002. Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. *Canadian Journal of Soil Science* 82(4): 457-467.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. In *Methods of soil analysis Part 2* ed A.L. Page, 403-430, Madison, WI: American Society of Agronomy, Soil Science Society of America.

Qian, P., J.J. Schoenau and R.E. Karamanos. 1994. Simultaneous extraction of available phosphorus and potassium with a new soil test: a modification of the Kelowna extraction. *Communications in Soil Science and Plant Analysis* 25(5&6): 627-635.

Racz, G.J. 2001. Nutrient and heavy metal contents of hog manure – effects on soil quality and productivity. In *Livestock Options for the Future: A National Conference on Livestock & the Environment,* Winnipeg, MB.

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

SAS Institute Inc. 2001. SAS STAT7 user's guide, Version 8.2 SAS Institute, Inc., Cary, NC.

Sawyer, J.E., M.A. Schmitt and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Agronomy Journal* 82(5): 963-969.

Sawyer, J.E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens and D.H. Vanderholm. 1991. Corn production associated with liquid beef manure application methods. *Journal of Production Agriculture* 4(3): 335-344.

Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8(2): 186-189.

Sutton, A.L. 1994. Proper animal manure utilization. *Journal of Soil and Water Conservation* 49(2): 65-70.

Thomas, R.L., R.W. Sheard and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agronomy Journal* 59: 240-243.

Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39(4): 287-300.

CHAPTER 4: SOIL NUTRIENT LEVELS AND CROP PERFORMANCE AT VARIOUS LATERAL POSITIONS FOLLOWING LIQUID MANURE INJECTION

4.1 Summary

A three-year field experiment was conducted to investigate soil nutrient distribution and crop response at different lateral positions relative to centerlines of injected manure bands in soil. Liquid swine manure was injected using coulter- and furrower-type tools at three rates (1.02, 2.04, and 3.06 litter per one meter of manure band). Levels of available soil nutrients (NO_3-N, NH_4-N, and P_2O_5), soil EC, and soil pH were measured at various lateral positions. Plant characteristics (number of tillers, number of heads, and length of main stem), plant biomass, and total N and P in plant biomass were measured for crop rows at different lateral positions. The soil NO_3-N, NH_4-N, and P_2O_5 concentrations and soil EC were significantly lower at a farther position from centerlines of manure band, especially at the highest rate. The variations of the soil pH with the positions were inconsistent. Plants in the crop row further from a manure band had 25% fewer tillers, 20% fewer seed heads, 10% shorter main stem, 60% less plant biomass, and 25% lower total N in the plant biomass, compared to those in the crop row close to the band.

Keywords: *Soil; Crop; Manure; Nutrient; Lateral position; Injection.*

4.2 Introduction

Injection is a recommended method of liquid manure application as it can reduce odor emissions and ammonia volatilization (Chen et al., 2001; Meisinger and Jokela, 2000; Schmitt et al., 1995), when compared with surface application of liquid manure. Manure is injected in bands which contain variable volumes of manure, depending on the tool spacing of the injector and the manure application rate. A manure band may be defined as the manure that has been placed into a slot in the soil formed by an injection tool along the direction of travel. The volume of manure per meter of band was defined as "micro-rate" of manure application by Rahman et al. (2004). Very large tool spacing and high micro-rate may result in excessive manure within the manure bands and insufficient amount of nutrients between the manure bands, referred as banding effect. This uneven nutrient distribution in soil may cause uneven crop responses (Sawyer et al., 1990, 1991; Warner and Godwin, 1988).

Although injection is known to conserve nitrogen for plant growth, there are previous reports of production problems, particularly with corn, due to the banding effect. Poor corn root distribution in manure bands (Schmitt and Hoeft, 1986) and plant stunting and yellowing where manure was injected (Schmitt and Hoeft, 1986; Westerman et al., 1983) have been described in the literature. Based on their observations of soil chemical properties and nutrient distribution with knife- and sweep-injected liquid cattle manure, Sawyer et al. (1990) concluded that conditions inhibitory to corn root growth existed for 7-8 weeks after knife-injection of manure. Their observations have implications for cereal production on the Canadian Prairies where knife or coulter injection is frequently used to reduce soil disturbance and prevent soil erosion.

To avoid banding effects, one wishes that manure nutrient spread far in the lateral direction that is defined as the direction perpendicular to the travel direction of the injector. Lateral spread of manure nutrients in soil is affected by the width of the manure bands initially placed into the soil. Wider bands favor a more uniform nutrient distribution in the soil. The width of manure band varies with the type of injection tool. Winged tools, such as sweeps and furrowers, place manure in wider bands compared to non-winged tools, such as discs and knives (Rahman et al., 2004). Following injection, nutrients in a manure band will move both laterally and vertically within the soil, changing their lateral distribution in the soil over time. This process is affected by the nutrient concentrations in the manure bands initially placed in the soil, i.e. micro-rate.

There have been limited numbers of studies on lateral distributions of manure nutrients in soil following manure injection. Petersen et al. (2003) studied the distribution of dissolved compounds in slurry applied to soil. They reported strong gradients of Br- with distance from the injection slit in the lateral direction. Sawyer et al. (1990) observed highest concentrations of inorganic nitrogen at the center of manure band and lower concentrations at lateral distances of 0.13 m or greater, with knife injection of liquid beef manure. McCormick et al. (1983) also reported similar N distribution after injecting liquid swine manure. Sawyer et al. (1991) reported decreased N concentrations and lower yield in corn plants at 0.25, 0.51, and 0.76 m distances from knife injected manure band compared to plants growing in the center of the manure band.

There is little documentation in the literature to address banding effects of different micro-rates of manure application under different injector types. The objectives of this study were to investigate (1) soil nutrient levels (mainly nitrogen and phosphorous) and (2) crop performance (plant development characteristics and biomass) at different lateral positions relative to the centerline of an injected manure band, under different micro-rates and different injector types.

4.3 Materials and methods

4.3.1 Site and field equipment description

Experiments were conducted in two different fields in the growing seasons of 2002, 2003, and 2004 at Brandon Research Centre, Agriculture and Agri-Food Canada in Brandon, Manitoba, Canada. The site (49°51'N, 99°58'W) did not have a previous history of manure application. The site was tilled using a field cultivator before the manure injection operation in the spring. The experiment was moved to a different field in the second year due to the availability of the field. However, those two fields were very close within the research center, and both fields had a clay surface texture.

4.3.2 Field equipment

Liquid swine manure was injected using an injector system that included a 4.5 m^3 tanker equipped with a positive displacement pump and bypass to continually mix the manure in the tank. Tanker-mounted load cells were used to calibrate the application rate and to monitor the weight of manure applied to the plot. A 2.1 m wide implement mounted on a three-point hitch behind the tank supported gangs of injection tools. A non-winged and a winged tool were used to create contrasting manure band widths (narrow and wide). These two tools are best described as coulter and furrower, respectively, according to ASAE Standards (2004). The coulter had a diameter of 460 mm and was set to a gang angle of 14°. The furrower was

120 mm wide, had a sweep angle of 52°, and a rake angle of 11°. A hoe-type seeder was used for seeding the field at a row spacing of 0.3 m.

4.3.3 Experimental design

Six combinations of two injection tool types (coulter and furrower) and three micro-rates (referred to as rates hereafter) (r_1 = 1.02, r_2 = 2.04, and r_3 = 3.06 L m^{-1}) were set up in a completely randomized block design, replicated four times, forming a total of 24 plots in four blocks.

To compare soil nutrient levels and crop performance following manure injection, all plots received the same gross manure application rate, 34,000 L ha^{-1}. The different treatment rates were achieved by using different tool spacings, while the manure flow rate from the tank and the forward speed of the injector were kept constant during the injection. The injection tools were spaced 0.3 m apart for the r_1 plots, 0.6 m apart for the r_2 plots, and 0.90 m apart for the r_3 plots.

4.3.4 Selection of lateral positions for comparisons in soil nutrient and crop performance

Following injection operation, paths of the injection tools or center of manure bands were marked with flags on the plots to be used as references for subsequent seeding operations and soil sampling. During seeding, seed rows were positioned 0.15 m away from, but parallel to adjacent manure bands to create the desired positions of crop rows relative to the manure band (fig. 4.1).

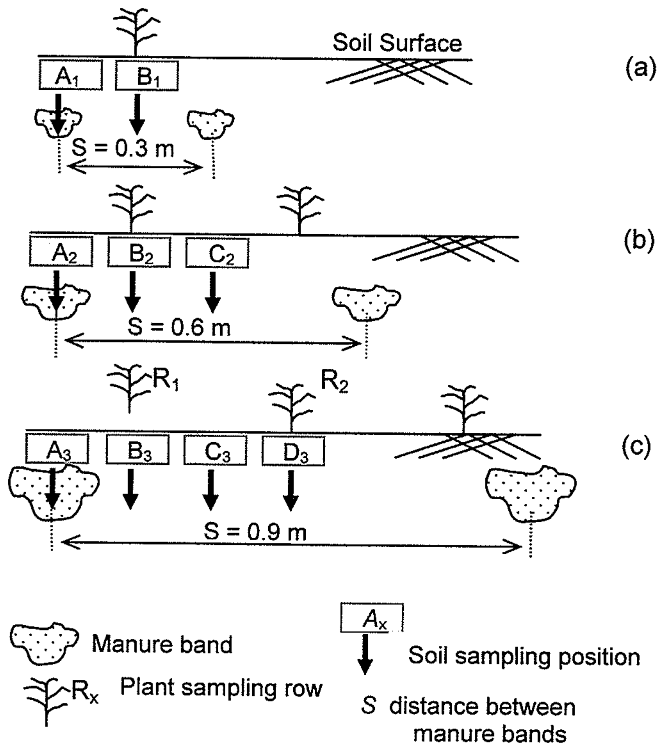


Figure 4.1. Schematic diagram of manure band, soil sampling position, and plant rows: (a) rate r_1=1.02 L m^{-1}, (b) rate r_2=2.04 L m^{-1}, and (c) rate r_3=3.06 L m^{-1}.

The experimental design created three different patterns of manure bands in soil, as shown in fig. 4.1. With increasing rate, a band contained more manure, but bands were positioned farther apart. Under each injection tool, lateral positions studied were A_1 and B_1 in the r_1 treatment, A_2, B_2, and C_2 in the r_2 treatment, and A_3, B_3, C_3, and D_3 in the r_3 treatment (fig. 4.1). Position A's were located on the centerline of manure band. Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centerline of manure band, respectively. For the r_1 and r_2 plots, all crop rows were 0.15 m away from the centerline of a manure band, which could not be used for comparison of crop performance. For the r_3 plots, there were two distinct crop rows: R_1 and R_2 laid at 0.15 and 0.45 m distances from the centerline of a manure band, respectively. The treatments and positions are summarized in table 4.1.

Table 4.1. Symbolic designations for manure application rate and soil and plant sampling positions.

Rate		Lateral position			
		Soil sampling		Plant sampling	
Symbol	Value ($L\ m^{-1}$)	Symbol	Distance from manure band (m)	Symbol	Distance from manure band (m)
r_1	1.02	A_1	0		
		B_1	0.15		
r_2	2.04	A_2	0		
		B_2	0.15		
		C_2	0.30		
r_3	3.06	A_3	0		
		B_3	0.15	R_1	0.15
		C_3	0.30	R_2	0.45
		D_3	0.45		

4.3.5 Measurements

4.3.5.1 Soil nutrients

Following manure injection, soil samples were taken for nutrient analyses in each plot at each of the soil sampling positions shown in fig. 4.1. Soil core samplers with a 19 mm diameter were used to take soil cores. In 2002, the sampling was done in one depth range (0-0.3 m), while in 2003 and 2004 it was done in an additional depth range (0.3-0.6 m). Along each position, samples were collected from three random locations in each plot. The soil cores collected from those three locations were pooled according to depth to form a composite sample of the respective position. Samples were then sent to the laboratory for nutrient analysis.

The first soil sampling was carried out three weeks after the manure application. By then the crop had reached a state of full emergence. During the first sampling in each year, the sampling locations were flagged for use as references in subsequent samplings. Then sampling was carried out every two to three weeks, depending on the weather conditions.

The samples were analyzed in the interest of knowing soil nitrogen and phosphorus concentrations. Additional analysis was also performed on soil electrical conductivity and soil pH.

4.3.5.2 Plant development characteristics

Plant samples were collected at the soft dough stage for comparing plant development characteristics between the two different crop rows (R_1 and R_2) in the r_3 treatment (fig. 4.1). Whole plants were collected by randomly uprooting 40 plants per plot, 20 from each of R_1 and R_2 rows between any two random but consecutive manure bands. The number of heads and tillers per plant were counted and the length of main stem was measured using a ruler.

4.3.5.3 Biomass, and total N and P in the biomass

Plant samples for biomass measurement were taken also at the soft dough stage. Crop rows of 0.50-m length were cut 0.07 m above ground level at three random locations from each of two crop rows (R_1 and R_2 shown in fig. 4.1) to determine plant biomass, and total N and P in the biomass. The samples for each row from the three locations were combined to form a composite sample. Samples were weighed to determine the mass per unit length of crop row. Then, plant samples were digested using the standard acid (H_2SO_4-H_2O_2) digestion method described in Thomas et al. (1967). A Technicon Autoanalyzer was used to colorimetrically determine total N and P in the digest.

4.3.6 Statistical analyses

The data were analyzed using SAS software (SAS Institute Inc., 2001). Analysis of Variance was carried out using the general linear model (GLM) procedure to calculate mean values of variables of interest at different positions within each treatment. Least Significant Difference (LSD) test was employed to determine mean differences within treatment at different positions under each combination of injection tool type and rate. Considering the inherently high variability in soils, all comparisons were made at a probability of 0.1 ($P < 0.1$). Data were analyzed within a year due to the great differences in precipitation between years.

4.4 Results and discussion

4.4.1 Background information on weather, soil, and manure

The weather was highly variable during the three years. Total precipitation over the growing seasons of 2002, 2003, and 2004 was 251, 185, and 369 mm, respectively, in contrast to a 16-year average precipitation of 290 m. At the time of manure injection, the soils had a low bulk density of approximately 0.8-0.9 Mg m^{-3} due to spring tillage before the injection, and the soil moisture contents were 24, 34, and 36% (dry basis) in 2002, 2003, and 2004, respectively. The average total N was 2.9 kg 1,000 L^{-1} in the manure, of which approximately 90% existed in the form of NH_4-N. The average total P in the manure was 0.6 kg 1,000 L^{-1}.

4.4.2 Soil nitrate nitrogen (NO_3-N)

In 2002, a trend of decreasing soil NO_3-N with position farther from centerline of manure band was observed (table 4.2). In the first of five sampling periods, levels of soil NO_3-N were significantly higher at position A_1 than at position B_1, when the furrower tool was used. Three weeks after manure injection, soil concentrations of NO_3-N at position A_2 were two and four times higher than those at positions B_2 and C_2, respectively, when the coulter was used for manure injection. After the last sampling, the reverse trend was observed, likely due to a combination of denitrification due to the low oxygen content of the soil close to the manure band and uptake of nitrogen by the crop. Positions A_2, B_2, and C_2 had similar soil NO_3-N when the furrower was used. Position effects were more pronounced in the r_3 treatments, where soil NO_3-N significantly decreased with the distance from the centerline of manure band in four out of five sampling periods when using the furrow tool.

Table 4.2. Levels of extractable soil NO_3-N ($\mu g\ g^{-1}$) at varying lateral positions at a soil depth of 0-0.3 m, 2002.

Rate ($L\ m^{-1}$)	Position*	Weeks after injection (wk)				
		3	5	7	9	11
Coulter						
r_1=1.02	A_1	44.0 a**	20.1 a	10.2 a	3.7 a	1.7 a
	B_1	23.8 a	10.3 b	5.1 a	6.8 a	2.7 a
r_2=2.04	A_2	38.0 a	5.7 a	1.7 a	2.3 a	1.1 ab
	B_2	13.1 b	4.2 a	1.8 a	2.3 a	1.0 b
	C_2	7.5 b	3.8 a	5.3 a	1.9 a	1.5 a
r_3=3.06	A_3	68.8 a	31.7 a	8.0 b	3.5 ab	1.5 a
	B_3	24.0 b	14.9 b	19.8 a	5.8 a	1.5 a
	C_3	15.0 b	2.6 c	4.0 c	1.9 ab	1.3 a
	D_3	12.5 b	1.7 c	4.5 b	1.4 b	1.0 a
Furrower						
r_1=1.02	A_1	42.4 a	17.9 a	13.9 a	2.7 a	1.9 a
	B_1	19.0 b	5.0 a	8.1 a	3.1 a	2.4 a
r_2=2.04	A_2	18.2 a	14.7 a	1.8 a	1.1 a	1.0 a
	B_2	24.0 a	13.8 a	3.8 a	2.1 a	1.1 a
	C_2	19.9 a	8.5 a	2.8 a	1.8 a	1.1 a
r_3=3.06	A_3	66.3 a	35.5 a	42.1 a	8.4 a	2.3 a
	B_3	25.9 b	17.3 b	5.2 ab	3.1 b	3.8 a
	C_3	14.6 bc	5.5 c	2.9 b	3.1 b	1.6 a
	D_3	7.5 c	3.4 c	2.0 b	1.7 b	1.5 a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

In 2003, the overall trend with position of soil NO_3-N (table 4.3) was consistent with that in 2002. Using the coulter, significant differences were observed once where position A_3 had higher soil NO_3-N than positions B_3, C_3 and D_3, nine weeks after injection at the 0-0.3 m depth. When the furrower was used, position A_2 had significantly higher soil NO_3-N than positions B_2 and C_2 at the 0-0.3 m depth at all sampling periods. Similarly, in plots where manure was injected using the furrower, position A_3 had significantly higher soil NO_3-N than positions B_3, C_3, and D_3 at the 0-0.3 m depth at all sampling periods. These trends were observed at the 0.3-0.6 m depth, but they were less pronounced.

Table 4.3. Levels of extractable soil NO_3-N ($\mu g\ g^{-1}$) at varying lateral positions at two soil depths, 2003.

Rate ($L\ m^{-1}$)	Position*	3 wk after injection		6 wk after injection		9 wk after injection	
		0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)
Coulter							
r_1=1.02	A_1	24.8 a**	12.4 a	9.5 a	10.0 a	14.2 a	9.5 a
	B_1	39.9 a	13.0 a	12.7 a	9.4 a	17.1 a	8.7 a
r_2=2.04	A_2	39.0 a	14.8 a	9.3 a	8.6 a	18.0 a	4.9 a
	B_2	17.6 a	15.9 a	11.3 a	10.8 a	13.3 a	12.5 a
	C_2	20.6 a	14.8 a	6.0 a	11.9 a	11.6 a	8.3 a
r_3=3.06	A_3	33.2 a	15.8 a	9.9 a	12.8 a	41.0 a	10.4 a
	B_3	21.5 a	14.2 a	11.1 a	9.4 a	16.4 b	10.4 a
	C_3	13.8 a	15.3 a	15.0 a	11.7 a	13.1 b	11.4 a
	D_3	13.2 a	11.6 a	14.9 a	17.3 a	8.8 b	6.0 a
Furrower							
r_1=1.02	A_1	27.2 a	13.5 a	16.2 a	13.7 a	24.0 a	12.4 a
	B_1	27.5 a	13.4 a	18.1 a	13.9 a	17.6 a	9.6 b
r_2=2.04	A_2	47.8 a	12.1 a	25.2 a	10.0 a	29.7 a	9.4 a
	B_2	23.6 b	12.3 a	8.2 b	10.0 a	13.3 b	7.0 a
	C_2	11.0 b	10.8 a	10.7 b	10.2 a	14.2 b	9.7 a
r_3=3.06	A_3	53.6 a	16.6 a	46.7 a	16.3 ab	42.7 a	12.1 a
	B_3	28.5 b	15.6 a	13.7 b	19.2 a	20.7 b	9.4 a
	C_3	24.4 b	18.7 a	14.1 b	11.8 b	15.2 b	8.8 a
	D_3	15.5 b	16.5 a	7.6 b	13.4 ab	12.0 b	7.2 a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

Similarly, results in 2004 indicated that soil NO_3-N decreased with increasing distance from the center of manure band (table 4.4). Significant position effects were observed over the growing season and after harvest. Again this position effect was more pronounced at the 0-0.3 m soil depth than 0.3-0.6 m depth and in the r_3 treatment than in the r_1 and r_2 treatments.

Table 4.4. Levels of extractable soil NO_3-N ($\mu g\ g^{-1}$) at varying lateral positions at two soil depths, 2004.

Rate ($L\ m^{-1}$)	Position*	3 wk after injection		6 wk after injection		19 wk after injection	
		0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)
Coulter							
r_1=1.02	A_1	24.3 a**	15.5 a	17.4 a	14.2 a	8.1 a	2.3 b
	B_1	12.3 b	20.6 a	8.8 a	11.7 a	7.2 a	3.3 a
r_2=2.04	A_2	36.9 a	26.6 a	34.1 a	16.0 a	6.7 a	2.5 a
	B_2	26.5 a	19.1 b	4.8 b	11.4 ab	1.3 a	1.9 a
	C_2	13.0 b	19.0 b	4.4 b	10.2 b	0.8 a	0.7 a
r_3=3.06	A_3	23.1 a	21.1 ab	23.1 a	15.0 a	8.3 a	3.2 a
	B_3	12.3 ab	13.8 bc	10.4 b	12.2 ab	4.0 a	2.5 a
	C_3	10.3 b	21.9 a	4.2 c	9.4 b	1.8 a	0.8 a
	D_3	15.0 ab	13.2 c	4.4 c	11.4 b	2.5 a	0.9 a
Furrower							
r_1=1.02	A_1	21.8 a	24.3 a	18.7 a	15.9 a	1.3 a	1.0 a
	B_1	21.7 a	21.6 a	10.7 b	16.4 a	1.4 a	3.6 a
r_2=2.04	A_2	19.5 a	17.6 a	32.4 a	16.3 a	11.3 a	0.8 a
	B_2	20.2 a	15.6 a	11.8 b	14.0 b	5.9 ab	2.3 a
	C_2	14.2 a	16.2 a	7.9 b	13.0 b	4.8 b	2.2 a
r_3=3.06	A_3	15.0 a	10.0 a	42.5 a	18.0 a	13.8 a	2.5 a
	B_3	20.6 a	14.0 a	15.7 b	11.9 b	5.7 b	2.7 a
	C_3	8.6 a	11.4 a	3.9 b	9.4 b	3.5 b	2.8 a
	D_3	8.5 a	14.4 a	3.3 b	7.6 b	5.0 b	1.9 a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

4.4.3. Soil ammonium nitrogen (NH_4-N)

The data of soil NH_4-N for 2004 are presented in table 4.5. Similar to the soil NO_3-N, decreasing concentrations of soil NH_4-N were observed with increasing distance from centerline of manure band. This position effect was significant for the r_2 and r_3 rates at both the 0-0.3 and 0.3-0.6 m depths under both injection tools. Levels of soil NH_4-N (0.44-1.33 $\mu g\ g^{-1}$) in 2002 were low at all periods of sampling possibly due to nitrification. There were few significant effects of position on soil NH_4-N during this growing season. Therefore, the data are not presented. Soil NH_4-N was not measured in 2003.

Table 4.5. Levels of extractable soil NH_4-N ($\mu g\ g^{-1}$) at varying lateral positions at two soil depths, 2004.

Rate ($L\ m^{-1}$)	Position*	3 wk after injection		6 wk after injection	
		0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)
Coulter					
r_1=1.02	A_1	16.4 a**	7.6 a	13.9 a	11.0 a
	B_1	8.5 a	7.4 a	14.2 a	11.5 a
r_2=2.04	A_2	23.2 a	9.6 a	13.2 a	9.7 a
	B_2	10.1 b	6.2 b	9.7 a	9.4 a
	C_2	9.4 b	7.3 b	8.3 a	9.8 a
r_3=3.06	A_3	66.0 a	12.4 a	12.7 a	9.1 a
	B_3	10.8 b	10.0 b	9.6 a	9.3 a
	C_3	10.8 b	7.6 c	9.3 a	10.7 a
	D_3	9.6 b	7.6 c	9.4 a	10.8 a
Furrower					
r_1=1.02	A_1	11.8 a	9.7 a	12.6 a	12.4 a
	B_1	16.0 a	8.7 a	11.7 a	11.3 a
r_2=2.04	A_2	26.9 a	11.5 a	14.4 a	9.2 b
	B_2	12.9 ab	9.1 a	9.6 b	11.0 a
	C_2	9.1 b	7.0 a	9.4 b	10.1 ab
r_3=3.06	A_3	31.8 a	11.2 a	13.2 a	9.7 a
	B_3	17.6 ab	7.5 ab	8.6 b	11.3 a
	C_3	10.3 b	6.0 b	7.6 b	9.4 a
	D_3	8.1 b	6.6 b	7.2 b	9.7 a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

Position effects on soil NO_3-N and NH_4-N observed in this study are consistent with those of Sawyer et al. (1990), who observed that the highest concentrations of inorganic nitrogen were present at centers of manure band, with lower concentrations at lateral distances of 0.13 m. McCormick et al. (1983) also reported similar N distribution effects after injecting liquid swine manure.

4.4.4 Soil phosphate (P_2O_5)

Measurements in 2004 indicated that concentrations of soil P_2O_5 were consistently lower at all positions further from centerline of manure band (table 4.6). This was expected since manure P is relatively immobile in soil, particularly soils with high clay content. Soil P_2O_5 at position A was the highest and significantly different from positions B, C, and D at both soil depths over the growing season and after harvest. Data collected in 2003 showed the similar soil response but concentration differences were lower (data shown in Table A1 in Appendix A). The data of 2002 showed few significant differences between treatments (data shown in Table A2 in Appendix A).

Table 4.6. Extractable soil P_2O_5 ($\mu g\ g^{-1}$) at varying lateral positions at two soil depths, 2004.

Rate ($L\ m^{-1}$)	Position*	3 wk after injection 0-0.3 (m)	3 wk after injection 0.3-0.6 (m)	6 wk after injection 0-0.3 (m)	6 wk after injection 0.3-0.6 (m)	19 wk after injection 0-0.3 (m)	19 wk after injection 0.3-0.6 (m)
Coulter							
r_1=1.02	A_1	73.5 a**	58.2 a	65.0 a	52.3 a	74.7 a	58.2 a
	B_1	74.4 a	49.4 a	67.2 a	59.7 a	67.4 a	54.8 a
r_2=2.04	A_2	93.9 a	62.1 a	60.4 a	60.9 a	61.3 a	45.0 a
	B_2	72.3 ab	47.9 a	50.6 a	55.2 b	48.3 a	58.3 a
	C_2	67.4 b	76.7 a	49.6 a	54.3 b	52.6 a	45.4 a
r_3=3.06	A_3	123.0 a	50.0 a	57.6 a	54.9 a	92.6 a	47.5 a
	B_3	68.2 b	39.5 bc	49.0 b	51.4 a	52.04 b	44.8 a
	C_3	69.2 b	47.4 ab	51.4 b	54.7 a	58.4 b	49.4 a
	D_3	70.7 b	34.5 c	51.1 b	52.8 a	67.9 ab	49.0 a
Furrower							
r_1=1.02	A_1	73.8 a	67.1 b	67.7 a	65.6 a	81.6 a	66.5 a
	B_1	92.6 a	87.6 a	66.6 a	63.7 a	67.6 b	57.8 a
r_2=2.04	A_2	75.8 a	48.0 a	62.4 a	38.3 a	66.2 a	44.6 a
	B_2	67.7 a	43.3 ab	51.5 b	34.3 a	47.8 b	38.0 a
	C_2	62.9 a	38.2 b	49.3 b	37.0 a	48.8 b	39.2 a
r_3=3.06	A_3	93.1 a	40.6 a	70.2 a	54.8 ab	77.4 a	56.3 a
	B_3	74.5 ab	50.4 a	60.2 ab	57.6 a	60.9 b	53.9 a
	C_3	68.9 ab	49.0 a	50.9 b	42.6 b	58.7 b	55.8 a
	D_3	63.4 b	62.1 a	54.2 b	41.1 b	59.2 b	38.1 b

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

4.4.5 Soil electrical conductivity (EC)

Soil EC also decreased with increasing distance from the manure band. In 2002, a decrease in soil EC with distance from the manure band was observed when manure was injected using the coulter, although there was no significant difference observed between positions A_1 and B_1 at all sampling periods (table 4.7). In contrast, when manure was injected using the furrower, the soil EC at position A_1 was higher than that at B_1 at all sampling periods. At the highest rate, the soil EC measured in the manure band was frequently higher than the soil EC at the other sampling positions, regardless of the type of injection tool. Soil EC was not determined in 2003. The same decreasing trend was observed in 2004 (table 4.8) as in 2002. Differences among positions were also similar to those observed in 2002, but were less consistent. These observations are consistent with those reported by Peterson et al. (2003), who observed a horizontal gradient in soil EC after injecting swine and cattle slurries using disc injection tools, with the highest EC occurring in the injection slit. However, when using a harrow tine injection tool, they reported similar EC levels at varying positions relative to injection slit, which they attributed to horizontal distribution of slurry liquids or initial mixing of slurry into a large soil volume.

Table 4. 7. Soil EC (dS m^{-1}) at varying lateral positions at a soil depth of 0-0.3 m, 2002.

Rate (L m^{-1})	Position*	Weeks after injection (wk)				
		3	5	7	9	11
Coulter						
r_1=1.02	A_1	0.84 a**	0.71 a	1.61 a	0.52 a	0.50 a
	B_1	0.62 a	0.63 a	0.60 a	0.55 a	0.49 a
r_2=2.04	A_2	0.79 a	0.63 a	0.60 ab	0.53 a	0.50 a
	B_2	0.56 a	0.56 a	0.57 b	0.49 a	0.48 ab
	C_2	0.55 a	0.61 a	0.62 a	0.50 a	0.44 b
r_3=3.06	A_3	1.20 a	0.78 a	0.63 a	0.54 a	0.48 a
	B_3	0.59 b	0.64 b	1.31 a	0.53 a	0.47 a
	C_3	0.56 b	0.60 b	0.66 a	0.53 a	0.39 a
	D_3	0.54 b	0.58 b	0.61 a	0.51 a	0.43 a
Furrower						
r_1=1.02	A_1	0.83 a	0.71 a	0.64 a	0.53 b	0.52 a
	B_1	0.63 b	0.55 b	0.57 b	0.57 a	0.48 b
r_2=2.04	A_2	0.62 a	0.66 a	0.63 a	0.55 a	0.55 a
	B_2	0.66 a	0.69 a	0.62 a	0.55 a	0.53 a
	C_2	0.63 a	0.60 a	0.62 a	0.51 a	0.47 a
r_3=3.06	A_3	1.12 a	0.85 a	0.75 a	0.61 a	0.50 a
	B_3	0.70 b	0.68 b	0.65 b	0.55 ab	0.54 a
	C_3	0.60 c	0.58 c	0.61 b	0.50 b	0.49 a
		0.55 c	0.55 c	0.61 b	0.49 b	0.50 a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

Table 4.8. Soil EC, dS m^{-1} at varying lateral positions at two soil depths, 2004.

Rate (L m^{-1})	Position*	3 wk after injection 0-0.3 (m)	3 wk after injection 0.3-0.6 (m)	6 wk after injection 0-0.3 (m)	6 wk after injection 0.3-0.6 (m)	19 wk after injection 0-0.3 (m)	19 wk after injection 0.3-0.6 (m)
Coulter							
r_1=1.02	A_1	0.68 a**	0.70 a	0.65 a	0.70 a	0.51a	0.55 a
	B_1	0.58 a	0.71 a	0.58 a	0.68 b	0.53a	0.62 a
r_2=2.04	A_2	0.69 a	0.75 a	0.70 a	0.66 a	0.52a	0.58 a
	B_2	0.72 a	0.69 b	0.52 b	0.65 a	0.50a	0.60 a
	C_2	0.61 a	0.69 b	0.52 b	0.63 a	0.50a	0.59 a
r_3=3.06	A_3	0.69 a	0.73 a	0.71 a	0.71 a	0.51a	0.63 a
	B_3	0.66 a	0.68 b	0.60 b	0.70 ab	0.51a	1.32 a
	C_3	0.61 a	0.73 a	0.52 c	0.69 ab	0.50a	0.91 a
	D_3	0.61 a	0.71 ab	0.61 b	0.68 b	0.51a	0.72 a
Furrower							
r_1=1.02	A_1	0.73 a	0.75 a	0.66 a	0.80 a	0.53a	0.71 a
	B_1	0.64 a	0.76 a	0.62 a	0.72 a	0.51a	0.77 a
r_2=2.04	A_2	0.55 a	0.64 b	0.63 a	0.72 a	0.51a	0.61 a
	B_2	0.58 a	0.70 a	0.52 b	0.69 ab	0.47a	0.61 a
	C_2	0.49 a	0.64 b	0.49 b	0.67 b	0.47a	0.57 a
r_3=3.06	A_3	0.65 a	0.79 a	0.77 a	1.14 a	0.60a	1.03 a
	B_3	0.64 a	0.75 a	0.60 b	1.32 a	0.49b	1.18 a
	C_3	0.51 a	0.69 a	0.54 b	0.84 a	0.46b	1.28 a
	D_3	0.52 a	0.67 a	0.44 c	0.67 a	0.49b	1.18 a

*A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

**Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

4.4.6 Soil pH

Soil pH has been shown to be an important factor, which controls the soil microbial community in general, and the community of denitrifiers in particular (Simek and Hopkins, 1999). Rate effects on soil pH in the surface layer (0-0.3 m) are likely the result of proton (H^+) production during nitrification of ammonium (table 4.9). Soil pH within manure band tended to be lower at the higher rate compared to the lower rate, although no significant difference was detected. Conversely soil pH tended to increase with increasing distance from the centerline of manure band applied with either the coulter or furrower, although the effect was not consistent for all combinations of tools and rates (table 4.9). Soil pH was not measured in 2003. Results of the field experiment conducted in 2004 indicated little lateral variation (data not reported).

Table 4.9. Soil pH at varying lateral positions at the depth of 0-0.3 m, 2002.

Rate ($L\ m^{-1}$)	Position*	Weeks after injection (wk)				
		3	5	7	9	11
Coulter						
r_1=1.02	A_1	7.63 a**	7.63 a	7.70 b	7.85 a	7.75 a
	B_1	7.68 a	7.68 a	7.85 a	7.80 a	7.80 a
r_2=2.04	A_2	7.43 a	7.58 a	7.75 a	7.73 a	7.83 a
	B_2	7.55 b	7.63 a	7.75 a	7.68 a	7.80 a
	C_2	7.60 b	7.68 a	7.75 a	7.70 a	7.80 a
r_3=3.06	A_3	7.35 c	7.53 b	7.68 a	7.63 a	7.75 a
	B_3	7.50 b	7.55 b	7.60 a	7.65 a	7.68 b
	C_3	7.55 ab	7.65 a	7.63 a	7.68 a	7.65 b
	D_3	7.63 a	7.65 a	7.70 a	7.65 a	7.68 b
Furrower						
r_1=1.02	A_1	7.53 b	7.58 b	7.73 a	7.63 a	7.85 a
	B_1	7.60 a	7.73 a	7.78 a	7.65 a	7.83 a
r_2=2.04	A_2	7.68 a	7.70 a	7.75 a	7.75 b	7.78 a
	B_2	7.68 a	7.73 a	7.75 a	7.83 a	7.78 a
	C_2	7.70 a	7.75 a	7.78 a	7.83 a	7.78 a
r_3=3.06	A_3	7.40 c	7.68 a	7.60 b	7.65 a	7.83 a
	B_3	7.53 b	7.50 a	7.68 a	7.65 a	7.80 a
	C_3	7.58 ab	7.58 a	7.65 ab	7.73 a	7.80 a
	D_3	7.60 a	7.65 a	7.68 a	7.70 a	7.75a

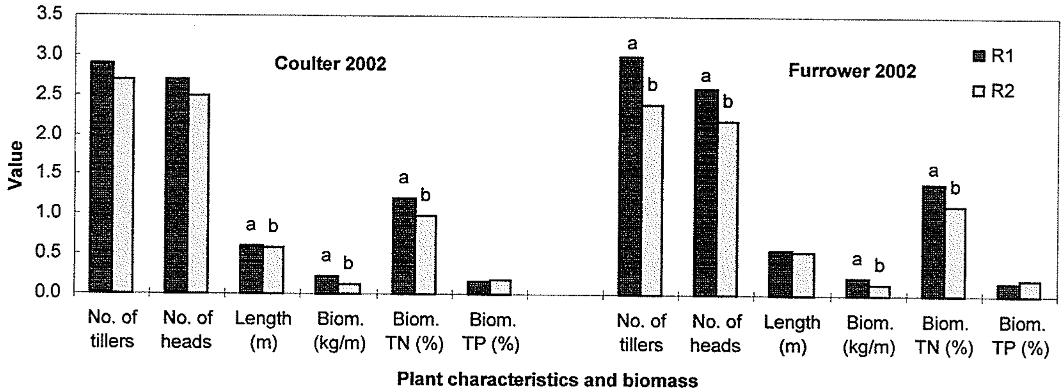
* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

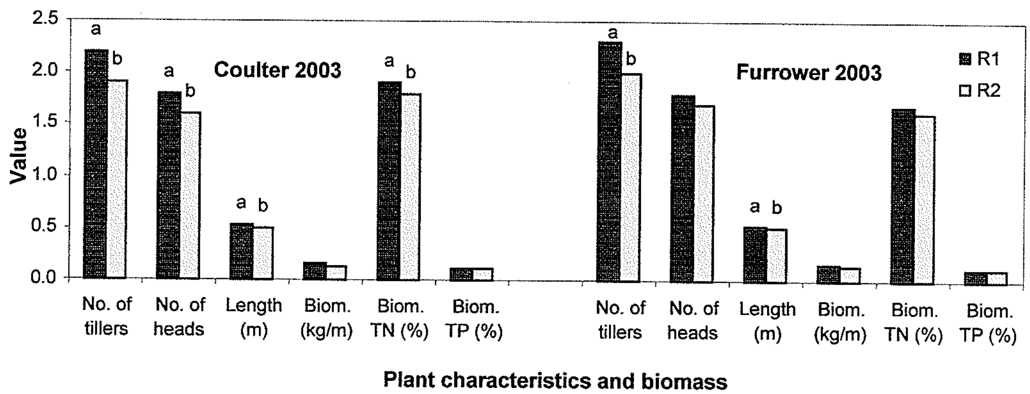
4.4.7 Plant development characteristics and biomass

Better plant performance was obtained in crop rows closer to a manure bands as determined by a number of plant development characteristics (fig. 4.2). In 2002, a significantly higher number of tillers and heads per plant were observed for the crop row R_1 than for R_2, when manure was injected using the furrower (fig. 4.2a). For the length of main stem, a similar difference was observed when manure was applied using the coulter. Plant biomass of R_1 was significantly higher than that of R_2 when manure was injected using either tool. In 2003, number of tillers and stem length were significantly greater for R_1 than for R_2 when manure was applied using either tool (fig. 4.2b). When the coulter was used, the number of heads per plant for R_1 was significantly higher than that for R_2. In 2004, R_1 had greater number of tillers than R_2 when using the furrower, and there were no significant differences in other crop parameters between these two crop rows for both the coulter and furrower (fig. 4.2c). Extremely dry soil conditions and high temperatures during crop anthesis may have masked some of the position effects.

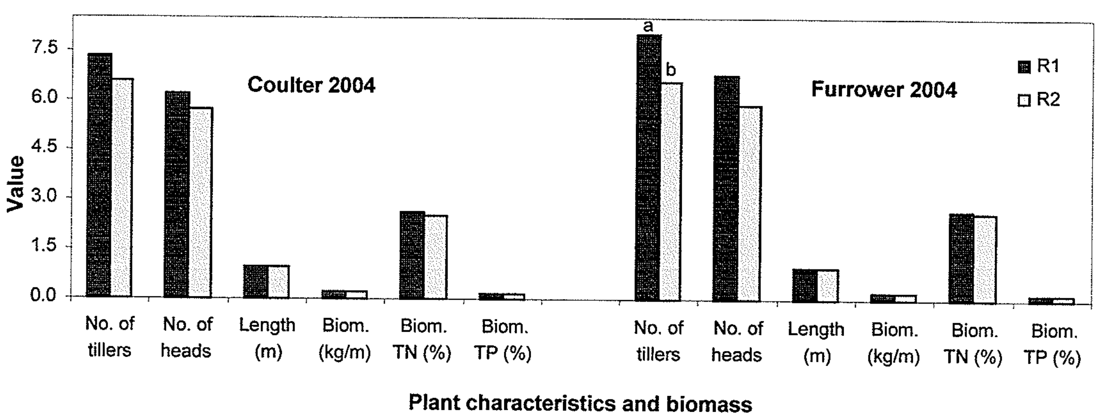
Total N in plant biomass was consistently higher for R_1 than for R_2, this difference between these rows being significant in three out of six measurements during the three-year period (fig. 4.2). There were no significant differences in total P in plant biomass between the two rows. The results are consistent with observations by Sawyer et al. (1991) who reported lower plant nitrogen concentrations in corn offset at parallel distances of 0.25, 0.51, and 0.76 m from knife injected manure bands compared to corn planted in the centers of manure band.



(a)



(b)



(c)

Figure 4.2. Comparisons in plant development characteristics (number of tillers and heads, and length of main stem) and biomass, total N and total P in biomass between two crop rows; R1 and R2; R1 and R2 are 0.15 and 0.45 m from center of an injected manure band, respectively; values within each variable followed by the same letter are not significantly different; (a) 2002; (b) in 2003; (c) 2004.

4.5 Conclusions

Availability of soil nutrients was highest at centre lines of manure bands and was lower at further lateral distance from the manure bands, irrespective of the type of injection tool used. These trends were observed for all soil nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and phosphate (P_2O_5). The differences in soil nutrients were more pronounced at the 0-0.3 m soil depth interval than at 0.3-0.6 m depth interval and when manure was injected at the highest rate. The increased availability of nutrients in close proximity to the manure bands compared to the middle was substantiated by better plant performance and consistently higher total N in plant biomass observed at the plant row closer to a manure band. Considering the differences in lateral nutrient distribution in soil and the differences in crop performance between the two crop rows, large tool spacing such as 0.9 m may be avoided in order to obtain uniform soil nutrient distribution and plant development, regardless of tool type to be used. The positional differences in soil nutrient levels should also be considered when sampling for soil nutrient analysis following manure injection, so that representative soil nutrient levels can be obtained.

4.6 Acknowledgements

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4.7 References

ASAE Standards. 2004. Terminology and definitions for agricultural tillage implements. In *ASAE Standards*, ASAE S414.1 FEB04. St Joseph, MI: ASAE.

Chen, Y., Q. Zhang and D. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. *Applied Engineering in Agriculture* 17(4): 489-496.

McCormick, R.A., D.W. Nelson, A.L. Sutton and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformations in soil treated with liquid swine manure. *Agronomy Journal* 75 (6): 947-950.

Meisinger, J.J. and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. In *Proc. from Managing Nutrients and Pathogens from Animal Agriculture*, pp 334-354. PA: Camp Hill.

Petersen, S.O., H.H. Nissen, I. Lund and P. Ambus. 2003. Redistribution of slurry components as influenced by injection methods, soil, and slurry properties. *Journal of Environment Quality* 32(6): 2399-2409.

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

SAS Institute Inc. 2001. *SAS Proprietary Software Release 8.2*. SAS Institute Inc.. NC: Cary.

Sawyer, J.E., M.A. Schmitt and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Agronomy Journal* 82(5): 963-969.

Sawyer, J.E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens and D.H. Vanderholm. 1991. Corn production associated with liquid beef manure application methods. *Journal Production Agriculture* 4(3): 335-344.

Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal Production Agriculture* 8(2): 186-189.

Schmitt, M.A. and R.G. Hoeft. 1986. Manure injection can sometimes injure corn crop. *Crops and Soils Magazine* 38(8): 19-22.

Simek, M. and D.W. Hopkins. 1999. Regulation of potential denitrification by soil pH in long-term fertilized arable soils. *Biology and Fertility of Soils* 30(1/2): 41-47.

Thomas, R.L., R.W. Sheard and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agronomy Journal* 59: 240-243.

Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39(4): 287-300.

Westerman, P.W., L.M. Safley, Jr. and J.C. Barker. 1983. Potential harmful effects from land applying animal wastes. ASAE Paper No. 83-2612. St. Joseph, Mich.: ASAE.

CHAPTER 5: A PROTOCOL FOR SOIL NUTRIENTS SAMPLING AFTER LIQUID MANURE INJECTION[‡]

5.1 Summary

A soil sampling protocol that enables accounting for banding effects of manure injection was developed based on soil nutrients data from field trials of liquid manure injection at three tool spacings: 0.3-, 0.6-, and 0.9-m. The data were taken at several lateral positions (0, 0.15, 0.30, and 0.45 m) relative to centre lines of manure bands. Levels of soil NO_3-N, NH_4-N, and P were considered in the development of the sampling protocol. The data showed that soil NO_3-N, NH_4-N, and P concentrations were lower at the position farther away from the centre of manure band. A directed paired-sampling approach, i.e. sampling at two positions along a transect perpendicular to the injector travel direction was developed to address the position effect on soil nutrient concentrations. This approach allows for a more accurate estimate of the average NO_3-N and P concentrations in soil when compared to the traditional random sampling method provided that information on injector travel direction and tool spacing is available. ***Keywords:*** *sampling, protocol, manure, injection, position, tool spacing, soil, nutrient.*

5.2 Introduction

Soil sampling is performed to obtain relevant information about a given soil based on fundamental objectives such as chemical analysis, soil survey, soil fertility status, and

[‡] This chapter has been published in the Canadian Biosystems Engineering Journal (as attached in Appendix 3).

environmental concerns (Crépin and Johnson 1993). According to De Gruijter (2002) the decision on how many, where, how, and when samples are to be collected often depends on the purpose of a given study, the budget, and logistical constraints.

Soil sampling techniques may be broadly categorized as judgmental, random, or systematic (Petersen and Calvin 1998) with none of them being universal. Judgmental sampling is a technique in which samples are collected from the most typical sites or locations (based on a researcher's judgement) representing a population. Those locations within a field can be repeatedly sampled year to year (referred as to Benchmark soil sampling). Random sampling is a technique in which a given number of samples are obtained from a population, each with an equal chance of being selected. Systematic sampling technique is a method in which samples are collected at regular distances from each other in one or two dimensions. One example of two dimensional systematic sampling is grid sampling (precision sampling). According to Mohamed et al. (1996) and Thompson et al. (2004), grid soil sampling enables assessment of field-scale soil nutrient variability. However, they reported that such sampling is costly. Grid sampling may take the forms of rectangular or triangular grids (McBratney et al. 1981; Petersen and Calvin 1998). Grid size depends on the desired precision and the spatial variability of the soil (McBratney et al. 1981).

Results of soil nutrient analysis depend on the soil samples used for the analysis (Donohue 2002; Anderson et al. 1992). This is because soils are characterized by high degree of spatial variability in their nutrient status (Penney et al. 1996; Mallarino 1996). Donohue (2002) emphasized the importance of getting a good soil sample by indicating how small the sample size is relative to the mass of the soil in the sampled area. Mallarino (1996) related high lateral variability to soil types and management practices such as tillage and fertilizer or manure application. Schnug et al. (1998) pointed out that even uniform addition of inputs in crop production results in over and under supply of resources. McBratney et al. (1981) described a method for designing optimal sampling schemes for the purpose of earth's surface survey. This method was based on the assumption that spatial dependence is expressed quantitatively in some way.

Soil sampling for nutrient analysis is required by researchers and extension specialists for developing practices of manure management and crop production. Government environmental officers also need to take soil samples when they do soil nutrients auditing following manure application. The traditional randomised soil sampling is the most common method. Soil sampling following liquid manure injection can be problematic in terms of spatial variability of soil nutrients. Liquid manure is injected into soil as bands and the centre-to-centre distance of two adjacent bands is determined by the injection tool spacing. Higher nutrient concentrations are expected at the centre of manure bands than at lateral distances away from the manure bands. For example, Petersen et al. (2003) measured about 55 mg kg^{-1} Br^{-} concentration in the centre of slurry injection band as compared to about 21 mg kg^{-1} Br^{-1} at a further distance from the band. Sawyer et al. (1990) reported 60 to 80 mg kg^{-1} inorganic N in the injected beef manure band and less than10 mg kg^{-1} inorganic N at the lateral distances of 1.27 m away from the band. McCormick et al. (1983) measured 491 and 87 mg kg^{-1} inorganic N concentrations at 0.25 and 0.90 m distances, respectively from the centre of the injected swine manure band. Similar observations were reported when inorganic fertilizers were band applied (Rehm and Lamb 2004; Zebarth et al. 1999; James and Hurst 1995).

There is limited information in the scientific literature with respect to practical soil sampling protocol such as proper sampling locations and time of sampling to address manure injection and banding of nutrients. The main goal of this study was to develop a soil sampling protocol to account for the banding effect from manure injection. This goal was achieved using existing soil nutrient data taken at different lateral positions relative to manure bands injected with different injection tool spacings. The specific objectives were to (1) examine patterns of soil nutrient variations with the lateral position and over the time after manure injection, and (2) propose a practical soil sampling protocol with regard to where and when to take the soil samples for nutrient analysis.

5.3 Methodology

The soil sampling protocol was developed based on soil nutrient data gathered through a previous field study (Assefa et al. 2005, 2006) conducted on clay soil in 2002, 2003, and 2004 in Manitoba. In this previous study, liquid swine manure was injected using a manure injector equipped with coulter (460-mm in diameter) and furrower (120-mm in width) injection tools at three different tool spacings: 0.3-, 0.6- and 0.9-m. After the manure injection, soil nutrient data (NO_3-N, NH_4-N, and P) were taken from different lateral positions: A_1 and B_1 for the 0.3-m tool spacing, A_2, B_2, and C_2 for the 0.6-m tool spacing, and A_3, B_3, C_3, and D_3 for the 0.9-m tool spacing (Fig. 5.1). Position A's were located on the centre lines of manure bands. Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively.

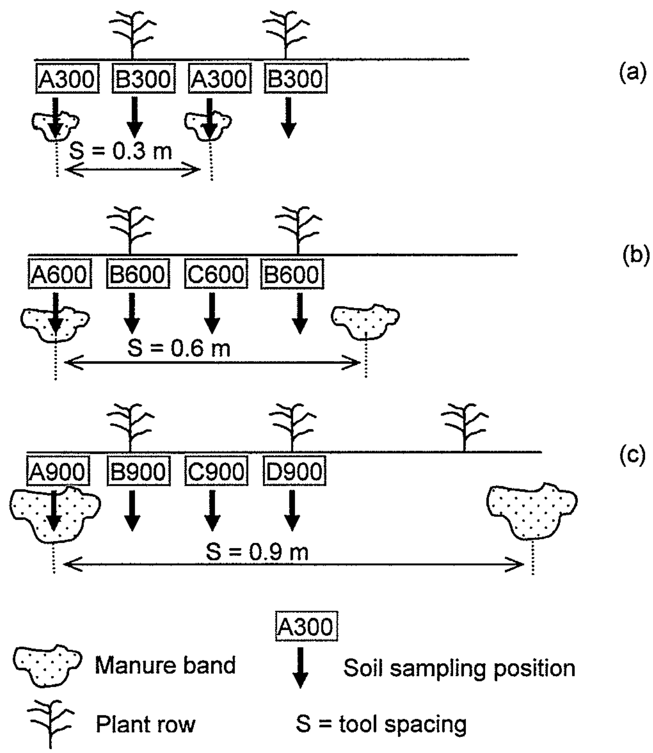

Figure 5.1. A schematic diagram of soil cross-section showing manure bands, soil sampling positions, and plant rows for (a) 0.3-m tool spacing, (b) 0.6-m tool spacing, and (c) 0.9-m tool spacing (After Assefa et al. 2005).

The commonly used sampling depth is 0-0.6 m for soil nitrogen analysis and shallower depth for soil phosphorus analysis in Manitoba. Therefore, data from a depth of 0-0.6 m were used for NO_3-N and NH_4-N analysis, and those from a depth of 0-0.3 were used for P analysis. The data used in this paper were mainly from 2004 as the year 2003 was characterised by extremely dry (2nd driest in 19 years) weather and the 2002 data were taken only at 0-0.3 m depth. The background soil NO_3-N (0-0.6 m) and P (0-0.3 m) levels in 2004 were 115 kg/ha and 31 kg/ha, respectively, prior to the manure injection. The nutrient contents in the manure are translated into application rates of approximately 119 kg/ha of nitrogen and 18 kg/ha of P. Data from the two injection tool types were pooled together for the analysis because effects of the coulter and furrower were not significantly different in most cases (Assefa et al. 2005). Another reason for this data pooling was for simplicity. Analysis of variance was carried out using the general linear model (GLM) procedure using SAS software (SAS Institute Inc. 2001). Considering the inherently high variability in soils, all comparisons were made at a probability of 0.1 ($P < 0.1$).

5.4 Results and discussion

In the development of the sampling protocol, the spatial variations of soil properties (McBratney et al. 1981) and the effect of plant row on nutrient use were not taken into consideration. As shown in Fig. 5.1, the plant rows were equally spaced 0.3 m apart for all tool-spacing treatments, while the manure bands were not. Positions B and D always had a plant row on them, while Positions A and C had no plant row. Thus, it was expected that nutrient uptake by the plants at those positions were different, which may have contributed to the differences in nutrient concentrations between positions. This confounding effect of plant rows on spatial distribution of N was not considered in the following discussion on the spatial distributions of soil nutrients. The only spatially-dependent variable accounted for was the position effect.

5.4.1 Soil nutrient concentrations at different lateral positions

Position-nutrient curves are plotted in Figs. 5.2-5.4 using the 2004 data taken at the 3^{rd}, 6^{th}, and 19^{th} week after manure injection. Although the data were highly variable, a clear decreasing trend in soil NH_4-N, NO_3-N, and P concentrations with farther position (particularly up to 0.15 m) from centre line of manure band was observed, as discussed in Assefa et al. (2005). For the 0.3-m tool spacing, the curves can be represented by straight lines, as there were only two positions, A_1 and B_1 (Fig. 5.1). For the 0.6-m or 0.9-m tool spacing, the position-nutrient curves can be expressed by polynomials of the second degree. As expected, position effects were more pronounced for the 0.9-m tool spacing than those for the smaller tool spacings, and more pronounced for the NO_3-N concentrations than for the P concentrations.

5.4.2 Forms of soil nitrogen over time

The decreasing trend with further position from manure band in NH_4-N concentration was less pronounced at the 6^{th} week after injection than at the 3^{rd} week after manure injection (Fig. 5.2) perhaps due to the nitrification that levelled off the NH_4-N in the soil over time. The nitrification increased the NO_3-N concentration on the manure band (Fig. 5.3), which makes the decreasing trend in NO_3-N more pronounced at the 6^{th} week. At the nineteenth week (after harvest), the decreasing trend of NO_3-N with distance diminished due to crop use.

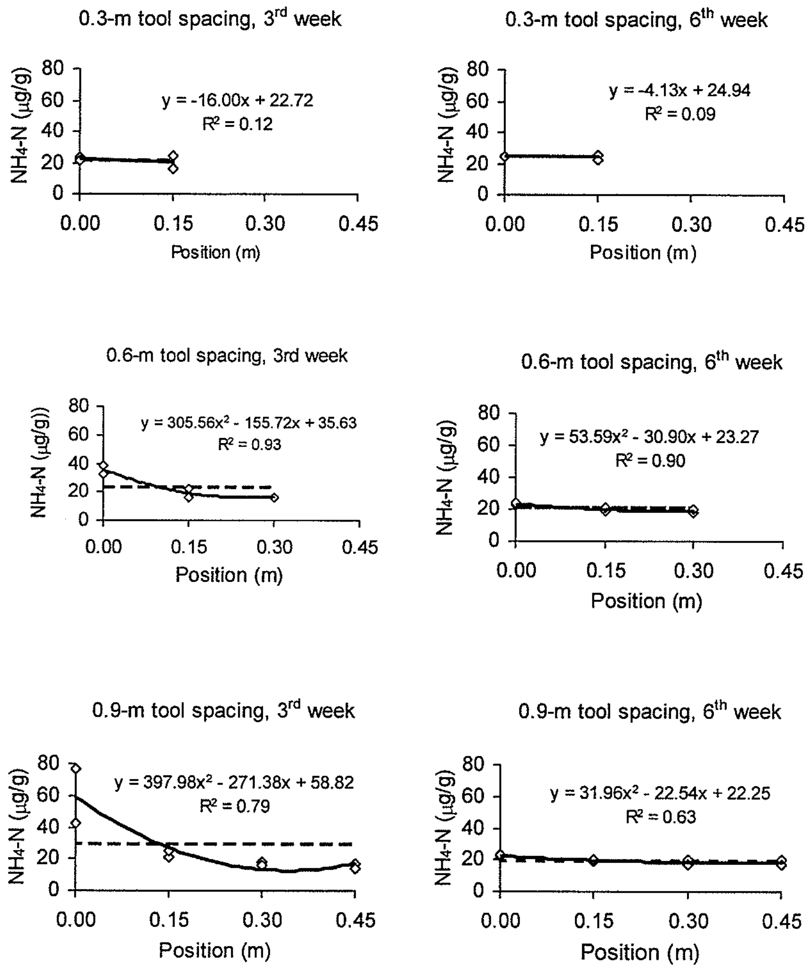

Figure 5.2. Soil NH_4-N concentrations at 0-0.6 m depth at different lateral positions relative to the centre of a manure band; the two data points at each lateral position represent the average values for the coulter and furrower injection tools, respectively; each data point is the average of four replicates; 2004. The average value over all positions is shown by a horizontal dash line.

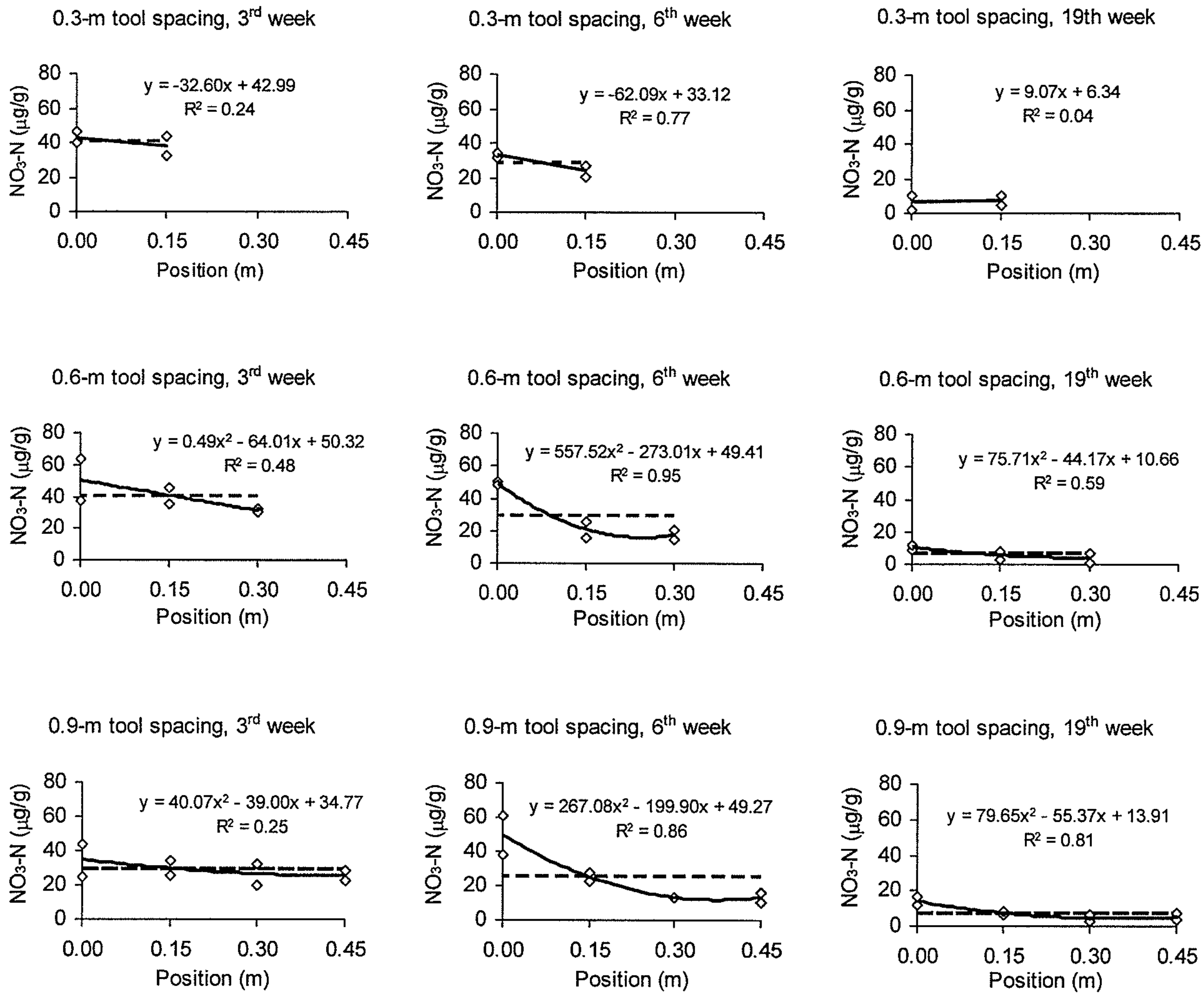

Figure 5.3. Soil NO_3-N concentrations at 0-0.6 m depth at different lateral positions relative to the centre of a manure band; the two data points at each lateral position represent the average values for the coulter and furrower injection tools, respectively; each data point is the average of four replicates; 2004. The average value over all positions is shown by a horizontal dash line.

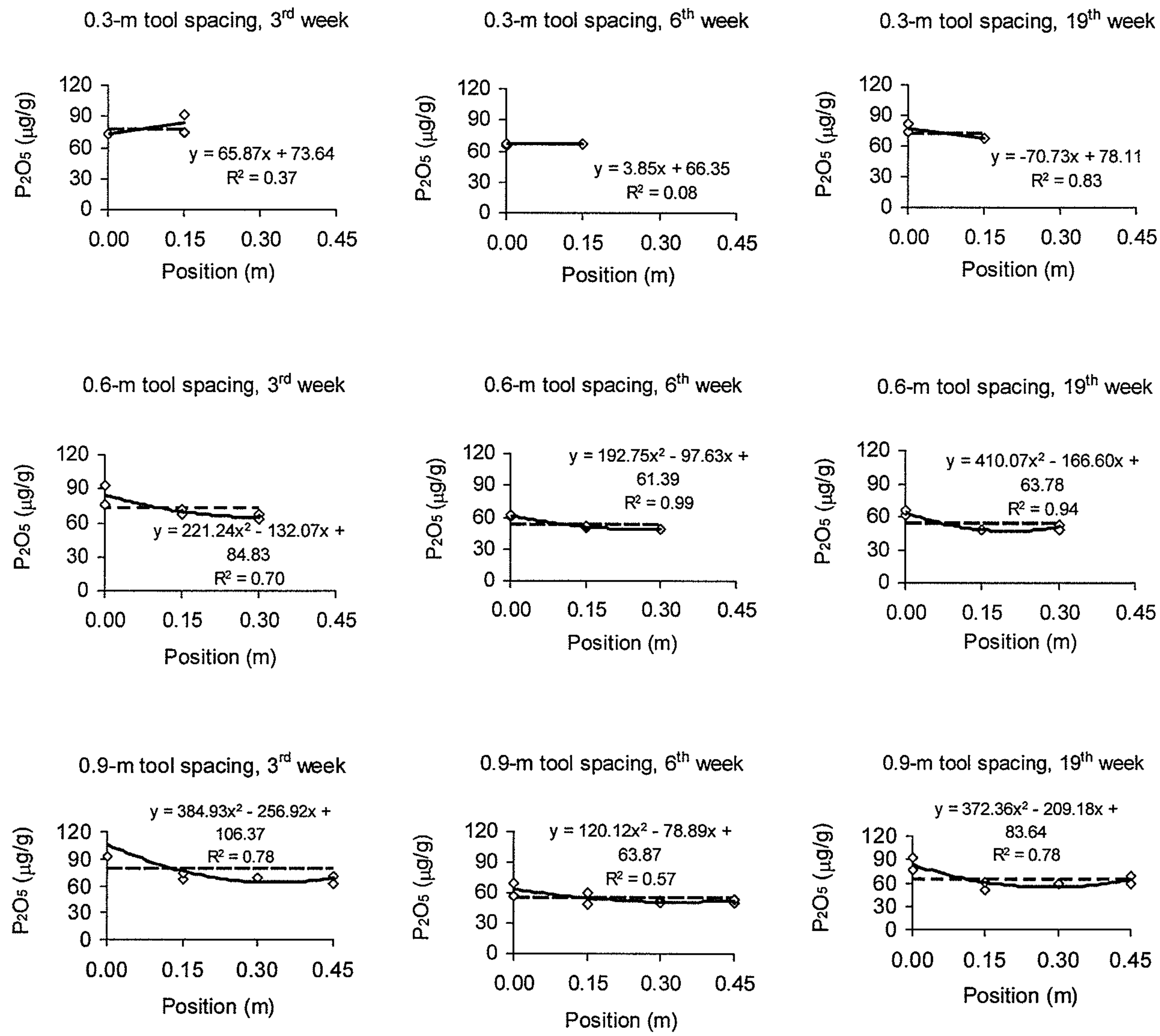

Figure 5.4. Soil P_2O_5 concentrations at 0-0.3 m depth at different lateral positions relative to the centre of manure band; the two data points at each lateral position represent the average values for the coulter and furrower injection tools, respectively; each data point is the average of four replicates; 2004. The average value over all positions is shown by a horizontal dash line.

5.4.3 Variations in nutrient concentration over time

The general trend was that concentrations of soil NO_3-N (Fig. 5.5a) and P (Fig. 5.5b) decreased over time, although the data were highly variable. This was attributable to the nutrient use of the plants. Denitrification and movement to the deeper soil layer could also be a reason for the decrease in NO_3-N. The soil P levels among positions (especially at 0.15 m distance and further from manure band) remained fairly constant over time, while significant differences in soil NO_3-N between some positions were observed at the earlier weeks (at the 3rd and 6th week). No data were taken for the following 13 weeks during which crop maturity and harvest were achieved. The position effect on the soil NO_3-N was not found at the 19th week. Therefore, it is unknown when the position effect vanished.

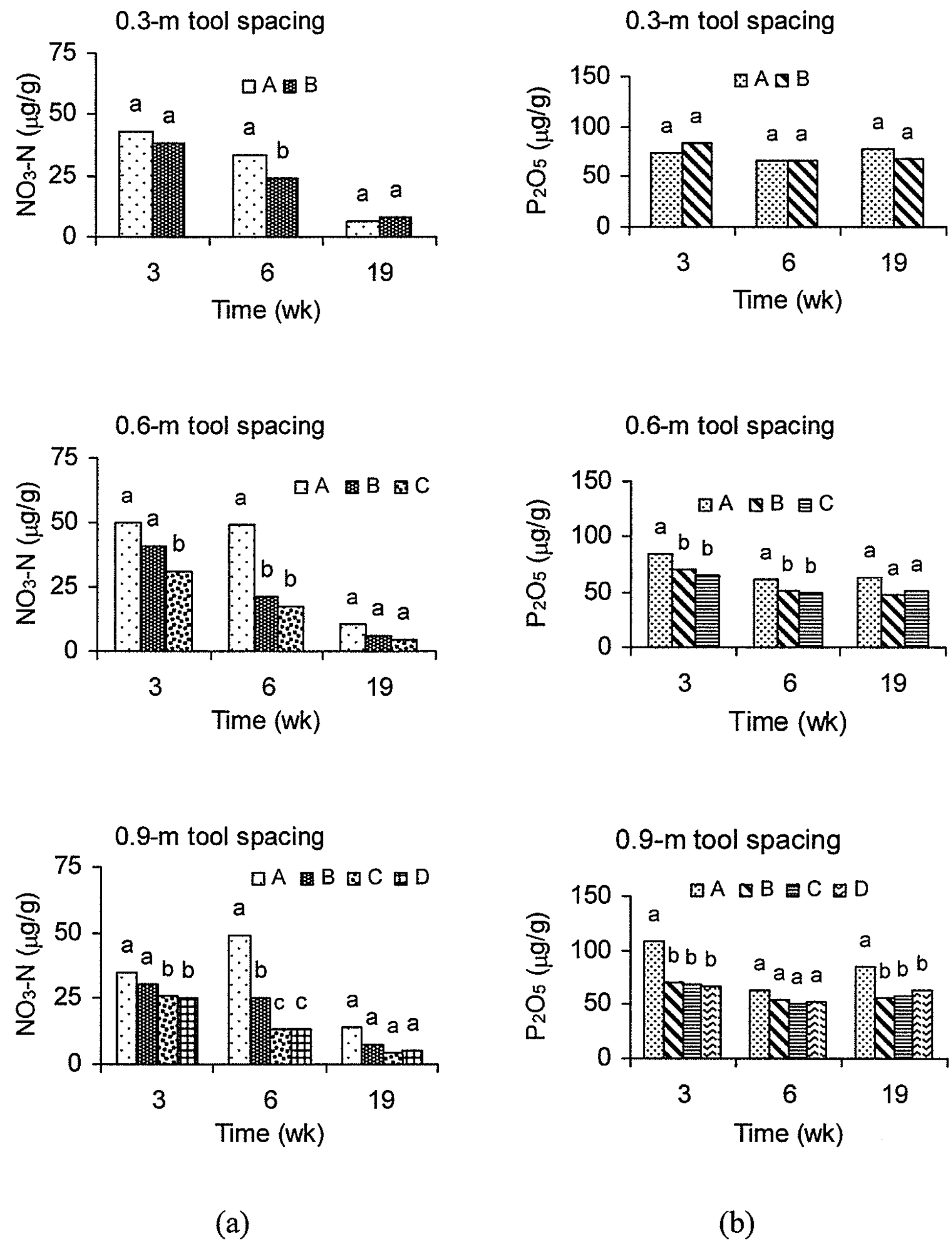

Figure 5.5. Soil nutrient concentrations at different lateral positions weeks after manure injection for different injection tool spacings; Positions A's were located on the centre lines of manure bands; Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively; (a) soil NO_3-N at 0-0.6 m depth (b) soil P_2O_5 at 0-0.3 m depth; each data point represents the average value of the coulter and furrower injection tools and four replicates for each tool; 2004. Mean values for each tool spacing and each week followed by the same letter are not significantly different ($P > 0.1$).

The 2002 data (Fig. 5.6) further confirmed the larger differences in soil NO_3-N between lateral positions earlier in the season and that the differences decreased with time. Most importantly, the 2002 data show that these differences vanished after 9 weeks following manure injection for all tool spacings used. This may have resulted due to lateral movement of nutrients towards the mid position between two manure bands. Movement is expected to be slower for phosphorus, as phosphorus tends to bind to soil and may not disperse easily through the soil. This explains why the differences in soil P concentration between lateral positions had little changes over time (Fig. 5.5).

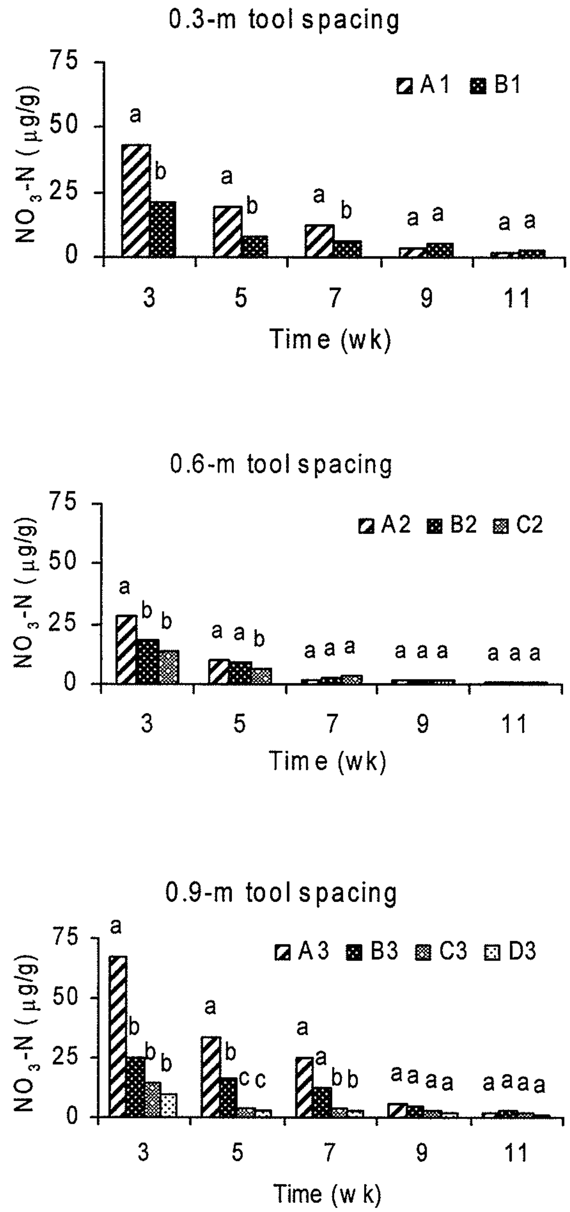

Figure 5.6. Soil NO_3-N concentration at 0-0.3 m depth at different lateral positions weeks after manure injection for different injection tool spacings; Positions A's were located on the centre lines of manure bands; Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively; each data point represents the average value of the coulter and furrower injection tools and four replicates; 2002. Mean values for each tool spacing and each week followed by the same letter are not significantly different (P > 0.1).

5.5 Soil sampling protocol

The aforementioned results showed that soil NO_3-N, NH_4-N, and P are not evenly distributed laterally in soil due to the banding effect following fertilizer application. The traditional randomised soil sampling protocol may result in sampling either more on manure bands or more at some distance away from the manure band, which will lead into uncertainty of the nutrient levels of a given soil.

5.5.1 Sampling procedure for soil nitrate-nitrogen

5.5.1.1 Time for sampling

The data shown in Fig. 5.2 suggests that considerable amount of soil nitrogen was still in the NH_4-N form up to 3 weeks after injection. Thus sampling within the first 3 weeks of application may lead to samples reflecting mainly high levels of NH_4-N. Consequently, levels of NO_3-N were not as elevated as they could be once most of NH_4-N would have been nitrified. It is advisable to schedule field sampling aimed at monitoring NO_3-N to a time when more than 3 weeks have elapsed between manure injection and the sampling.

5.5.1.2 Situations of relatively uniform NO_3-N levels after injection

While few liquid manure injection equipment are configured with a tool spacing of 0.3 m, an injection equipment that is set up in this fashion is expected to provide relatively uniform manure distribution shortly after liquid manure injection. Soil sampling after 9 weeks allows for the manure NH_4-N to be nitrified and for some of the soil NO_3-N to be taken up by plants. Fall sampling from a field injected in the spring ensures that the banding effect has greatly diminished if it has not completely disappeared. Accordingly, the traditional randomized sampling approach can be used where either the tool spacing is of the order of 0.3 m or less, or sampling occurs 9 weeks after manure injection.

5.5.1.3 Sampling protocols for NO_3-N within 3 to 9 weeks from time of injection with a tool spacing larger than 0.3 m

If sampling for soil NO_3-N must be carried out within 9 weeks of manure injection, significant variability in soil NO_3-N between manure bands may be expected. An ideal sampling protocol would be to sample at different lateral positions to account for the banding effect to ensure obtaining representative soil nutrient levels. However, this would be very tedious. The following practical approaches are proposed for different scenarios as discussed below.

Information on injector travel direction and tool spacing can usually be obtained from the producer or the custom applicator. If this is the case, soil sampling should be performed along a transect which is perpendicular to the injector travel direction. Sampling along the direction of maximum variation was also suggested by McBratney et al. (1981). Two sub-samples need to be taken along the transect and the distance between these two samples should be half of the tool spacing. This approach is referred to as *directed paired-sampling* approach. This approach will increase the probability that both the zone enriched with NO_3-N near or in the liquid manure band and the zone into which manure NO_3-N has not moved yet are sampled. As compared with the traditional randomised sampling, the *directed paired-sampling* approach doubles the number of soil samples to be taken, which adds additional cost to soil sampling. If 15 random locations are sampled in a field as commonly done in Manitoba for soil nutrient auditing, the *directed paired-sampling* requires a total of 30 samples, which appears to be practical.

If the injector travel direction and tool spacing are unknown, one has to resort to the traditional randomised sampling method. The nutrient level results from this case may be assessed with considerations of data variations.

5.5.2 Sampling procedure for soil phosphorus

Sampling approaches for phosphorus can be tailored to those proposed for nitrogen. One exception is that sampling for phosphorus analysis needs to consider banding effects at any time of the year.

5.6 Comparison between the traditional randomized sampling and the *directed paired-sampling*

To illustrate the improvement in soil sampling accuracy by proceeding with the *directed paired-sampling* approach, a simulation of field variability was performed by randomly sampling around a liquid manure band for two situations: one sub-sample was taken at each of 15 field locations, and two sub-samples (spaced by one half of the injection tool spacing) were taken at each of the same field locations. The former represents the traditional randomised sampling approach, and the latter represents the *directed paired-sampling* approach. In the simulation, the regression equations fitted to the nutrient data (Figs. 5.2-5.4) were used to predict the nutrient levels at any random position relative to a manure band between two adjacent manure bands. The accuracy of each sampling approach was assessed by the differences between the values predicted using the regression equations and the measured average values that are represented by the horizontal lines in Figs. 5.2-5.4.

This simulation was carried out 20 times, where a random number generator was used to set the sampling location for each of the 15 sampling locations. This is equivalent to carrying out 20 different samplings in the same field. Based on the simulation, at the 3rd or 19th week after injection, the predicted NO_3-N values remain relatively close to the measured averages in most instances, regardless of the sampling method used. In such situations, either the traditional randomised sampling or the *directed paired-sampling* approach would result in NO_3-N measurements in close agreement with the averages measured at any location in the field. However, the simulation results illustrate the advantages of the *directed paired-sampling* for the data taken at the 6th week after injection. This was the stage at which a significant nitrification of NH_4-N would occur but would not allow a significant use of nutrients by the crop.

The simulation results (Fig. 5.7) suggest that the *directed paired-sampling* approach allows for obtaining a more accurate estimate of the average NO_3-N more than half of the time, and maintains the error well below 20% most of the time. The traditional randomised sampling approach may result in obtaining field variability ranging over the 20% of the measured averages. Understandably, the benefits of taking paired samples at each sampling location are greater when the injection tool spacing is greater.

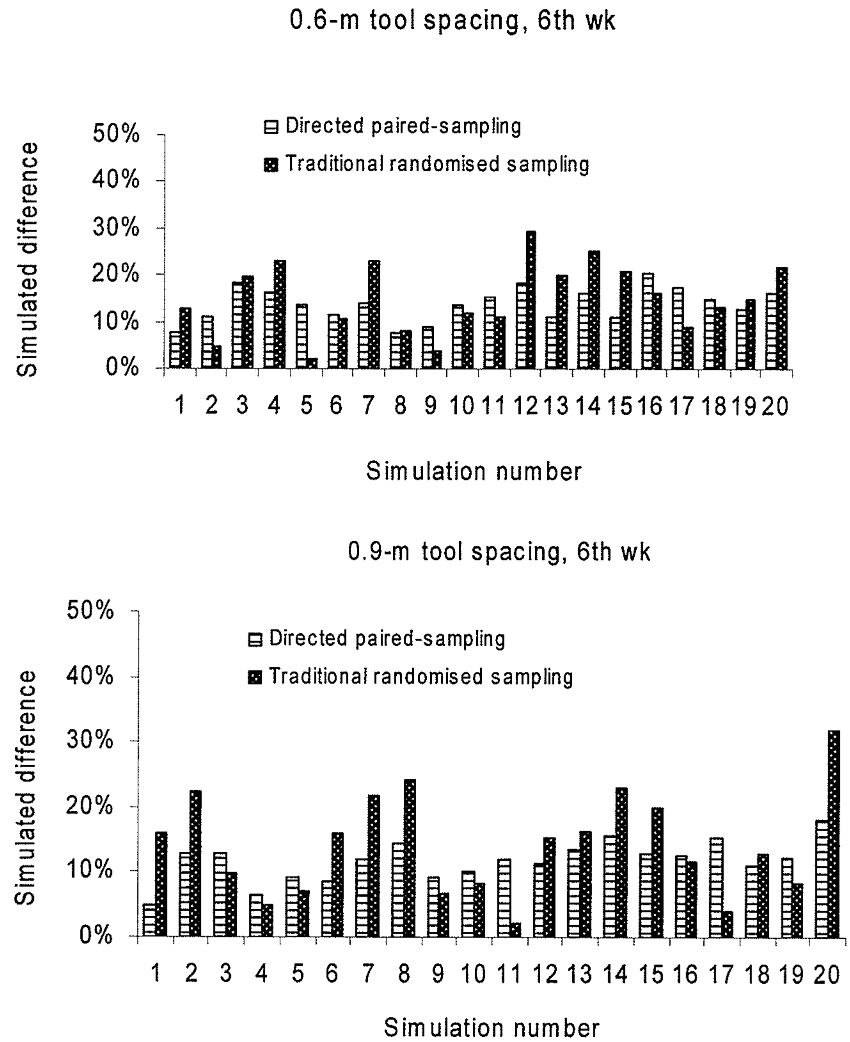

Figure 5.7. Simulated differences in NO_3-N levels (in the top 0.6 m depth of soil and at the 6th week after injection) between the predicted values and the measured averages, for two sampling approaches: traditional randomised sampling and *directed paired-sampling* at each of 15 field locations. The simulation was repeated 20 times.

Similar simulations were also performed for the phosphorus data (results shown on Figure A1 in Appendix A). The predicted values of phosphorus were within 10 to 12 % of the measured averages for injection tool spacings of 0.6- and 0.9-m, respectively.

5.7 Conclusions

Compared to the traditional randomised sampling approach, the *directed paired-sampling* approach enables achieving a more representative estimate of the average soil NO_3-N in a field with manure injected at larger spacing than 0.3 m especially between 3 and 9 weeks after manure injection. The *directed paired-sampling* approach decreases the risk of obtaining field variability ranging beyond 20% of the measured averages. However, additional cost is associated with the *directed paired-sampling* due to the double number of samples to be taken. When the tool spacing of injection equipment is 0.3 m, or if soil sampling can be delayed until 9 weeks or more after manure injection, the traditional randomised sampling approach can be used. Note that the protocol developed took no account of spatial variations in soil properties and the effect of the nutrient use by plant. The conclusions were drawn using the data from a given experimental condition. Care should be taken for applications of the results.

5.8 Acknowledgements

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5.9 References

Anderson, D.L., E.A. Hanlon, O.P. Miller, V.R. Hoge and O.A. Diaz. 1992. Soil sampling and nutrient variability in dairy animal holding areas. *Soil Science* 153(4): 314-321.

Assefa, B., Y. Chen, K. Buckley and W. Akinremi. 2005. Soil nutrient levels and crop performance at varying positions relative to manure bands. CSAE/SCGR Paper No. 05-075. Winnipeg, MB: CSAE.

Assefa, B., Y. Chen, K. Buckley and W. Akinremi. 2006. Effects of manure injection tool type and tool spacing on soil nutrient levels and spring barley performance. *Canadian Biosystems Engineering* 48: 2.45-2.54.

Crépin, J. and R.L. Johnson. 1993. Soil sampling for environment assessment. In *Soil Sampling and Methods of Analysis* ed. M.R. Carter, 5-18. Boca Raton, FL: Lewis Publishers.

De Gruijter, J.J. 2002. Sampling. In *Methods of Soil Analysis. Part 4 - Physical Methods,* eds. J.H. Dane and G.C. Topp, 45-79. Madison, WI: Soil Science Society of America, Inc.

Donohue, S.J. 2002. Evaluation of soil nutrient variability for development of turfgrass soil test sampling methods. *Communications in Soil Science and Plant Analysis* 33(15-18): 3335 -3345.

James, D.W. and R.L. Hurst. 1995. Soil sampling techniques for band-fertilizer, no till fields with Monte Carlo simulations. *Soil Science Society of America Journal* 59(6): 1768-1772.

Mallarino, A.P. 1996. Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales. *Soil Science Society of America Journal* 60(5): 1473-1481.

McBratney, A.B., R. Webster and T.M. Burgess. 1981. The design of sptimal sampling schemes for local estimation and mapping or regionalised variables - I Theory and method. *Computers & Geosciences* 7(4): 331-334.

McCormick, R.A., D.W. Nelson, A.L. Sutton and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformations in soil treated with liquid swine manure. *Agronomy Journal* 75(6): 947-950.

Mohamed, S.B., E.J. Evans and R.S. Shiel. 1996. Mapping techniques and intensity of soil sampling for precision farming. In *Precision Agriculture: Proceedings of the 3rd International Conference*, 217-226. Minneapolis, MN. June 23-26.

Penney, D.C., S.C. Nolan, R.C. McKenzie, T.W. Goddard and V. Kryzanowski. 1996. Yield and nutrient mapping for site specific fertilizer management. *Communications in Soil Science and Plant Analysis* 27(5-8): 1265-1279.

Petersen, R.G. and L.D. Calvin. 1998. Sampling. In *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods.* ed. A. Klute, 33-51. Madison, WI: American Society of Agronomy, Inc., Soil Science Society of America, Inc.

Petersen, S.O., H.H. Nissen, I. Lund and P. Ambus. 2003. Redistribution of slurry components as influenced by injection methods, soil, and slurry properties. *Journal of Environmental Quality* 32(6): 2399-2409.

Rehm, G.W. and J.A. Lamb. 2004. Impact of banded potassium on crop yield and soil potassium in ridge-till planting. *Soil Science Society of America Journal* 68(2): 629-636.

SAS Institute Inc. 2001. SAS proprietary software release 8.2. Cary, NC.

Sawyer, J.E., M.A. Schmitt and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Agronomy Journal* 82(5): 963-969.

Schnug, E., K. Panten and S. Haneklaus. 1998. Sampling and nutrient recommendation – the future. *Communications in Soil Science and Plant Analysis* 29(11-14): 1455-1462.

Thompson, A.N., J.N. Shaw, P.L. Mask, J.T. Touchton and D. Rickman. 2004. Soil sampling techniques for Alabama, USA Grain Fields. *Precision Agriculture*, 5(4): 345-358.

Zebarth, B.J., M.F. Younie, J.W. Paul, J.W. Hall, and G.A. Telford. 1999. Fertilizer banding influence of spatial and temporal distribution of soil inorganic nitrogen in corn field. *Soil Science Society of America Journal* 63(6): 1924-1933.

CHAPTER 6: MODEL DEVELOPMENT FOR SIMULATING THE LATERAL MOVEMENT OF MANURE NO_3-N IN SOILS

6.1 Summary

Understanding manure NO_3-N movement in the soil is essential to determine manure placement for efficient use of the NO_3-N in the manure. A two dimensional model for simulating NO_3-N movement in soils following spring manure injection was developed. The transport domain for modeling NO_3-N movement was a cross sectional area defined by two hypothetical lines mid way between centerlines of two consecutive manure bands in the vertical plane. Hydrus-2D software package was used in the computation of Richards flow and convection-dispersion (CDE) solute transport equations. The model was calibrated and validated with the data obtained from previous field experiments conducted at the Brandon Research Centre, Brandon, Manitoba, Canada in the growing seasons of 2003 and 2004 on clay soils (26.0% sand, 21.4% silt, and 52.6% clay). The data used were collected from the treatment where liquid swine manure was injected at 0.9 m spacing at 3.06 L m^{-1} rate (volume of manure per meter of manure band). Calibration was performed by inversely optimizing soil hydraulic (α and n) and transport parameters (longitudinal dispersivity, D_L, and transversal dispersivity, D_T) simultaneously using the field data collected in 2004. The model was validated against data collected in 2003. Results indicated that the model predicted soil NO_3-N concentrations satisfactorily with few noted underestimations and *overestimations. It was concluded that manure nitrate-nitrogen applied to soil for crop production does not move laterally beyond 0.15 m from manure band, consistent with the experimental data.* ***Keywords:*** *modeling, soil, nitrate-nitrogen, movement, manure, injection, crop.*

6.2 Introduction

Increased manure output from more intensified livestock operations has led to enormous research on manure handling and land application. To date land application of manure has been considered the most economical practice of manure management. Amongst several application methods, injection has been established as the recommended method of application particularly for liquid manures. However, manure is placed in soil as bands in the injection method. Thus, the uniformity of manure nutrient distribution in soil needs to be addressed. The manure nutrient distribution in soil depends on several factors among which the lateral movement of manure nutrients between manure bands following manure injection is important.

Nitrate-nitrogen movement in soil can be described by the phenomenon of solute transport in soil. Studies of solute transport in the soil using numerical models are becoming more common with the availability of well-established governing flow and transport equations as well as software. Numerical modeling of solute transport requires input parameters and specifications of appropriate initial and boundary conditions.

The frequently used governing equations are the Richards's equation for water flow and the equilibrium convection-dispersion equation (CDE) or the mobile-immobile equation (MIM) for solute transport (Abbasi et al. 2004; Jacques et al. 2002; Inoue et al. 2000; Ventrella et al. 2000). Some deviations of model predictions from observations of solute concentrations in field soils have been reported when using the CDE especially in surface soils (Jacques et al. 1998; Snow et al. 1994). In contrast, Abbasi et al. (2003, 2004) reported no differences in results obtained when using CDE and MIM equations.

Model input parameters (soil hydraulic and solute transport parameters) are often difficult to measure at field scale, primarily due to labour and budget constraints (Abbasi et al. 2003). The method of inverse optimisation of those parameters from measured variables during transient field experiments has been considered a promising approach for determining input parameters (Abbasi et al. 2003, 2004; Jacques et al. 2002; Inoue et al. 2000). Inverse optimisation is a method of parameter estimation using initial guesstimated parameter values and repeated simulation leading to the best possible set of parameters to reproduce experimentally obtained data (Simunek et al. 2002; Hopmans et al. 2002; Simunek et al. 1999).

The applicability of a numerical model that is based on the water flow and solute transport equations can be evaluated using combinations of the numerical model, time series measurement of water content, pressure head, and solute concentrations with inverse optimization techniques (Abbasi et al. 2004; Jacques et al. 2002). This can be done by simultaneously or sequentially optimizing soil hydraulic and solute transport parameters under imposed proper initial and boundary conditions (Abbasi et al. 2004; Abbasi et al. 2003; Jacques et al. 2002; Inoue et al. 2000). In the simultaneous approach both soil hydraulic and transport parameters are optimized at the same time. In the sequential approach they are optimized separately in two steps. In the first step hydraulic parameters are optimized. In the second step transport parameters are optimized using the hydraulic parameters optimized in the first step. Simultaneous estimation has been reported to be more beneficial in that it takes advantage of cross-over effects between state variables and parameters (Sun and Yeh 1990) and reduced estimation errors as compared to sequential estimation (Mishra and Parker 1989; Simunek et al. 2002). Finally, comparison of model predicted (using optimized parameters) variables with a separate set of experimentally obtained data other than that used in parameter optimization determines how good the model is.

Hydrus-2D developed by Simunek et al. (1999) is a commonly used model that simulates water and solute movement (such as manure nutrient) in two-dimensional (vertical or horizontal plane) variably saturated porous media (Simunek et al. 1999), such as soil. The code numerically solves the Richards equation and the convection-dispersion equation (CDE) for analyzing water flow and solute transport in saturated-unsaturated media. The program allows for incorporation of sink terms in the flow and transport equations to account for water and nutrient uptakes by plant roots. It also includes the Levenberg-Marquardt (Marquardt 1963) optimization procedure to inversely estimate soil hydraulic and solute transport parameters from measured transient flow and transport data.

Several researchers have used the Hydrus-2D model to simulate water and solute transport in agricultural soils in the vertical and horizontal (lateral) directions. For example, Abbasi et al. (2003, 2004) simulated bromide transport in irrigated bare soils using Hydrus-2D. Coquet et al. (2005) used Hydrus-2D to simulate water flow and Bromide transport in their study that examined the effect of tillage on the dynamics of water and Bromide movement in cultivated soils. Gardenas et al. (2005) used Hydrus-2D to model nitrate leaching under various fertigation scenarios, who also noted existence of limited information on soil nitrate distribution.

Manure nitrate-nitrogen can be considered much like other solutes in terms of moving through the soil medium. However, most work done in the past focused on the vertical movement and there was little literature on simulation of lateral movement of manure nitrate-nitrogen. The objectives of this study were to: (1) develop a model to simulate manure nitrate-nitrogen movement away from the manure band injected in the soil over a growing season, (2) inversely optimize soil hydraulic and transport parameters using a set of data collected from field experiments and Hydrus-2D software package, and (3) validate the model using a separate data set collected from field experiments.

6.3 Model development and assumptions

The model development consisted of determination of the solute transport and flow equations and soil hydraulic functions, definition of the transport domain, and specification of the initial and boundary conditions. Hydrus-2D code was used in both inverse and forward solution of the equations. Soil hydraulic parameters required for solution of the equations were described using van Genuchten (1980) and Mualem (1976) models embedded in Hydrus-2D. With the initial and boundary conditions imposed, the soil hydraulic and transport parameters were estimated simultaneously, using Hydrus-2D.

The following assumptions were used in the model development:

1. Manure nutrients from a manure band do not move beyond a hypothetical line midway between that band and an adjacent manure band.
2. The soil where manure is placed is assumed to be saturated by liquid manure at the instant of manure injection.
3. The cross-section of manure band is rectangular in shape at the time of manure placement.

4. The soil is homogeneous and isotropic; there is no hysteresis effect; the water table lies far below the domain.

5. All of the NH_4-N in the manure would be converted to NO_3-N immediately upon manure application and nitrogen dynamics there after (mineralization/immobilization) is neglected.

Assumption 1 is based on the fact that manure placed in contiguous manure bands moves towards the middle of the bands with a net effect of no movement past midway between the bands. Assumption 2 is based on the fact that manure is delivered to soil at a "point" which is the outlet of the manure delivery tube behind the injection tool. Assumptions 3, 4, and 5 were made for the purpose of simplicity.

6.3.1 Transport equation

Hydrus-2D numerically solves the Fickian-based convection-dispersion equation (CDE) given below for solute transport (Simunek et al. 1999; Gardenas et al. 2005):

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} - NU(c, x_i, t) \qquad \textbf{(6. 1)}$$

where θ is the volumetric water content ($L^3\ L^{-3}$), t is time (T), c is NO_3-N concentration in the liquid phase ($M\ L^{-3}$), x_i *and* $x_j (i, j = 1, 2)$ are spatial coordinates (L), D_{ij} are components of dispersion coefficient tensor ($L^2\ T^{-1}$), q_i is the ith component of the volumetric flux density ($L\ T^{-1}$), and NU is the local NO_3-N uptake by plant roots ($M\ L^{-3}\ T^{-1}$). The volumetric flux density (q) to be employed in the above equation determines the nature of transport of dissolved nitrate-nitrogen with flowing water. Thus use of flow equation is required to calculate the volumetric flux density.

6.3.2 Flow equation

The governing flow equation for two-dimensional isothermal flow of water in the unsaturated soil zone is given by the mixed form of Richard's equation (Simunek et al. 1999; Celia et al. 1990).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{ij}^{A}\right)\right] - S \qquad \textbf{(6. 2)}$$

where K is the unsaturated hydraulic conductivity function (L T^{-1}), K_{ij}^{A} are components of a dimensionless anisotropy tensor K^{A}, h is the pressure head (L), and S is a sink term (T^{-1}). The hydraulic conductivity function in two dimensions is in turn given by:

$$K(h,x,z) = K_s(x,z)K_r(h,x,z) \qquad \textbf{(6. 3)}$$

where K_r is the relative hydraulic conductivity and K_s is the saturated hydraulic conductivity (L T^{-1}) and x and z are lateral and vertical coordinates (L), respectively. The sink term has been defined by Feddes et al. (1978) as follows:

$$S(h) = a(h)S_{\max} \qquad \textbf{(6. 4)}$$

where $a(h)$ is a prescribed dimensionless function of the soil pressure head ranging between 0 and 1, and $S_{\max}$ is the potential water uptake rate (T^{-1}).

6.3.3 Soil hydraulic parameters

The closed-form of van Genuchten's (1980) water retention function and Mualem's (1976) conductivity model were employed in Hydrus-2D to calculate moisture content and hydraulic conductivity. The van Genuchten water retention equation is given by:

$$\theta = \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \tag{6. 5}$$

where θ_r is the residual volumetric water content (L^3 L^{-3}), θ_s is the saturated volumetric water content (L^3 L^{-3}), α and n are the retention curve-fitting parameters and $m = 1 - 1/n$.

Mualem's hydraulic conductivity function is given by:

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{6. 6}$$

where $K(h)$ is the unsaturated hydraulic conductivity (L T^{-1}), K_s is the saturated hydraulic conductivity (L T^{-1}), m and l are empirical parameters, and S_e is a dimensionless relative saturation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6. 7}$$

6.3.4 Computational domain

Injection of liquid manure created manure bands such as that shown in Fig 6.1a. The distance between the centres of adjacent manure bands is equal to the injection tool spacing. The domain for investigating lateral movement of manure NO_3-N in the soil is defined based on Fig. 6.1a. It is the cross sectional area encompassed by two hypothetical lines (Fig. 6.1b). Each of the hypothetical lines lies mid way between centerlines of two consecutive manure bands in the vertical plane. This arrangement results in having a manure band situated midway between the hypothetical lines. The size of the domain is defined by the distance between two successive manure bands and the depth of interest for soil nutrient movement.

6.3.5 Domain discretisation and manure placement in the domain

The domain is discretized into a uniform grid mesh (Fig. 6.2) using the mesh generation feature of Hydrus-2D. The shaded area (A) within the domain represents the cross-section of the manure band placed at the time of injection. The cross-sectional area of the manure band may vary with the manure application rate and injection tool spacing (Rahman et al. 2004). The vertical location of manure band within the domain mainly depends on the injection depth. It would be rational to consider that the manure band is surrounding a point centered about the injection depth.

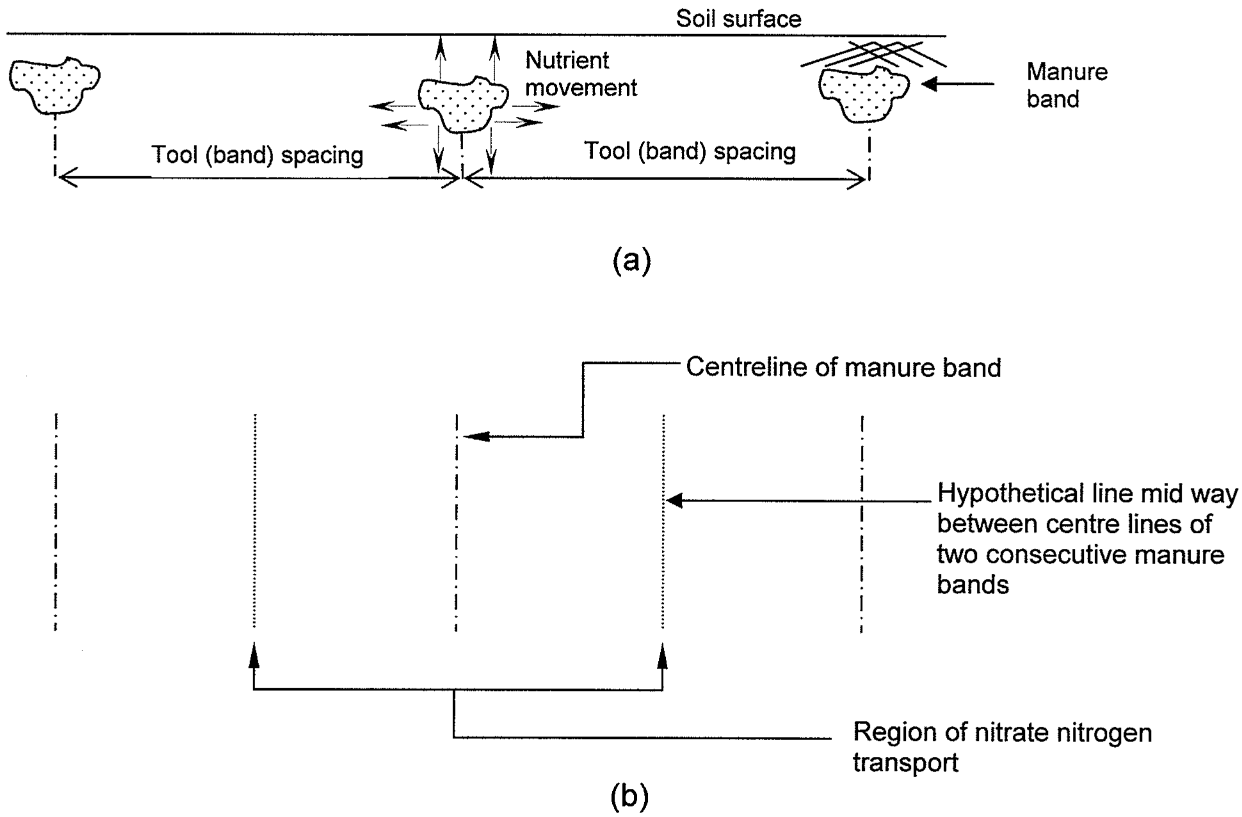


Figure 6.1. A schematic diagram showing (a) the cross-section of manure band and hypothesized direction of manure nutrient movement and (b) definition of transport region (top view).

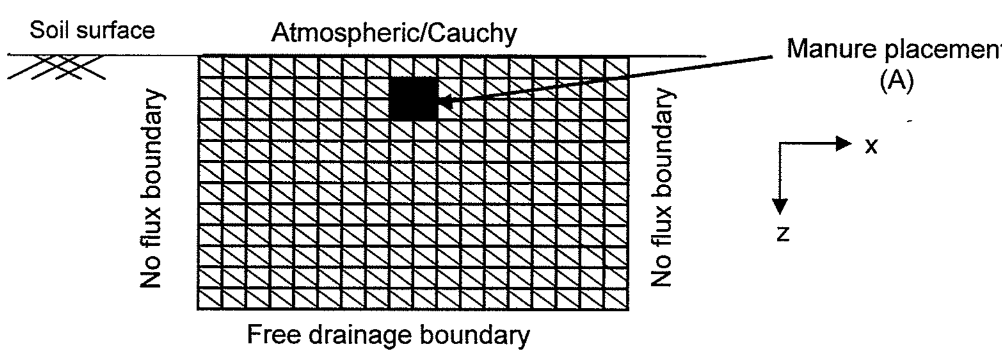


Figure 6.2. Cross sectional view of the discretised computational domain in the vertical plane with imposed boundary conditions.

6.3.6 Initial and boundary conditions

According to the aforementioned assumption 2, the initial water content of the soil within the area A in Fig. 6.2 is the saturated water content of the soil. The initial NO_3-N concentration within the area A includes the nutrient concentration from both manure and soil. According to the aforementioned assumption 5, the sum total of NO_3-N and NH_4-N in the manure plus soil NO_3-N background level is taken as the initial NO_3-N concentration in the area A.

Boundary conditions specified for the domain are shown in Fig. 6.2. At the upper boundary, atmospheric and Cauchy conditions are used for solving water flow and solute transport equations, respectively. The atmospheric boundary condition is specified as (Simunek et al. 1999):

$$\left| K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j}+K_{iz}^{A}\right)n_i \right| \le E \qquad \textbf{(6. 8)}$$

$$h_A \le h \le h_s \qquad \textbf{(6. 9)}$$

where E is the maximum potential rate of infiltration or evaporation under the current atmospheric conditions and h_A and h_s are minimum and maximum pressure heads allowed under the prevailing soil conditions. While h_s is usually set equal to zero, h_A is determined from the equilibrium conditions between soil water and atmospheric water vapour, with -100 m being the default value in Hydrus-2D. At the bottom, free drainage boundary condition is applied to both water flow and solute movement. No flux boundary condition is imposed on the sidewalls of the transport region for both flow and solute transport.

6.3.7 Model inputs

The model inputs include those related to transport equation, flow equation, transport domain, and weather condition. Inputs related to the transport equation are initial soil NO_3-N concentration, c_i (M L^{-3}); longitudinal dispersivity, D_L (L); and transverse dispersivity, D_T (L). For the flow equation the inputs are initial soil water content, θ_i (L^3 L^{-3}); saturated water content, θ_s (L^3 L^{-3}); residual water content, θ_r (L^3 L^{-3}); saturated hydraulic conductivity, K_s (L T^{-1}); empirical constants α (L^{-1}) and n (dimensionless). The inputs, c_i and θ_i, can be easily measured. The other inputs are more difficult to measure. However, they can be obtained through calibration using the measured values of c_i and θ_i, as described in the following sections. Weather related inputs for the model include precipitation (L) and evapotranspiration (L T^{-1}). Other inputs are dimensions of the manure placement (L), dimensions of the domain (L), which are given for a specific application.

6.4 Data source for model calibration and validation

The data used for model calibration and validation were obtained from the field experiments carried out at the Brandon Research Centre, Brandon, Manitoba, Canada in the growing seasons of 2003 and 2004 on clay soils (26.0% sand, 21.4% silt, and 52.6% clay). Liquid swine manure was injected using an injector system, which included a tool bar arrangement that allowed the use of two different types of injection tools and three different injection tool spacings. The injection depth was 0.1 m. The field plots were seeded to spring barley following manure injection.

The data used included the background levels of soil NO_3-N and soil water content (Table 6.1) taken prior to manure injection, and soil nitrate-nitrogen concentrations taken three times during each growing season. The data of soil NO_3-N concentrations used in this study were averaged over the two types of tools at the largest (0.9 m) spacing. This spacing was chosen due to the fact that larger spacing between manure bands would have less risk of crossing effects between bands. Also, more data points were available for this spacing. Collection of soil samples during the growing season was done at 0, 0.15, 0.30, and 0.45 m distance from manure band and two depth ranges (0-0.3 and 0.3-0.6 m). The manure application rate for this spacing was equivalent to a micro-rate of 3.06 L m^{-1} (volume of manure per meter of manure band). More detailed description of the experiment including methods of nutrient analysis is found in chapters 3 and 4.

Table 6.1. Summary of initial soil water content (θ_i) and NO_3-N concentrations (c_i) used.

Growing season	Water content (θ_i, m^3 m^{-3})		NO_3-N concentration (c_i, μg g^{-1})		
	In the entire domain	In manure band	At 0-0.3 m soil depth	At 0.3-0.6 m soil depth	In manure band
2003	0.27	0.47	0.14	0.11	0.50
2004	0.29	0.47	0.14	0.11	0.61

Precipitation data during the growing seasons were obtained from the Brandon Research Centre. Crop evapotranspiration was estimated using FAO Penman-Monteith method (Richard et al. 1998) and the meteorological data obtained from the Brandon Research Centre weather station located within 1 km of the site. The estimated crop evapotranspiration (1.7 mm d^{-1}) and daily precipitation data (Fig. 6.3) obtained from the weather station were used as the atmospheric boundary conditions.

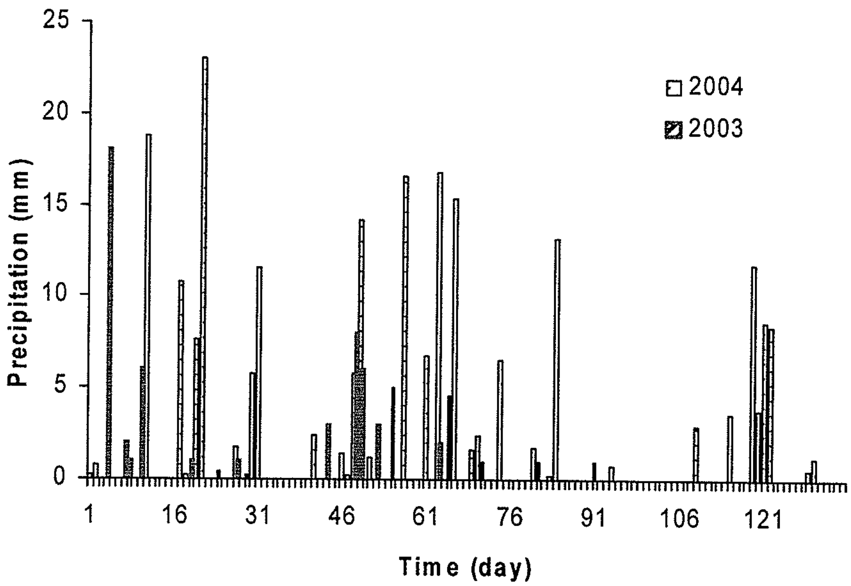


Figure 6.3. Precipitation data used in 2003 and 2004.

6.5 Model calibration

6.5.1 Calibration theory

The Rosetta code (Schaap et al. 2001) embedded in Hydrus-2D was used to estimate (θ_r, θ_s, and K_s) from soil texture. The remaining two hydraulic parameters (α and n) and the transport parameters (D_L and D_T) were inversely estimated by numerically solving the flow and transport equations with the Levenberg-Marquardt optimization procedure (Marquardt 1963). The procedure involves minimizing an objective function. According to Simunek (1999) the objective function to be minimized is defined as:

$$\Phi(q,b)=\sum_{j=1}^{m} v_j \sum_{i=1}^{n^*} w_{ij}\left[q_j(x,z,t_i)-q_j(x,z,t_i,b)\right]^2 \qquad \textbf{(6. 10)}$$

where n^* is number of observations for the j^{th} measurement set (i.e. water content and NO_3-N concentration), $q(x,z,t_i)$ are specific measurements at time t_i, location x, and depth z,

$q\left(x, z, t_i, b\right)$ are corresponding model predictions for the vector of optimized parameters b (i.e. α, n, D_L, and D_T), v_j and w_{ij} are weights associated with a particular measurement set or point, respectively.

6.5.2 Calibration procedure

The model was calibrated with the aforementioned data that was obtained in 2004. The width of the domain was equal to the tool spacing: 0.9 m wide, and the depth of the domain was 0.6 m which was the depth range of the data. Using the mesh generation feature of Hydrus-2D, the domain was discretized to a uniform 0.05 m grid mesh resulting in 432 triangular elements and 247 nodes (Fig. 6.2). The Galerkin finite element space weighting scheme was used to generate the mesh while the Crank-Nicholson time weighting scheme was used for time discretization (Simunek et al. 1999). The cross-section of manure band was approximated to an area of 0.1 x 0.1 m, which was two times of the diameter (0.05 m) of the manure delivery tube, considering the possibility of manure redistribution after being placed in the soil. The cross-section of the manure band was centered at the injection depth, which was 0.1 m.

Soil water contents and NO_3-N concentrations (Table 6.1) determined on soil samples collected from the site prior to manure application were used as the initial conditions throughout the rest of the domain. Precipitation data for the model input were those shown in Fig. 6.3. The data were the soil NO_3-N concentrations measured at varying positions (0.0, 0.15, 0.30, and 0.45 m) from the centerline of the selected manure band at different times over the growing season.

Optimization was performed both sequentially and simultaneously. The sequential optimization involved estimation of soil hydraulic parameters first and then, using those optimized hydraulic parameters, to estimate solute transport parameters. The soil hydraulic parameters were predicted using neural network predictions of the Rosetta code. Using the Rosetta predicted values as initial estimates, the hydraulic parameters were inversely optimized repeatedly by eliminating one parameter (i.e. keeping it constant at the value predicted by Rosetta) at a time and estimating the rest. In the simultaneous approach the soil hydraulic and transport parameters were optimized simultaneously. The simultaneous approach yielded better results and hence only results obtained by this method were discussed.

In the calibration process, the model was run several times using different initial estimates of parameters to match the measured versus model outputs of soil NO_3-N concentrations. Three of the hydraulic properties (θ_r, θ_s, and K_s) were kept constant at their Rosetta predicted values. The parameter l in Eq. 6.6 was assumed to be 0.5 (Mualem 1976). Two hydraulic (α and n) and two transport (D_L and D_T) parameters were inversely optimized from measured soil water contents and NO_3-N concentrations.

6.5.3 Model calibration results

Of all the results from the various runs, the best match is presented in curves in Fig. 6.4. The curves provide visual comparisons between the measured and the model outputs. The model outputs of the soil NO_3-N concentration matched the measurements very well except in one location (on the centreline of the manure band at 0.3-0.6 m depth) out of eight locations. It was determined that the inverse optimisation was satisfactory. Thus, the corresponding model inputs were taken as the optimal model parameters. Those parameters are summarised in Table 6.2. The optimized value of α (0.23) was similar to that estimated with Rosetta (Schaap et al. 2001) and the optimized value of parameter n (2.00) was the same as that assumed by van Genuchten (1980). Optimized longitudinal (D_L = 132.5 mm) and transversal (D_T = 0.1 mm) dispersivities in this study were different from those assumed by Gardenas et al. (2005) and Coquet et al. (2005) but within the range of values reported by Abbasi et al. (2004).

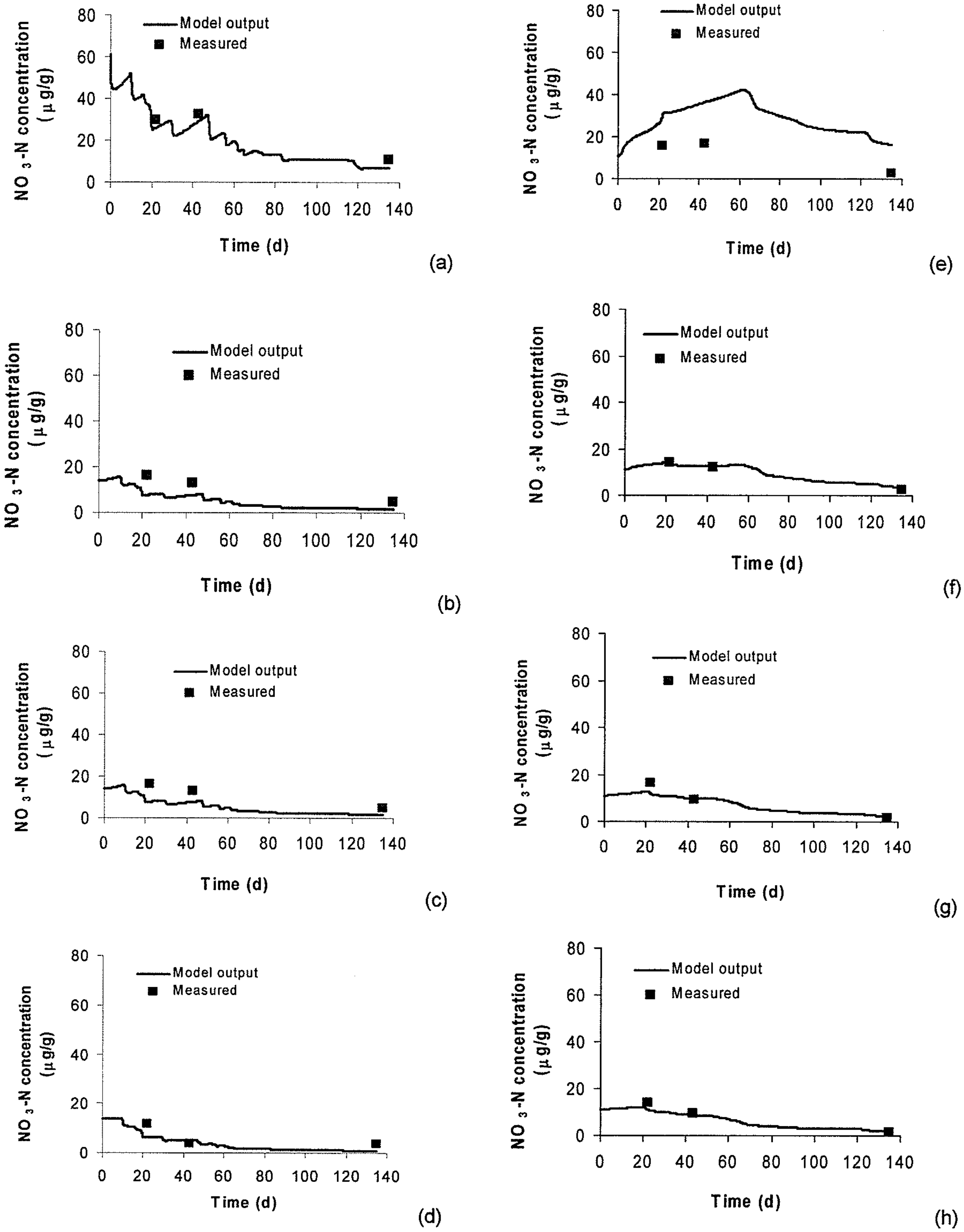


Figure 6.4. Model calibration results - measured (in 2004) versus model output values of soil NO_3-N; at 0-0.3 m depth for the lateral positions: (a) 0.0 m, (b) 0.15 m, (c) 0.30 m, (d) 0.45 m from the manure band; at 0.3-0.6 m depth for the lateral positions: (e) 0.0, (f) 0.15, (g) 0.30, and (h) 0.45 m from the manure band.

Table 6.2. Summary of the optimized soil hydraulic and transport parameters within the transport domain.

Hydraulic properties					Transport parameters	
θ_r ($m^3\ m^{-3}$)	θ_s ($m^3\ m^{-3}$)	K_s (mm d^{-1})	α (mm^{-1})	n	D_L (mm)	D_T (mm)
0.09	0.47	160.7	0.023	2.0	132.5	0.1

6.6 Model validation

To validate the model, the model was run using the optimised soil hydraulic and transport parameters (Table 6.2), initial soil water content and initial soil NO_3-N concentrations (Table 6.1). Precipitation data were given in Fig. 6.3 and evapotranspiration was calculated as described in Section 6.4 above. Model predictions of NO_3-N concentrations were discussed below in relation to trends over time and lateral distribution.

6.6.1 NO_3-N concentration over time

Measured versus predicted soil NO_3-N at various positions and depths over the 2003 growing season are given in Fig. 6.5. Overall the model simulation produced satisfactory results. Underestimations were noted at 0.0 and 0.15 m distance from the manure band at 0-0.3 m depth (Fig 6.5a, b) and overestimation occurred at 0.0 m from the manure band in the deeper soil (Fig 6.5e). Fig 6.5a and Fig. 6.5b shows that the measured soil NO_3-N increased towards the end of the season (August 19) which is contrary to what was expected. There was almost no precipitation between day 10 and day 40 thus the NO_3-N might have moved upwards due to moisture gradient. Compared to 0-0.3 m depth, at 0.3-0.6 m depth, the model did better job of estimating the soil NO_3-N at most positions. The disagreement between measured and predicted results may be explained by the highly variable nature of soil properties and soil nutrient concentrations.

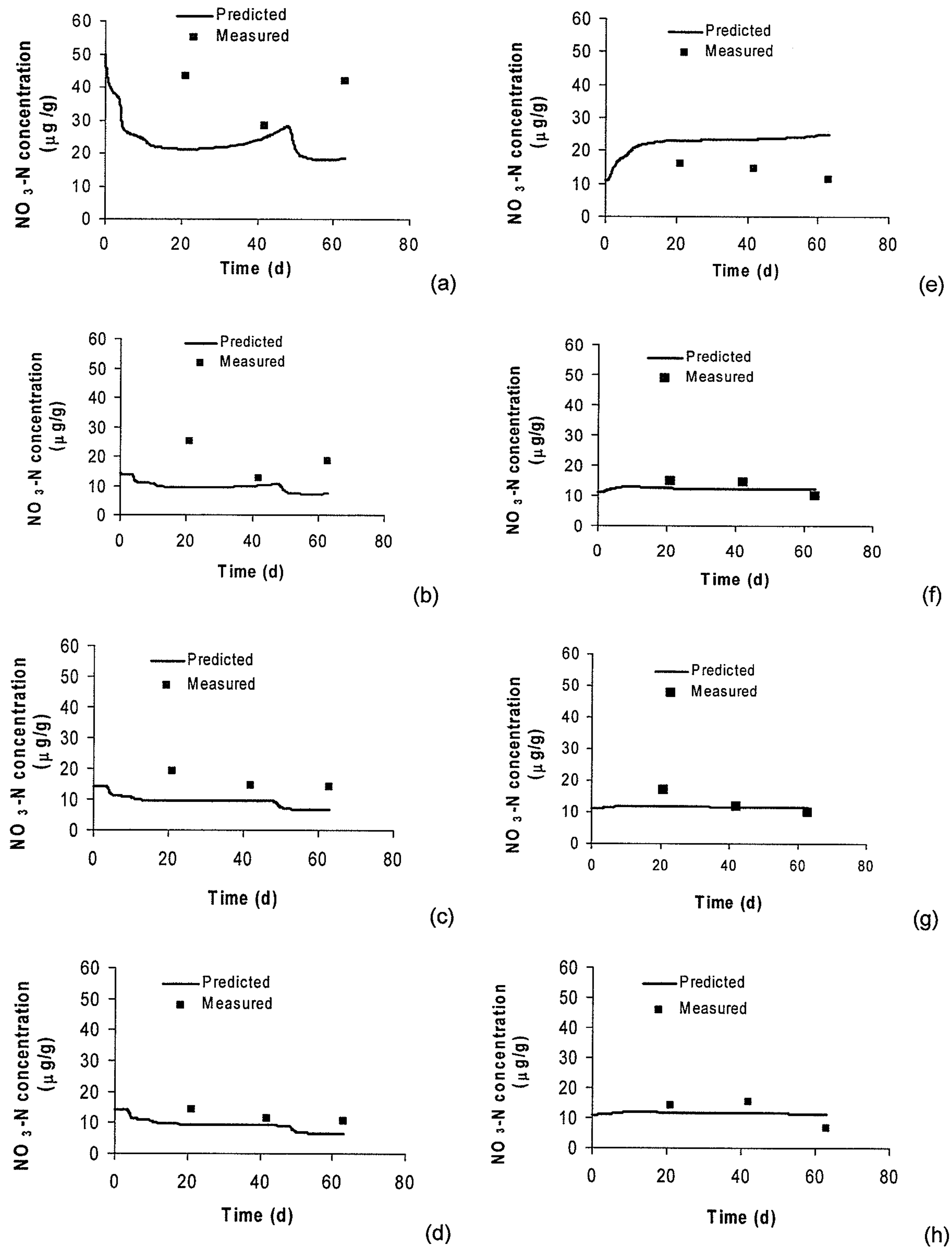


Figure 6.5. Model validations - measured (in 2003) versus predicted soil NO_3-N over time; at 0-0.3 m depth for the lateral positions: (a) 0.0 m, (b) 0.15 m, (c) 0.30 m, (d) 0.45 m from the manure band; at 0.3-0.6 m depth for the lateral positions: (e) 0.0 m, (f) 0.15 m, (g) 0.30 m, and (h) 0.45 m from the manure band.

6.7.2 Lateral distribution of NO_3-N in the soil

The model predicted lateral distribution of soil NO_3-N relative to the centerline of the manure injection path are shown in Fig. 6.6 a,b. The results confirmed that the further the position from the centreline of manure injection path the less is the NO_3-N concentration as implied in Fig 6.5. At both depth ranges the lateral distribution of the soil NO_3-N was limited to 0.15 m distance from the centre of the manure injection path. Soil NO_3-N decreased while going from day 1 to day 63 after manure injection at 0-0.3 m depth all along the horizontal distance. Contrary to this, at 0.3-0.6 m depth, soil NO_3-N increased while going from day 1 to day 21 within 0.15 m distance from the manure band. There were no changes between positions beyond 0.15 m away from the manure bands. This limited lateral distribution of soil nitrate-nitrogen after manure application implies that application of manure in smaller volumes at narrower spacings is advantageous over wider spacings, in terms of nitrate-nitrogen availability. This is in agreement with the better plant performance reported in Chapter 3 when liquid manure was injected at 0.3 m spacing than at 0.9 m spacing.

The findings in this study are consistent with Abbasi et al. (2004) who reported mixed results (i.e. underestimation and overestimation of Bromide concentrations). They attributed the discrepancies to insufficient data used in their optimization procedure of transport parameters estimation. Point measurements yielding poor representation of solute transport at the field scale (Tsang et al. 1996) can also contribute to disagreements between measured and predicted values. For example Ritsema and Dekker (1996) have reported underestimation of chemical fluxes attributed to point measurements. According to Xiang et al. (1992) considerable uncertainties exist with point measurements caused by human, instrumental, and hydrological errors.

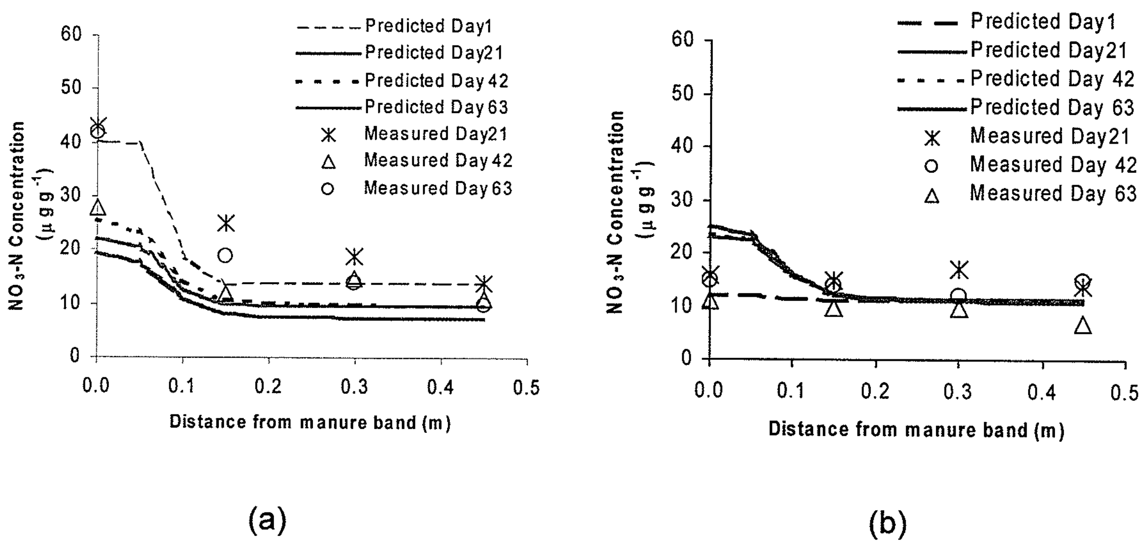


Figure 6.6. Model predicted and measured lateral distribution of NO_3-N concentration relative to centreline of manure band: (a) at 0-0.3 m soil depth; (b) at 0.3-0.6 m soil depth.

6.7 Conclusions

A two-dimensional model for simulating lateral movement of manure nitrate-nitrogen following land application of liquid swine manure was developed. The model parameters were inversely optimized (calibrated). Upon calibration a very good match was obtained between measured and model output values of soil NO_3-N. Subsequent to the calibration the model was validated successfully.

The model reproduced the soil nitrate-nitrogen concentrations fairly well. Thus the model enables estimation of the movement of nitrate-nitrogen within the soil following land application of liquid manure. The occurrences of some underestimations and overestimations may be indicative the importance of soils' spatial variability and nitrogen dynamics. Based on the results of the model prediction, it can be generalized that manure nitrate-nitrogen applied to soil for crop production does not move laterally beyond 0.15 m from manure band.

This evidence further supports the finding that swine liquid manure injection is best done at 0.3 m injection tool spacing. Considering nitrogen dynamics and including accurate measurements of some of the soils hydraulic properties such as hydraulic conductivity and saturated water content at the field scale may further improve the model performance.

6.9 References

Abbasi, F., J. Feyen and M.Th. van Genuchten. 2004. Two-dimensional simulation of water flow and solute transport below furrows: model calibration and validation. *Journal of Hydrology* 290(1-2): 63-79.

Abbasi, F., J. Simunek, J. Feyen, M.Th. van Genuchten and P.J. Shouse. 2003. Simultaneous inverse estimation of soil hydraulic and solute transport parameters from transient field experiments: homogeneous soil. *Transactions of the ASAE* 46(4): 1085-1095.

Assefa, B.A., Y. Chen, K. Buckley and W. Akinremi. 2006. Effects of manure injection type and tool spacing on soil nutrient levels and spring barley performance *Canadian Biosystems Engineering* 48: 2.45-2.54.

Celia, M.A., E.T. Bouloutas and R.L. Zarba. 1990. A general mass-conservative numerical solution of the unsaturated flow equation. *Water Resources Research* 26(7): 1483-1496.

Coquet, Y., J. Simunek, C. Coutadeur, M.Th. van Genutchten, V. Pot and J. Roger-Estrade. 2005. Water and solute transport in cultivated silt loam soil: 2. Numerical analysis. *Vadose Zone Journal* 4(3): 587-601.

Feddes, R.A., P.J. Kowalik and H. Zaradny. 1978. Simulation of field water use and crop yield. Simulation monographs. Wageningen, The Netherlands. In Simunek, J., M. Sejna, and M.Th. van Genuchten. 1999. The Hydrus2D software package for simulating two-dimensional movement of water, heat and multiple solutes in variably saturated media, version 2.0. IGWMC-TPS-53. International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Gardenas, A.I., J.W. Hopmans, B.R. Hanson and J. Simunek. 2005. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water Management* 74(3): 219-242.

Hopmans, J.W., J. Simunek, N. Romano and W. Durner. 2002. Inverse Methods. In *Methods of Soil Analysis: Part 4. Physical Methods* eds. J.H. Dane and G.C. Topp, 963-1008, Madison, WI: Soil Science Society of America.

Inoue, M., J. Simunek, S. Shiozawa and J.W. Hopmans. 2000. Simultaneous estimation of soil hydraulic and solute transport parameters from transient infiltration experiments. *Advances in Water Resource* 23(7): 677-688.

Jacques, D., J. Simunek, A. Timmerman and J. Feyen. 2002. Calibration of Richards' and convection-dispersion equations to field-scale water flow and solute transport under rainfall conditions. *Journal of Hydrology* 259(1-4): 15-31.

Jacques, D., J.D. Kim, J. Diels, J. Vandeborght, H. Vereecken and J. Feyen. 1998. Analysis of steady-state chloride transport through two homogeneous field soils. *Water Resources Research* 34(10): 2539-2550.

Marquardt, D.W. 1963. An algorithm for least squares estimation of non-linear parameters. *Journal of Industrial Applied Mathematics* 11(2): 431-441.

Mishra, S. and J.C. Parker. 1989. Parameter estimation for coupled unsaturated flow and transport. *Water Resources Research* 25(3): 385-396.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resource Research* 12(3): 513-522.

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

Richard, G.A., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper 56. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Ritsema, C.J. and L.W. Dekker. 1996. Influence of sampling strategy on detecting preferential flow paths in water-repellent sand. *Journal of Hydrology* 177(1-2): 33-45.

Schaap, M.G., F.J. Leij and M.Th. van Genuchten. 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology* 251(1-4): 163-176.

Simunek , J., D. Jacques, J.W. Hopmans, M. Inoue, M. Flury and M.Th. van Genuchten. 2002. Solute transport during variably-saturated flow - inverse methods. In *Methods of Soil Analysis: Part 1. Physical Methods* eds. J.H. Dane and G.C. Topp, 1435-1449, Madison, WI: Soil Science Society of America.

Simunek, J., M. Sejna and M.Th. van Genuchten. 1999. The Hydrus2D software package for simulating two-dimensional movement of water, heat and multiple solutes in variably saturated media, version 2.0. IGWMC-TPS-53. International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Snow, V.O., B.E. Clothier, D.R. Scotter and R.E. White. 1994. Solute transport in a layered soil: experiments and modeling using convection-dispersion approach. *Journal of Contaminant Hydrology* 16(4): 339-358.

Sun, N.Z. and W.W.G. Yeh. 1990. Coupled inverse problems in groundwater modeling: 1. Sensitivity analysis and parameter identification. *Water Resource Research* 26(10): 2507-2525.

Tsang, Y.W., C.F. Tsang, F.V. Hale and B. Dverstop. 1996. Tracer transport in a stochastic continuum model of fractured media. *Water Resources Research* 32(10): 3077-3092.

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of American Journal* 44: 892-898.

Ventrella, D., B. P. Mohanty, J. Simunek, N. Losavio and M.Th. van Genuchten. 2000. Water and chloride transport in a fine-textured soil: field experiments and modeling. *Soil Science* 165(8): 624-631.

Xiang, Y., F. Sykes and N.R. Thomson. 1992. A composite L_1 parameter estimator for model fitting in groundwater flow and solute transport simulation. *Water Resources Research* 29(6): 1661-1673.

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A furrower-type injection tool was found advantageous over a coulter-type in that some incidences of elevated soil nitrate, biomass production, and total N and P concentration in plant material were observed. The 0.3-m injection tool spacing resulted in the best plant development, and highest plant biomass production as compared to the 0.6- and 0.9-m tool spacings. Based upon the above, the furrower-type tool spaced 0.3-m apart was suggested as the best choice for liquid manure injection in spring barley production.

Availability of soil nutrients (NO_3-N, NH_4-N, and P_2O_5) was highest at centre lines of manure bands and decreased with lateral distance from the manure bands, with the differences in the nutrient availability being more pronounced at the highest rate. Large tool spacing such as 0.9 m may need to be avoided in order to obtain relatively uniform soil nutrient distribution and plant development, regardless of tool type to be used.

A *directed paired-sampling* approach allows obtaining a more representative estimate of the average soil NO_3-N than the traditional randomized sampling approach when manure is injected at larger spacing than 0.3 m. The *directed paired-sampling* approach decreases the risk of obtaining field variability ranging beyond 20% of the measured averages. When the tool spacing of injection equipment is 0.3 m, or if soil sampling can be delayed until 9 weeks or more after manure injection, the traditional randomized sampling approach can be used.

The model developed in this study predicted the soil nitrate concentrations satisfactorily. Model predictions showed that manure nitrate applied to soil for crop production does not move laterally beyond 0.15 m from the manure band. This evidence further supports the finding that swine liquid manure injection is best done at the 0.3 m spacing.

7.2 Recommendations

Similar experiments need to be carried out on different soil types and under varying climatic conditions to confirm the observed trends since this experiment was carried out on one type of soil under less than optimum growing conditions. Spatial variations (particularly lateral) of soil nutrient levels should be considered when sampling for soil nutrient analysis following manure injection. Considering nitrogen dynamics and including accurate measurements of some of the hydraulic properties, such as hydraulic conductivity and saturated water content at the field scale, may further improve the model performance. Findings of this study should be used cautiously.

APPENDIX A

Table A1. Extractable soil P_2O_5 (µg/g) at varying lateral positions at two soil depths, 2003.

Table A2. Extractable soil P_2O_5 (µg/g) concentration at varying positions relative to manure band, 2002.

Figure A1. Simulated differences in soil P_2O_5 levels.

Table A1. Extractable soil P_2O_5 (μg/g) at varying lateral positions at two soil depths, 2003.

Rate (L m^{-1})	Position*	3 wk after injection		6 wk after injection		19 wk after injection	
		0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)	0-0.3 (m)	0.3-0.6 (m)
Coulter							
r_1=1.02	A_1	38.6a	10.9b	28.7a	11.6a	37.2a	11.4a
	B_1	46.1a	13.1a	31.0a	11.4a	41.7a	16.4a
r_2=2.04	A_2	43.3a	13.9a	34.5a	11.4a	39.9a	10.7a
	B_2	40.2a	16.6a	29.7a	15.6a	38.7a	23.5a
	C_2	33.9a	15.6a	30.5a	19.0a	36.1a	21.1a
r_3=3.06	A_3	39.6a	14.2a	37.1a	14.4a	62.3a	15.2a
	B_3	36.2a	15.1a	33.7a	13.2a	38.4c	19.5a
	C_3	35.3a	16.1a	36.1a	14.2a	42.6b	20.0a
	D_3	33.4a	14.8a	31.0a	18.6a	38.1c	15.7a
Furrower							
r_1=1.02	A_1	43.5a	21.4a	30.3a	12.7a	40.1a	13.9a
	B_1	30.2a	16.7a	31.7a	13.6a	37.2a	16.4a
r_2=2.04	A_2	48.0a	23.0a	41.1a	12.2a	44.1a	13.1a
	B_2	42.6a	13.6a	35.7a	17.4a	34.8a	12.9a
	C_2	32.0a	12.7a	35.7a	15.7a	37.2a	16.1a
r_3=3.06	A_3	47.8a	17.1a	50.8a	15.6a	43.2a	14.1ab
	B_3	38.1b	14.3b	36.6b	17.6a	39.6a	14.1ab
	C_3	37.5b	16.3ab	30.8bc	14.2a	42.4a	14.7a
	D_3	39.5b	16.2ab	29.7c	14.6a	36.4a	12.2b

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

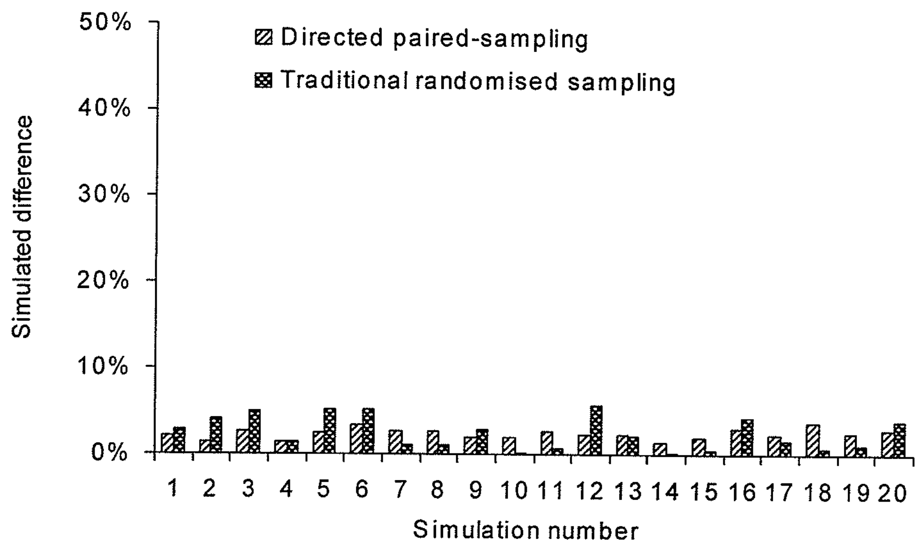
Table A2. Extractable soil P_2O_5 (μg/g) concentration at varying positions relative to manure band, 2002.

Rate (L m^{-1})	Position*	Weeks after injection				
		3	5	7	9	11
Coulter						
r_1=1.02	A_1	96.4a*	72.7a	80.1a	86.0a	90.9a
	B_1	95.7a	78.8a	81.3a	91.0a	87.5a
r_2=2.04	A_2	110.8a	86.8a	93.1a	65.5a	73.3b
	B_2	104.5a	85.2a	70.6a	64.2a	73.3b
	C_2	100.6a	91.0a	173.8a	85.6a	81.8a
r_3=3.06	A_3	110.2a	88.6ab	227.3a	87.3a	83.5ab
	B_3	98.9a	89.2ab	221.6a	89.5a	77.3b
	C_3	98.3a	97.7a	227.8a	86.5a	86.4a
	D_3	97.8a	85.8b	221.6a	91.8a	86.4a
Furrower						
r_1=1.02	A_1	103.2a	93.8a	174.9a	65.4a	84.7a
	B_1	108.0b	92.6a	177.8a	81.4a	89.8a
r_2=2.04	A_2	93.2b	82.4a	77.7a	74.4a	85.2a
	B_2	102.8a	86.8a	73.0a	76.7a	85.2a
	C_2	98.3ab	90.5a	83.9a	73.5a	89.2a
r_3=3.06	A_3	115.8a	96.4a	231.5a	110.0a	96.0ab
	B_3	116.5a	83.8a	107.4a	75.7a	90.9b
	C_3	111.5a	102.5a	101.4a	108.2a	102.3a
	D_3	111.3a	88.1a	57.8a	97.8a	100.6a

* A, B, C, and D refer to positions at the center of manure band, 0.15, 0.30, 0.45 m away from the center of manure band, respectively. Position subscripts 1, 2, and 3 refer to the respective positions within micro-rates r_1, r_2, and r_3.

** Values, within a column under the same rate and tool type, followed by the same letter are not significantly different.

0.6 m tool spacing, 6th wk



0.9 m tool spacing, 6th wk

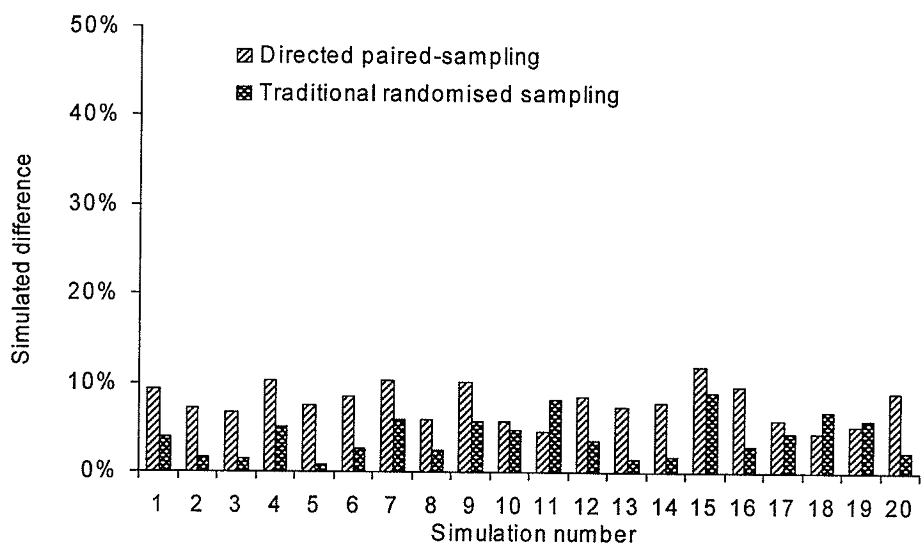


Figure A1. Simulated differences in soil P_2O_5 levels (in the top 0.3 m depth of soil and at the 6th week after injection) between the predicted values and the measured averages, for two sampling approaches: traditional randomised sampling and *directed paired-sampling* at each of 15 field locations. The simulation was repeated 20 times.

APPENDIX 1

Permission obtained to include published manuscripts in this thesis

Date: Tue, 28 Aug 2007 23:50:33 -0500 [08/28/07 11:50:33 PM CDT]
From: ranjan@cc.umanitoba.ca
To: umassefa@cc.umanitoba.ca
Subject: Re: Permission to have published manuscripts included in my thesis
Headers: Show All Headers

Hello Bereket,
Permission is granted to incorporate the papers into your thesis. Please indicate where the original paper is published in your thesis giving credit to the CBE Journal.
Thanks
Ranjan

At Tue, 28 Aug 2007 23:19:26 -0500, umassefa wrote:

Hi Dr. Ranjan,

I would like to include two manuscripts published in the Canadaian Biosystems Engineering Journal in my thesis as attachements in the appendix in their published formats with proper acknowledgements. The titles and citations of the manuscripts are as follows:

Effects of manure injection tool type and tool spacing on soil nutrient levels and spring barley performance
Assefa, B., *Chen, Y., Buckley, K. and Akinremi, W. 2006. Canadian Biosystems Engineering 48: 2.45 - 2.54. *Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada. Email: ying chen@umanitoba.ca

A protocol for soil nutrient sampling after liquid manure injection
Assefa, B. and *Chen, Y . 2007. Canadian Biosystems Engineering 49: 2.7 - 2.13.
*Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada. Email: ying chen@umanitoba.ca

These manuscripts are integral parts of my Ph.D study hence I respectfully request you to please give me permission to include them attached in the appendix of the thesis as published.

Thank you

Bereket

APPENDIX 2

Chapter 3 in its published format

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

B. Assefa[1], Y. Chen[1*], K. Buckley[2] and W. Akinremi[3]

[1]*Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada;* [2]*Brandon Research Center, Agriculture & Agri-Food Canada, Brandon, Manitoba R7A 5Y3, Canada; and* [3]*Department of Soil Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada. *Email: ying_chen@umanitoba.ca*

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_2O_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_2O_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

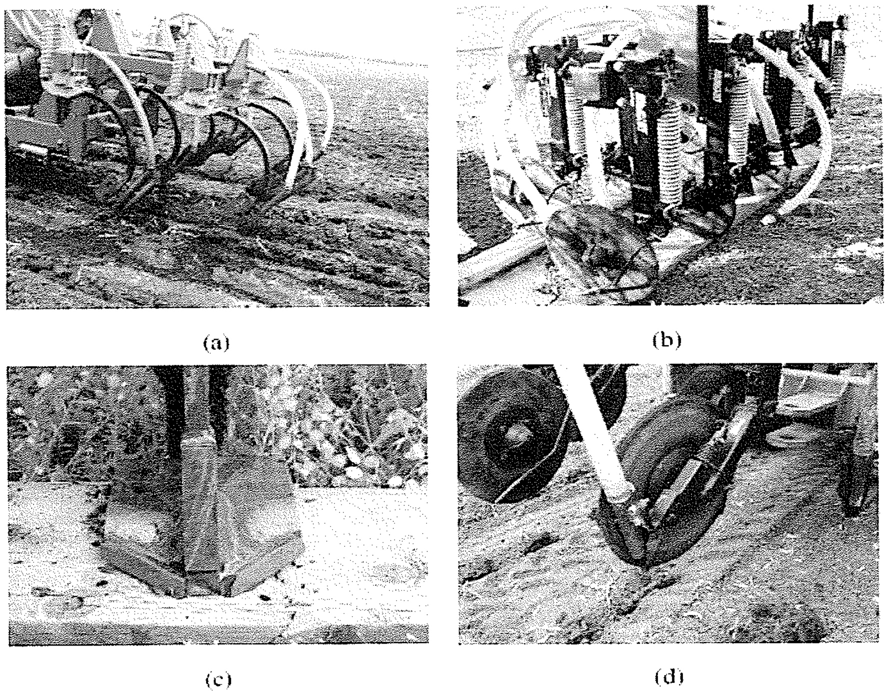


Fig. 1. Injection implement: (a) toolbar fitted with furrowers, (b) toolbar fitted with coulters, (c) close up of the furrower, (d) close up of the coulter.

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

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.

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 105°C. 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 105°C. 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 60°C 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 60°C 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/m³)	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).

REFERENCES

Alberta Research Council. 1996. Methods manual for chemical analysis of water and wastes. Method 19103 565, Potassium, dissolved, automated photometry method. Edmonton, AB: Alberta Research Council.

AOAC. 1990. *Official Methods of Analysis of AOAC*, 15th edition. Arlington, VA: Association of Official Analytical Chemists International.

ASAE. 2004a. ASAE S358.2 Moisture measurement-Forages. In *ASAE Standards 2004*, 584. St. Joseph, MI: ASABE.

ASAE. 2004b. ASAE S414.1 FEB04. Terminology and definitions for agricultural tillage implements. In *ASAE Standards 2004*, 274-285. St. Joseph, MI: ASABE.

Ashworth, J. and Mrazek K. 1995. "Modified Kelowna" test for available phosphorus and potassium in soil. *Communications in Soil Science and Plant Analysis* 26(5&6): 731-739.

Chen, Y. and R. Samson. 2002. Integration of liquid manure into conservation tillage corn systems. *Transactions of the ASAE* 45(3): 629-638.

Chen, Y. and S. Tessier. 2001. Criterion for design and selection of injection tools to minimize liquid manure on the soil surface. *Transactions of the ASAE* 44(6): 1421-1428.

Clesceri, L.S., A.E. Greenbert, A.D. Eaton and M.A.H. Franson. 1998. *Standard Methods for the Examination of Water and Wastewater*, 20th edition. Washington, DC. American Public Health Association.

Comfort, S.D., K.A. Kelling, D.R. Keeney and J.C. Converse. 1988. The fate of nitrogen from injected liquid manure in a silt loam soil. *Journal of Environmental Quality*. 17: 317-322.

Eghball, B. and D.H. Sander. 1989. Band spacing effects of dual-placed nitrogen and phosphorus fertilizers on corn. *Agronomy Journal* 81(2): 178-184.

Fitzmaurice, J., E.S. Jacques, A. Waddell and R. Eilers. 1999. Soils of the Brandon Research Centre – updated from Hopkins and St. Jacques, 1985. Special Report Series 99-2. Brandon, MB: Land Resource Unit, Brandon Research Centre, Agriculture and Agri-Food Canada.

Greenbeg, A.E., L.S. Clesceri and A.D. Eaton. 1992. *Standard Methods for Examination of Water and Wastewater*, 18th edition. Washington, DC: American Public Health Association.

Grevers, M. and J. Schoenau. 2001. Swine manure - a dilute fertilizer with extra's. In *Proceedings of the 2001 Soils & Crops Workshop*, 452-456. Saskatoon, SK: University of Saskatchewan.

Hamm, J.W., F.G. Radford and E.H. Halstead. 1970. The simultaneous determination of nitrogen, phosphorus and potassium in sodium bicarbonate extracts of soils. In *Advances in Automatic Analysis, Vol. 2: Industrial Analysis Technicon International Congress*, 65-69. Orlando, FL: Futura Publishing.

Hendershot, W.H., H. Lalande and M. Duquette. 1993. Soil reaction and exchangeable acidity. In *Soil Sampling and Methods of Soil Analysis*, ed. M.R. Carter, 141-144. Boca Raton, FL: CRC Press.

Hoff, J.D., D.W. Nelson and A.L. Sutton. 1981. Ammonia volatilization from liquid swine manure applied to cropland. *Journal of Environmental Quality* 10(1): 90-95.

Maxwell, T.M., D.E. Kissel, M.G. Wagger, D.A. Whitney, M.L. Cabrera and H.C. Moser. 1984. Optimum spacing of preplant bands of N and P fertilizer for winter wheat. *Agronomy Journal* 76(2): 243-247.

Maynard, D.G. and Y.P. Kalra. 1993. Nitrate and exchangeable ammonium nitrogen. In *Soil Sampling and Methods of Soil Analysis*, ed. M.R. Carter, 25-38 Boca Raton, FL: CRC Press.

McCormick, R.A., D.W. Nelson, A.L. Sutton and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformation in soil treated with liquid swine manure. *Agronomy Journal* 75(6): 947-950.

McKeague, J.A. 1976. Soluble salts. Manual on soil sampling and methods of analysis. Subcommittee of Canada Soil Survey Committee. Ottawa, ON: Agriculture and Agri-Food Canada.

Mooleki, S.P., J.J. Schoenau, G. Hultgreen, G. Wen and J.L. Charles. 2002. Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. *Canadian Journal of Soil Science* 82(4): 457-467.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. In *Methods of soil analysis Part 2*, ed. A.L. Page, 403-430. Madison, WI: American Society of Agronomy and Soil Science Society of America.

Qian, P., J.J. Schoenau and R.E. Karamanos. 1994. Simultaneous extraction of available phosphorus and potassium with a new soil test: A modification of the Kelowna extraction. *Communications in Soil Science and Plant Analysis* 25(5&6): 627-635.

Racz, G.J. and M.M. Fitzgerald. 2001. Nutrient and heavy metal contents of hog manure – effects on soil quality and productivity. In *Livestock Options for the Future: A National Conference on Livestock & the Environment*, http://www.gov.mb.ca/agriculture/livestock/livestockopt/papers/racz.pdf (2006/11/03).

Rahman, S., Y. Chen, K. Buckley and W. Akinremi. 2004. Slurry distribution in soil as influenced by slurry application micro-rate and injection tool type. *Biosystems Engineering* 89(4): 495-504.

SAS Institute Inc. 2001. SAS STAT7 User's Guide, Version 8.2. Cary, NC: SAS Institute, Inc.

Sawyer, J.E., M.A. Schmitt and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Agronomy Journal* 82(5): 963-969.

Sawyer, J.E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens and D.H. Vanderholm. 1991. Corn production associated with liquid beef manure application methods. *Journal of Production Agriculture* 4(3): 335-344.

Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8(2): 186-189.

Sutton, A.L. 1994. Proper animal manure utilization. *Journal of Soil and Water Conservation* 49(2): 65-70.

Thomas, R.L., R.W. Sheard and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agronomy Journal* 59: 240-243.

Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39(4): 287-300.

APPENDIX 3

Chapter 5 in its published format

TECHNICAL NOTE

A protocol for soil nutrient sampling after liquid manure injection

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Assefa, B. and Chen, Y. 2007. **A protocol for soil nutrient sampling after liquid manure injection.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 2.7 - 2.13. A soil sampling protocol that enables accounting for banding effects of manure injection was developed based on soil nutrient data from field trials of liquid manure injection at three tool spacings: 0.3, 0.6, and 0.9 m. The data were taken at several lateral positions (0, 0.15, 0.30, and 0.45 m) relative to the centre lines of the manure bands. Levels of soil NO_3-N, NH_4-N, and P were considered in the development of the sampling protocol. The data showed that soil NO_3-N, NH_4-N, and P concentrations were lower at the position farthest away from the centre of the manure band. A *directed paired-sampling* approach, i.e. sampling at two positions along a transect perpendicular to the injector travel direction was developed to address the position effect on soil nutrient concentrations. This approach allows for obtaining a more accurate estimate of the average NO_3-N and P concentrations in soil when compared to the traditional random sampling method provided that information on injector travel direction and tool spacing is available. **Keywords**: sampling, protocol, manure, injection, position, tool spacing, soil, nutrient.

Un protocole d'échantillonnage des sols qui prend en compte les effets de l'injection en bandes du lisier a été développé en considérant les contenus en éléments fertilisants dans le sol provenant d'essais d'injection de lisier pour trois écartements d'injecteurs: 0,3, 0,6 et 0,9 m. Les données étaient prises à différentes positions latérales (0, 0,15, 0,30 et 0,45 m) par rapport au centre des bandes de lisier. Les niveaux de NO_3-N du sol, de NH_4-N et de P étaient considérés dans le développement du protocole d'échantillonnage. Les données montraient que les concentrations en NO_3-N, NH_4-N et P étaient plus faibles à une position plus éloignée du centre de la bande de lisier. Une approche d'échantillonnage en paire dirigée, soit un échantillonnage à deux positions le long d'une ligne transversale perpendiculaire à la direction d'injection a été développé pour tenir compte de l'effet de la position sur les concentrations en éléments fertilisants du sol. Cette approche permet d'obtenir une estimation plus précise des concentrations moyennes de NO_3-N et de P dans le sol lorsque comparées à la méthode d'échantillonnage aléatoire traditionnelle, en autant que les informations sur la direction d'injection et la distance entre les injecteurs sont disponibles. **Mots clés**: échantillonnage, protocole, lisier, injection, position, espacement des injecteurs, sol, éléments fertilisants.

INTRODUCTION

Soil sampling is carried out to obtain relevant information about a given soil based on fundamental objectives such as chemical analysis, soil survey, soil fertility status, and environmental concerns (Crépin and Johnson 1993). According to De Gruijter (2002) the decision on how many, where, how, and when samples are to be collected often depends on the purpose of a given study, the budget, and logistical constraints.

Soil sampling techniques may be broadly categorized as judgmental, random, or systematic (Petersen and Calvin 1998) with none of them being universal. Judgmental sampling is a technique in which samples are collected from the most typical sites or locations (based on a researcher's judgement) representing a population. Those locations within a field can be repeatedly sampled year to year (referred as to benchmark soil sampling). Random sampling is a technique in which a given number of samples are obtained from a population, each with an equal chance of being selected. Systematic sampling technique is a method in which samples are collected at regular distances from each other in one or two dimensions. One example of two dimensional systematic sampling is grid sampling (precision sampling). According to Mohamed et al. (1996) and Thompson et al. (2004), grid soil sampling enables assessment of field-scale soil nutrient variability. However, they reported that such sampling is costly. Grid sampling may take the form of rectangular or triangular grids (McBratney et al. 1981; Petersen and Calvin 1998). Grid size depends on the desired precision and the spatial variability of the soil (McBratney et al. 1981).

Results of soil nutrient analysis depend on the soil sampling (Donohue 2002; Anderson et al. 1992). This is because soils are characterized by high degree of spatial variability in their nutrient status (Penney et al. 1996; Mallarino 1996). Donohue (2002) emphasized the importance of getting a good soil sample by indicating how small the sample size is relative to the mass of the soil in the sampled area. Mallarino (1996) related high lateral variability to soil types and management practices such as tillage and fertilizer or manure application. Schnug et al. (1998) pointed out that even uniform addition of inputs in crop production results in over and under supply of resources. McBratney et al. (1981) described a method for designing optimal sampling schemes for the purpose of earth's surface survey. This method was based on the assumption that spatial dependence is expressed quantitatively in a certain form.

Soil sampling for nutrient analysis is required by researchers and extension specialists for developing practices of manure

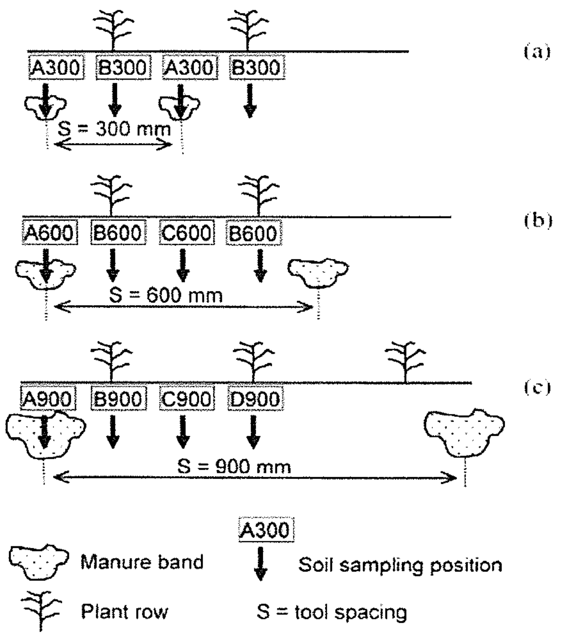

Fig. 1. A schematic diagram of soil cross-section showing manure bands, soil sampling positions, and plant rows for: (a) 0.3-m tool spacing, (b) 0.6-m tool spacing, and (c) 0.9-m tool spacing (after Assefa et al. 2005).

management and crop production. Government environmental officers also need to take soil samples when they do soil nutrient auditing following manure application. The traditional randomised soil sampling is the most common method. Soil sampling following liquid manure injection can be problematic in terms of spatial variability of soil nutrients. Liquid manure is injected into soil as bands and the centre-to-centre distance of two adjacent bands is determined by the injection tool spacing. Higher nutrient concentrations were observed at the centre of manure bands than at lateral distances away from the manure bands. Petersen et al. (2003) measured about 55 mg/kg of soil Br^- concentration (dry basis) in the centre of a pig slurry injection band as compared to about 21 mg/kg of soil Br^- at a further distance from the band. Sawyer et al. (1990) reported 60 to 80 mg/kg inorganic N on an injected beef manure band and less than10 mg/kg inorganic N at a lateral distance of 1.27 m from the band. McCormick et al. (1983) measured 491 and 87 mg/kg inorganic N concentrations at 25 and 90 mm distances, respectively, from the centre of injected swine manure bands. Similar observations were reported when inorganic fertilizers were band applied (Rehm and Lamb 2004; Zebarth et al. 1999; James and Hurst 1995).

There is limited information in the scientific literature with respect to practical soil sampling protocol such as proper sampling locations and time of sampling to address manure injection and banding of nutrients. The main goal of this study was to develop a soil sampling protocol to account for the banding effect from manure injection. This goal was achieved using existing soil nutrient data taken at different lateral positions relative to manure bands injected with different injection tool spacings. The specific objectives were to (1) examine patterns of soil nutrient variations with the lateral position and over the time after manure injection, and (2) to propose a practical soil sampling protocol with regard to where and when to take soil samples for nutrient analysis.

METHODOLOGY

The soil sampling protocol was developed based on soil nutrient data gathered through a previous field study (Assefa et al. 2005, 2006) conducted on clay loam soil in 2002, 2003, and 2004 in Manitoba. In this previous study, liquid swine manure was injected using a manure injector equipped with coulter (460-mm in diameter) and furrower (120-mm width) injection tools at three different tool spacings: 0.3, 0.6, and 0.9 m. After the manure injection, soil nutrient data (NO_3-N, NH_4-N, and P) were taken from different lateral positions: A1 and B1 for the 0.3-m tool spacing, A2, B2, and C2 for the 0.6-m tool spacing, and A3, B3, C3, and D3 for the 0.9-m tool spacing (Fig. 1). Position A's were located on the centre lines of manure bands. Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively.

The commonly used sampling depth is 0 - 0.6 m for soil nitrogen analysis and shallower for soil phosphorus analysis in Manitoba. Therefore, data from a depth of 0 - 0.6 m were used for NO_3-N and NH_4-N analysis, and those from a depth of 0 - 0.3 were used for P analysis. The data used in this paper were mainly from 2004 as the year 2003 was characterised by extremely dry weather and the 2002 data were taken only at 0 - 0.3 m depth. The background soil NO_3-N (0 - 0.6 m) and P (0 - 0.3 m) levels in 2004 were 115 kg/ha and 31 kg/ha, respectively, prior to the manure injection. The nutrient contents in the manure translate into application rates of approximately 119 kg/ha of nitrogen and 18 kg/ha of P. Data from the two injection tool types were pooled together for the analysis because effects of the coulter and furrower were not significantly different in most cases (Assefa et al. 2005). Another reason for this data pooling was for simplicity. Analysis of variance was carried out using the general linear model (GLM) procedure using SAS software (SAS 2001). Considering the inherently high variability in soils, all comparisons were made at a probability of 0.1 ($P < 0.1$).

RESULTS and DISCUSSION

In the development of the sampling protocol, the spatial variations of soil properties (McBratney et al. 1981) and the effect of plant rows on nutrient use were not taken into consideration. As shown in Fig. 1, the plant rows were equally spaced 0.3 m apart for all tool-spacing treatments, while the manure bands were not. Positions B and D always had a plant row on them, while Positions A and C did not. Thus, it was expected that nutrient uptake by the plants at those positions was different, which may have contributed to the differences in nutrient concentrations between positions. This confounding effect of plant rows on spatial distribution of N was not considered in the following discussion on the spatial distributions of soil nutrients. The only spatially-dependent variable accounted for was the position effect.

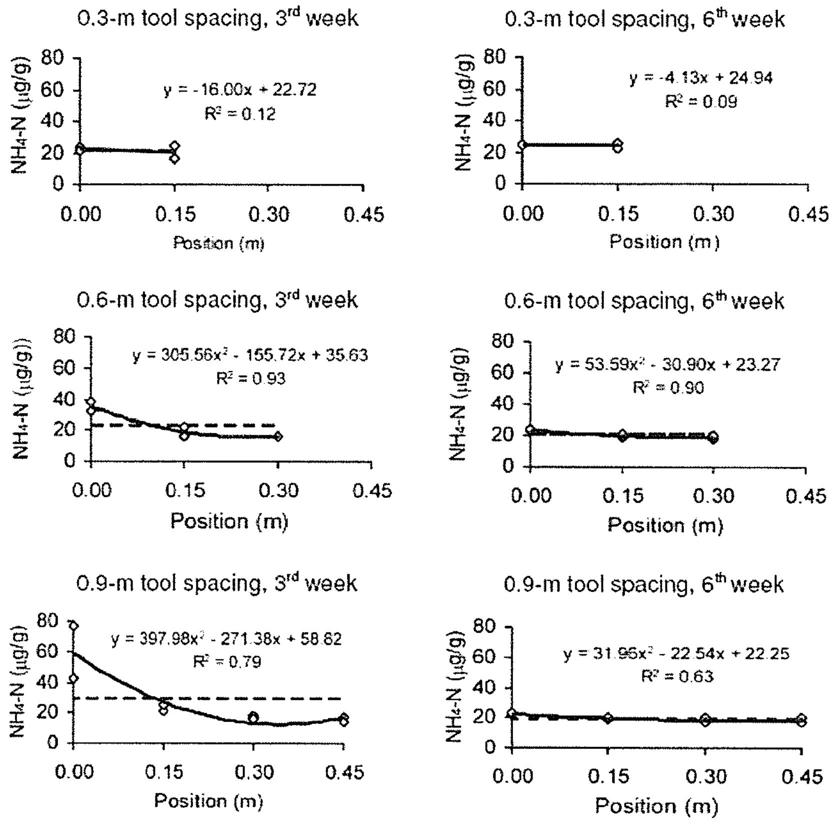

Fig. 2. Soil NH_4-N concentrations at 0-0.6 m depth at different lateral positions relative to the centre of a manure band in 2004. The two data points at each lateral position represent the average values for the coulter and furrower injection tools. Each data point is the average of four replicates. The average value over all positions is shown by a horizontal dashed line.

Soil nutrient concentrations at different lateral positions

Position-nutrient curves are plotted in Figs. 2 - 4 using the 2004 data taken at the third, sixth, and nineteenth week after manure injection. Although the data were highly variable, a clearly decreasing trend in soil NH_4-N, NO_3-N, and P concentrations with farther position from the centre line of the manure band was observed, as discussed in Assefa et al. (2005). For the 0.3-m tool spacing, the curves can be represented by straight lines, as there are only two positions, A1 and B1 (Fig. 1). For the 0.6-m or 0.9-m tool spacing, the position-nutrient curves can be expressed by polynomials of second degree. As expected, position effects were more pronounced for the 0.9-m tool spacing than those for the smaller tool spacings, and more pronounced for the NO_3-N concentrations than for the P concentrations.

Forms of soil nitrogen over time

The decreasing trend in NH_4-N concentration was less pronounced at the sixth week after injection than at the third week after manure injection (Fig. 2) perhaps due to the nitrification that levelled off the NH_4-N in the soil over time. The nitrification increased the NO_3-N concentration on the manure band (Fig. 3), which made the decreasing trend in NO_3-N become more pronounced at the sixth week. At the nineteenth week (after harvest), the decreasing trend of NO_3-N diminished due to crop use.

Variations in nutrient concentration over time

The general trend was that concentrations of soil NO_3-N (Figs. 5a) and P (Fig. 5b) decreased over time, although the data were highly variable. This was attributable to the nutrient use of the plants. Denitrification and movement to the deeper soil layer could also be the reason for the decrease in NO_3-N. The trends in soil P between positions remained fairly constant over time, while significant differences in soil NO_3-N between positions were observed at the earlier weeks (at the third and sixth week). No data were taken for the following 13 weeks during which crop maturity and harvest were achieved. The position effect on the soil NO_3-N was not found at the nineteenth week. Therefore, it is unknown when the position effect vanished.

The 2002 data (Fig. 6) further confirmed the larger differences in soil NO_3-N between lateral positions earlier in the season and that the differences decreased with time. Most importantly, the 2002 data show that these differences vanished after nine weeks after manure injection for all tool spacings used. This phenomenon was possibly caused by the gradient in nutrient concentration between two successive manure bands, which resulted in lateral movement of nutrients towards the middle of those manure bands. Nutrient movement is expected to be slower for phosphorus, as phosphorus tends to bind to soil and may not disperse easily through the soil. This explains why the differences in soil P concentration between lateral positions had little changes over time (Fig. 5).

SOIL SAMPLING PROTOCOL

The aforementioned results showed that soil NO_3-N, NH_4-N, and P are not evenly distributed laterally in soil due to the banding effect following fertilizer application. The traditional randomised soil sampling protocol may result in sampling either more on manure bands or more at some distance away from the manure band, which will lead into uncertainty of the nutrient levels of a given soil.

Sampling procedure for soil nitrate-nitrogen

Time for sampling The data shown in Fig. 2 suggest that considerable amount of soil nitrogen was still in NH_4-N form up to three weeks after injection. Thus sampling within the first three weeks of application may lead to samples reflecting mainly high levels of NH_4-N. Consequently, levels of NO_3-N were not as elevated as they could be once most of the NH_4-N would have been nitrified. It is advisable to schedule field

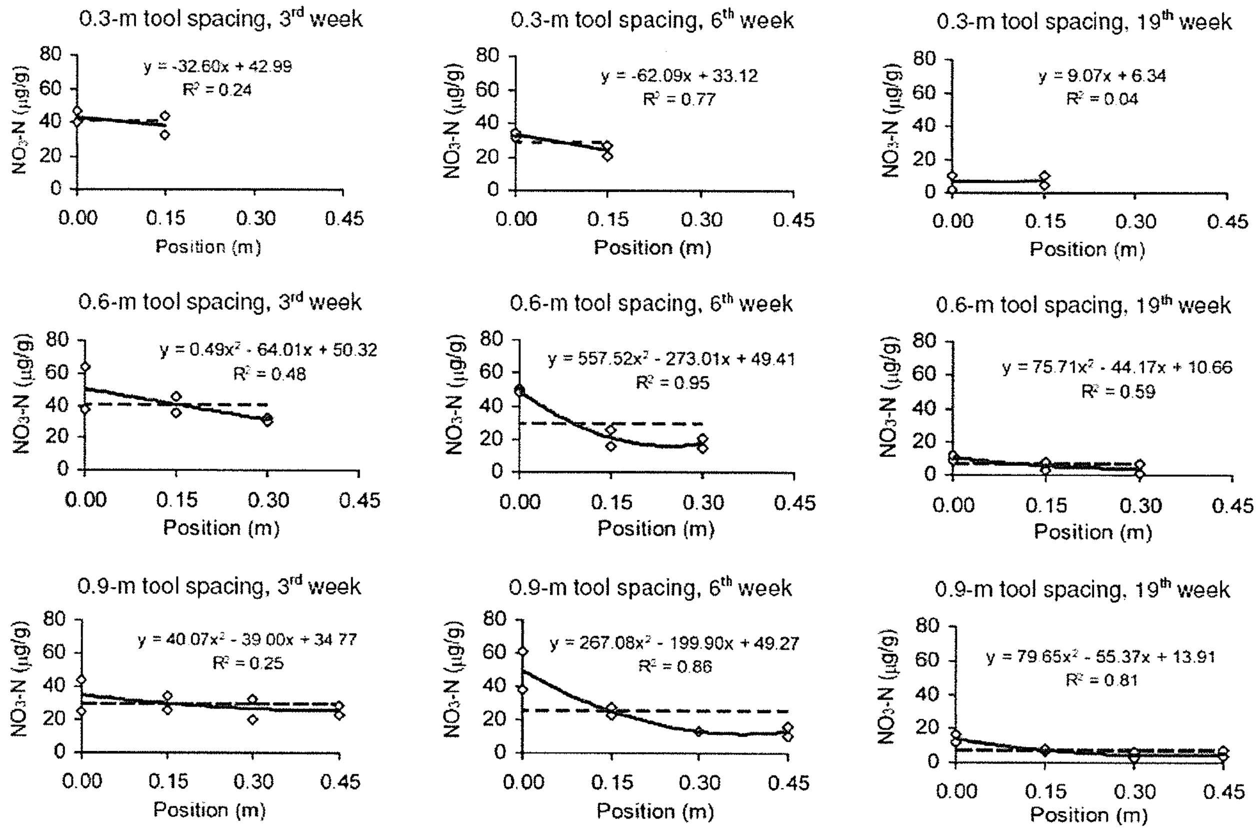

Fig. 3. Soil NO_3-N concentrations at 0-0.6 m depth at different lateral positions relative to the centre of a manure band in 2004. The two data points at each lateral position represent the average values for the coulter and furrower injection tools. Each data point is the average of four replicates. The average value over all positions is shown by a horizontal dashed line.

sampling aimed at monitoring NO_3-N to a time when more than three weeks have elapsed between manure injection and the sampling.

Situations of relatively uniform NO_3-N levels after injection
While little liquid manure injection equipment is configured with a tool spacing of 0.3 m, injection equipment that is set up in this fashion is expected to provide relatively uniform manure distribution shortly after liquid manure injection. Soil sampling after nine weeks allows for the manure NH_4-N to be nitrified and for the soil NO_3-N to be redistributed laterally. For example, fall sampling from a field injected in the spring ensures that the banding effect has greatly diminished if not vanished completely. Accordingly, the traditional randomized sampling approach can be used where either the tool spacing is of the order of 0.3 m or less, or sampling occurs nine weeks after manure injection.

Sampling protocols for NO_3-N within three to nine weeks from time of injection with a tool spacing greater than 0.3 m
If sampling for soil NO_3-N must be carried out within nine weeks of manure injection, significant variability in soil NO_3-N between manure bands may be expected. An ideal sampling protocol would be to sample at different lateral positions to account for the banding effect to ensure obtaining representative soil nutrient levels. However, this would be very tedious. The following practical approaches are proposed for different scenarios.

Information on injector travel direction and tool spacing can usually be obtained from the producer or the custom applicator. If this is the case, soil sampling should be performed along a transect which is perpendicular to the injector travel direction. Sampling along the direction of maximum variation was also suggested by McBratney et al. (1981). Two sub-samples need to be taken along the transect and the distance between these two samples should be half of the tool spacing. This approach is referred to as *directed paired-sampling* approach. This approach will increase the probability that both the zone enriched with NO_3-N near or in the liquid manure band and the zone into which manure NO_3-N has not moved yet are sampled. As compared with the traditional randomised sampling, the *directed paired-sampling* approach doubles the number of soil samples to be taken, which adds additional cost to soil sampling. If 15 random locations are sampled in a field as commonly done in Manitoba for soil nutrient auditing, the *directed paired-sampling* requires a total of 30 samples, which still appears to be practical.

If the injector travel direction and tool spacing are unknown, one has to resort to the traditional randomised sampling method.

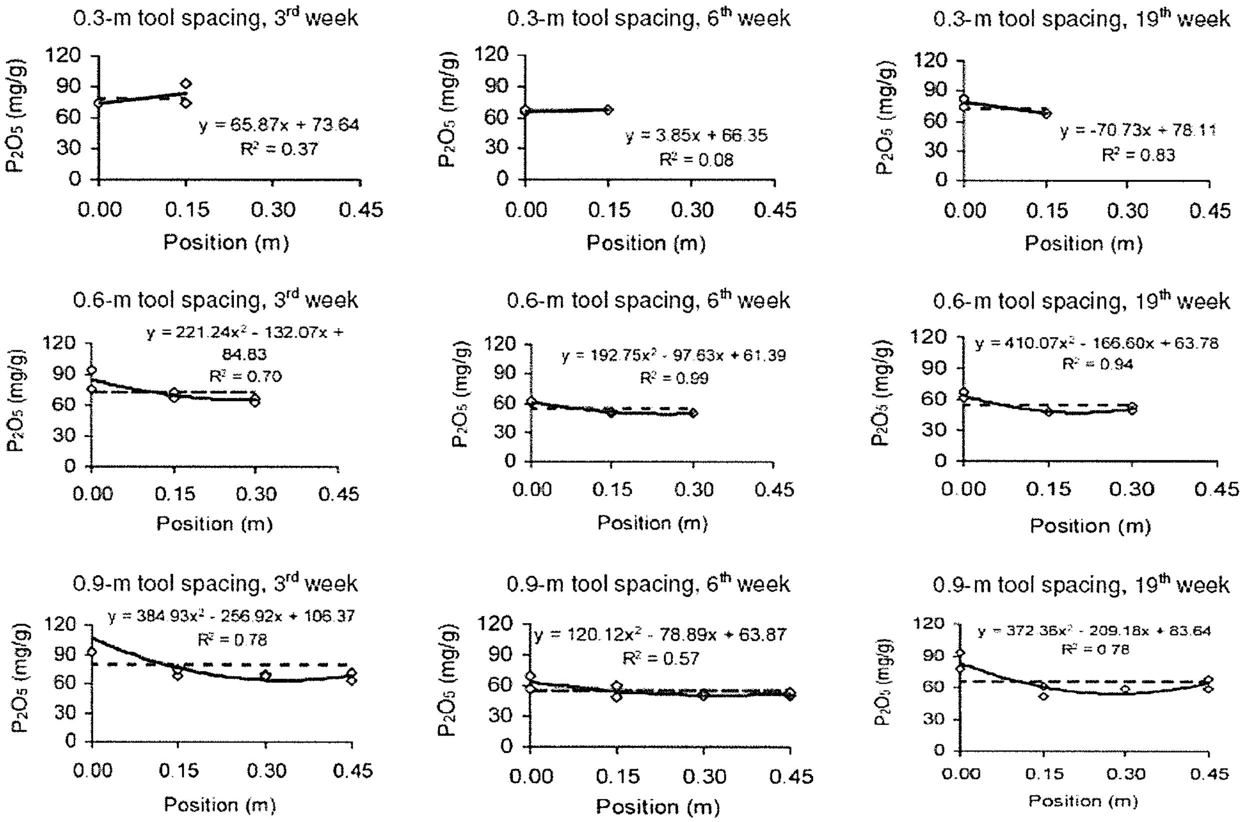

Fig. 4. Soil P_2O_5 concentrations at 0-0.3 m depth at different lateral positions relative to the centre of manure band in 2004. The two data points at each lateral position represent the average values for the coulter and furrower injection tools. Each data point is the average of four replicates. The average value over all positions is shown by a horizontal dashed line.

The nutrient level results from this case may be assessed with considerations of data variations.

Sampling procedure for soil phosphorus

Sampling approaches for phosphorus can be tailored to those proposed for nitrogen because position effects on trends of both nutrient concentrations are similar. One exception is that sampling for phosphorus analysis needs to consider banding effects at any time of the year.

Comparison between the traditional randomized sampling and the *directed paired-sampling*

To illustrate the improvement in soil sampling accuracy by proceeding with the *directed paired-sampling* approach, a simulation of field variability was performed by randomly sampling around a liquid manure band for two situations: one sub-sample was taken at each of 15 field locations, and two sub-samples (spaced by one half of the injection tool spacing) were taken at each of the same field locations. The former represents the traditional randomised sampling approach, and the latter represents the *directed paired-sampling* approach. In the simulation, the regression equations fitted to the nutrient data (Figs. 2 - 4) were used to predict the nutrient levels at any random position relative to a manure band between two adjacent manure bands. The accuracy of each sampling approach was assessed by the differences between the values predicted using the regression equations and the measured average values that are represented by the horizontal lines in Figs. 2 - 4.

This simulation was carried out 20 times, where a random number generator was used to set the sampling location for each of the 15 sampling locations. This is equivalent to carrying out 20 different samplings in the same field. The simulation results show that at the third or nineteenth week after injection, the predicted NO_3-N values remain relatively close to the measured averages in most instances (results not shown). In such situations, either the traditional randomised sampling or the *directed paired-sampling* approach would result in NO_3-N measurements in close agreement with the averages measured at any location in the field. However, the simulation results illustrate the advantages of the *directed paired-sampling* for the data taken at the sixth week after injection. This was the stage at which a significant nitrification of NH_4-N would occur but would not allow a significant use of nutrients by the crop.

The simulation results (Fig. 7) suggest that the *directed paired-sampling* approach allows for obtaining a more accurate estimate of the average NO_3-N more than half of the time, and maintains the error well below 20% most of the time. The traditional randomised sampling approach may result in obtaining field variability ranging over the 20% of the measured

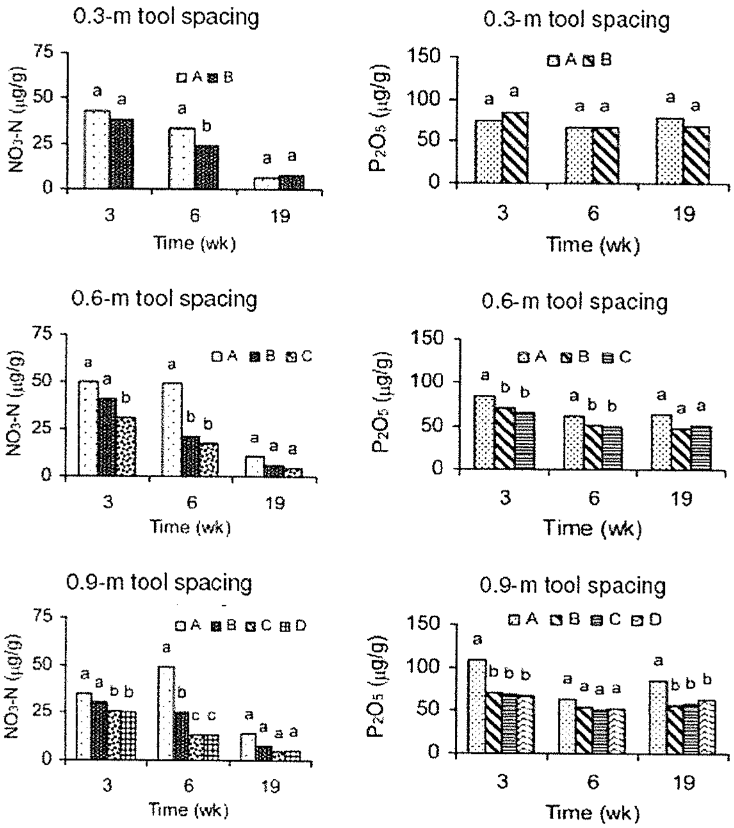

Fig. 5. Soil nutrient concentrations at different lateral positions weeks after manure injection for different injection tool spacings in 2004. Positions A's were located on the centre lines of manure bands; Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively; (a) soil NO_3-N at 0-0.6 m depth; (b) soil P_2O_5 at 0-0.3 m depth. Each data point represents the average value of coulter and furrower injection tools and four replicates. Mean values for each factor within a year and a column followed by same letter are not significantly different (P>0.1).

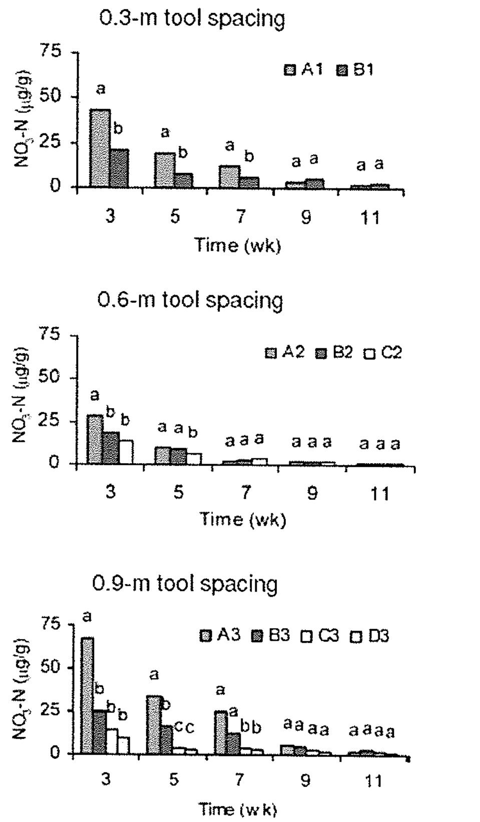

Fig.6. Soil NO_3-N concentration at 0-0.3 m depth at different lateral positions weeks after manure injection for different injection tool spacings in 2002. Positions A's were located on the centre lines of manure bands; Position B's, C's, and D's were 0.15, 0.30, and 0.45 m away from the centre lines of manure bands, respectively. Each data point represents the average value of the coulter and furrower injection tools and four replicates. Mean values for each factor within a year and a column followed by the same letter are not significantly different (P>0.1).

averages. Understandably, the benefits of taking paired samples at each sampling location are greater when the injection tool spacing is greater.

Similar simulations were also performed for the phosphorus data (results not shown). The predicted values of phosphorus were within 10 to 12% of the measured averages for injection tool spacings of 0.6 and 0.9 m, respectively.

CONCLUSIONS

Compared to the traditional randomised sampling approach, the *directed paired-sampling* approach allows obtaining a more representative estimate of the average soil NO_3-N in a field with manure injected at larger spacing than 0.3 m especially between three and nine weeks after manure injection. The *directed paired-sampling* approach decreases the risk of obtaining field variability ranging beyond 20% of the measured averages. However, additional cost is associated with the *directed paired-sampling* due to the double number of samples to be taken.

When the tool spacing of injection equipment is 0.3 m or less, or if soil sampling can be delayed until nine weeks or more after manure injection, the traditional randomised sampling approach can be used. Note that the protocol developed took no account of spatial variations in soil properties and the effect of the nutrient use by plants. The conclusions were drawn using the data from a given experimental condition. Care should be taken in application of the results.

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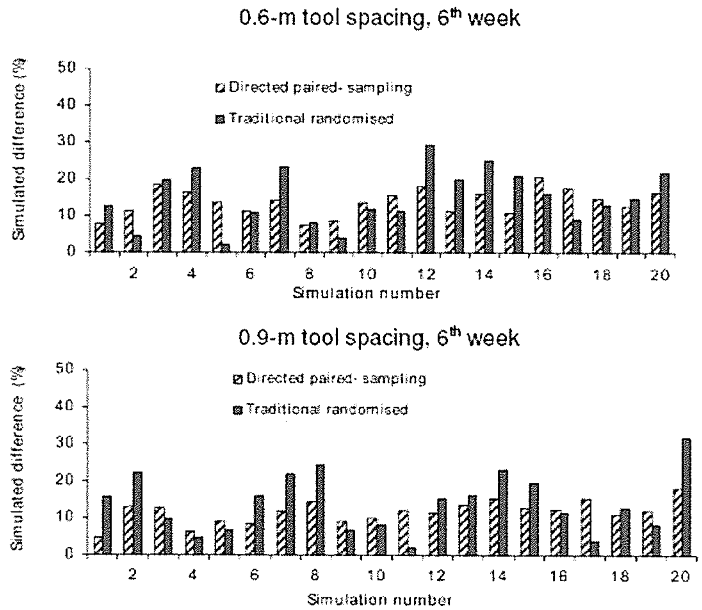

Fig. 7. Simulated differences in NO_3-N levels (in the top 0.6 m depth of soil and at the sixth week after injection) between the predicted values and the measured averages for two sampling approaches: traditional randomised sampling and directed paired-sampling at each of 15 field locations.

REFERENCES

Anderson, D.L., E.A. Hanlon, O.P. Miller, V.R. Hoge and O.A. Diaz. 1992. Soil sampling and nutrient variability in dairy animal holding areas. *Soil Science* 153(4): 314-321.

Assefa, B., Y. Chen, K. Buckley and W. Akinremi. 2005. Soil nutrient levels and crop performance at varying positions relative to manure bands. CSAE/SCGR Paper No. 05-075. Winnipeg, MB: CSBE/SCGAB.

Assefa, B., Y. Chen, K. Buckley and W. Akinremi. 2006. Effects of manure injection tool type and tool spacing on soil nutrient levels and spring barley performance. *Canadian Biosystems Engineering* 48: 2.45 - 2.54.

Crépin, J. and R.L. Johnson. 1993. Soil sampling for environment assessment. In *Soil Sampling and Methods of Analysis*, ed. M.R. Carter, 5-18. Boca Raton, FL: Lewis Publishers.

De Gruijter, J.J. 2002. Sampling. In *Methods of Soil Analysis. Part 4 - Physical Methods*, eds. J.H. Dane and G.C. Topp, 45-79. Madison, WI: Soil Science Society of America, Inc.

Donohue, S.J. 2002. Evaluation of soil nutrient variability for development of turfgrass soil test sampling methods. *Communications in Soil Science and Plant Analysis* 33(15-18): 3335 - 3345.

James, D.W. and R.L. Hurst. 1995. Soil sampling techniques for band-fertilizer, no till fields with Monte Carlo simulations. *Soil Science Society of America Journal* 59(6): 1768-1772.

Mallarino, A.P. 1996. Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales. *Soil Science Society of America Journal* 60(5): 1473-1481.

McBratney, A.B., R. Webster and T.M. Burgess. 1981. The design of optimal sampling schemes for local estimation and mapping of regionalised variables - I Theory and method. *Computers & Geosciences* 7(4): 331-334.

McCormick, R.A., D.W. Nelson, A.L. Sutton and D.M. Huber. 1983. Effect of nitrapyrin on nitrogen transformations in soil treated with liquid swine manure. *Agronomy Journal* 75(6): 947-950.

Mohamed, S.B., E.J. Evans and R.S. Shiel. 1996. Mapping techniques and intensity of soil sampling for precision farming. In *Precision Agriculture: Proceedings of the 3rd International Conference*, 217-226. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Penney, D.C., S.C. Nolan, R.C. McKenzie, T.W. Goddard and V. Kryzanowski. 1996. Yield and nutrient mapping for site specific fertilizer management. *Communications in Soil Science and Plant Analysis* 27(5-8): 1265-1279.

Petersen, R.G. and L.D. Calvin. 1998. Sampling. In *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods*, ed. A. Klute, 33-51. Madison, WI: American Society of Agronomy, Inc., Soil Science Society of America, Inc.

Petersen, S.O., H.H. Nissen, I. Lund and P. Ambus. 2003. Redistribution of slurry components as influenced by injection methods, soil, and slurry properties. *Journal of Environmental Quality* 32(6): 2399-2409.

Rehm, G.W. and J.A. Lamb. 2004. Impact of banded potassium on crop yield and soil potassium in ridge-till planting. *Soil Science Society of America Journal* 68(2): 629-636.

SAS. 2001. SAS proprietary software release 8.2. Cary, NC: SAS Institute Inc.

Sawyer, J.E., M.A. Schmitt and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Agronomy Journal* 82(5): 963-969.

Schnug, E., K. Panten and S. Haneklaus. 1998. Sampling and nutrient recommendation – the future. *Communications in Soil Science and Plant Analysis* 29(11-14): 1455-1462.

Thompson, A.N., J.N. Shaw, P.L. Mask, J.T. Touchton and D. Rickman. 2004. Soil sampling techniques for Alabama, USA Grain Fields. *Precision Agriculture* 5(4): 345-358.

Zebarth, B.J., M.F. Younie, J.W. Paul, J.W. Hall and G.A. Telford. 1999. Fertilizer banding influence of spatial and temporal distribution of soil inorganic nitrogen in corn field. *Soil Science Society of America Journal* 63(6): 1924-1933.