Pocket Injection of Liquid Manure Using the Aerway Rolling Tines

by

Song Ai

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

Master of Science

Department of Biosystems Engineering

University of Manitoba

Winnipeg, Manitoba, Canada

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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GENERAL ABSTRACT

Pocket injection method causes low soil disturbance, which is desired for forage field applications of liquid manure. Pocket characteristics are important, as they affect the performance of pocket injection. Following pocket injection, manure distribution in soil is also important as it affects the evenness of nutrient distribution in soil. A two-year field study was carried out in two forage fields in Manitoba using an existing AerWay aerator. Field treatments included two types of soil: clay loam and sandy soil, two types of the AerWay rolling tine: Shatter tine and Leaf tine; two tine swing angles: 0 and 5°; and two tine penetration depths: 125 and 150 mm. For each treatment, field measurements were performed on pocket characteristics, including volume, shape, and opening dimensions of soil pockets. The results showed that depending on the treatment, pocket opening area varied between 1,088 and 5,555 mm^2; pocket volume varied between 69 and 327 ml. In general, larger pockets, in terms of pocket opening area and pocket volume, were observed for the clay loam, Shatter tine, the 150 mm penetration depth, and the 5° swing angle, when compared to the sandy soil, Leaf tine, the 125 mm penetration depth, and the 0° swing angle, respectively. Thus, largest soil pockets were resulted from the treatment combination of Shatter tine operated at the 150 mm penetration depth and 5° swing angle in the clay loam field. This treatment combination would favour maximum manure application rate and minimum manure exposure on soil surface.

Field measurements were also conducted on pocket shape, liquid distribution (represented by liquid-soil mix zone), and liquid movement (represented by liquid content) in soil following pocket injection using water. Those measurements were performed in both the clay loam and sandy soil, but only for the treatment of Shatter tine working at the 150 mm

penetration depth and the 5° swing angle. Mathematical and regression equations were used to describe the pocket shape measured. The top view of pocket was described as an ellipse; the back view was simplified as a trapezoid; and the side view fitted second order polynomial equations. The liquid-soil mix zone areas of the sandy soil were 18,343 mm^2 averaged over two years. Up to a 56% larger zone area was observed in the clay loam. The liquid content around a soil pocket increased over time during a very short period of time and remained nearly constant afterwards during a period of approximately 24 hours.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Liquid manure has been used for crop production and soil improvement (Gilley and Risse 2000; Chen and Samson 2002). Of all manure application methods, such as injection, broadcasting, surface banding, and surface spreading with incorporation, injection method is recommended for reducing odour and ammonia emissions as well as surface runoff of manure nutrient (Hoff et al. 1981; Sutton 1994; Hanna et al. 2000; Chen et al. 2001). Although a number of technologies are available for liquid manure injection, technologies with low soil disturbance are needed for manure applications in forage fields. Existing manure injection tools, including sweeps, disks, and openers cause too much soil disturbance when being used in forage fields.

Aerators have low soil disturbance features, and they have been used for incorporation of manure in forage fields. The Ontario-based Holland Equipment developed an AerWay sub-surface deposition system (SSD) and a row crop box frame system (BF) for manure applications by modifying their existing aerators. Those AerWay manure application systems use rolling tines to create soil pockets; manure drop tubes located behind each tine band manure over the tine disturbed soil (Bittman et al. 2002). The major advantage, in terms of manure incorporation, is the enhancement of manure infiltration (Turpin et al. 2007b; Mueller et al. 1984; Rotz et al. 2007). Thus, this method is also called infiltration enhancement. The major drawback of infiltration enhancement is that some manure is placed on soil surface between pockets, although some manure goes into pockets.

To overcome the drawback of placing manure on soil surface in the infiltration enhancement method, researchers proposed the pocket injection method which involves the use of aerators (Leafloor 2004; Chen and Leafloor 2006). This new concept was implemented by Chen et al. (2009). They developed a prototype manure delivery device, named pulsing meter, for pocket injection. The prototype pulsing meter has been adapted on the current AerWay rolling tines in a field pocket injector.

Although a significant progress has been made in the area of pocket injection, research on pocket injection is still at its initial stage. Many questions need to be answered before pocket injector can be actually practiced by producers. One question is how easily manure can be placed in a soil pocket in a field situation, and another question is how much manure can be placed in a soil pocket. To answer these questions, one needs to study characteristics of soil pockets, such as the opening size of the pocket and the volume of the pocket. The opening size of the pocket affects the ease of manure placement. For example, a small pocket opening may result in manure being placed outside the pocket, ending up on the soil surface, which is not desired. A larger pocket volume is able to accommodate more manure which is often desired and critical in pocket injection (Chen et al. 2009).

There are more questions to answer when pocket injection is used. Those questions include how quickly manure in a pocket flows in the surrounding soil, and how far it flows from the pocket. Since manure is placed only in pockets, there is a possibility of uneven distribution of manure nutrients in soil. Manure or nutrient distribution in soil is important factor that affects crop performance and the environment. Liquid movement in and around a soil pocket is affected not only by the soil conditions, but also by characteristics of the pocket, such as pocket shape and volume. Thus, studying manure distribution in soil and pocket shape following pocket injection is also important to advance the pocket injection technology.

Little research related to pocket characteristics was carried in the past. Turpin et al. (2007a) reported some findings on degree of soil disturbance and the size of the soil pocket. No studies on actual field pocket shapes were found in the literature. Few studies (Hanna et al. 1998; Rodhe 2003; Rahman et al. 2004; Rahman et al. 2008) were found on manure distribution in soil, but they were for furrow injections. The most relevant study was the modeling work on liquid distribution in soil following pocket injection conducted by Wu and Chen (2009). The model was based on an assumed pocket shape. This assumption may limit the model applications. Measurements of field pocket shape and liquid distribution using soil pocket from field aerators are essential to improve the performance of the model and other models in the future.

In summary, characteristics of soil pockets are important for pocket injection. Liquid movement or distribution in soil following pocket injection has important implications to crop nutrient uptaking and the environment. However, little information is available in these regards. Pocket injection is still a new concept and the research is at its initial stage. Answers to the aforementioned questions will advance the technology of pocket injection.

1.2 General objectives

The goal of this study was to provide the essential information for advancing pocket injection method. The objectives were to:

1. examine the characteristics of soil pockets resulting from the AerWay rolling tines in forage fields;
2. measure manure distribution and liquid content in soil following pocket injection.

1.3 Thesis structure

This thesis has been structured in paper formats. General introduction and literature review are presented in chapters 1 and 2. Chapters 3 and 4 are parts of the thesis written in paper formats. Summary and recommendations are outlined in chapter 5.

1.4 References

Bittman, S., L.J.P. Van Vliet, N. Patni, G.C. Kowalenko, F. Bounaix and D.E. Hunt. 2002. A new high-speed technique for injecting swine and dairy slurry into permanent grassland and crop land. Investment Agriculture, final Report. Unpublished report. Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Agassiz, BC.

Chen, Y. and E. Leafloor. 2006. Liquid Fertilizer Injection System, Method and Apparatus. Canadian and US Patent offices: PCT/CA2005/000560.

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

Chen, Y., J. Wylde and S. Ai. 2009. Pre-commercialisation of a pulsing meter for liquid manure injection in forage fields. Project Report. Submitted to ACAAF Program Agriculture Agri-Food Canada, Ottawa, ON, Canada.

Gilley, J.E. and L.M. Risse, 2000. Runoff and soil loss as efectd by the application of manure. *Transactions of the ASAE* 43(6): 1583-1588.

Hanna, H.M., D.S. Bundy, J.C. Lorimor, S.K. Mickelson and S.W. Melvin. 1998. Evaluating land waste application machinery to meet odour and environmental objectives. Final project Report (NPPC Project No. 1851). Ames, Iowa: Iowa State University, Department of Agricultural and Biosystems Engineering.

Hanna, H.M.; D.S.Bundy, J.C. Lorimor, S.K. Mickelson, S.W. Melvin and D.C. Erbach. 2000. Manure incorporation equipment effects on odour, residue cover, and crop yield. *Applied Engineering in Agriculture* 16: 621-627.

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.

Kaleta, K., Y. Chen and J. Mak. 2009. Liquid manure infiltration as affected by the solids content of manure. ASABE/CSBE Paper No. SD09-504. St. Joseph, MI: ASABE.

Leafloor, E. 2004. Design of Machine for Grassland Injection of Liquid Manure. Undergraduate Thesis, Department of Biosystems Engineering, University of Manitoba, Canada.

Mueller, D.H., R.C. Wendt and T.C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. *Soil Science Society of America Journal* 48: 896-900.

Rodhe, H. 2003. Methods of determining the presence of slurry on the crop and in the upper soil layer after application to grassland. *Bioresource Technology* 90(1): 81-88.

Rotz, C.A., P. Kleinman, C. Dell, J. Schmidt and D. Beegle. 2007. Environmental and Economic Comparisons of Manure Application Methods on Dairy Farms. 2007 ASABE Annual International Meeting, ASABE17 - 20 June 2007, Minneapolis, Minnesota.

Rahman, S., Y.Chen, K. Buckey 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, J. Paliwal and B. Assefa. 2008. Models for Manure Distribution in Soil Following Liquid Manure Injection. *Transactions of the ASABE* 51(3): 873-879.

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

Turpin, K.M., D.R. Lapen, E. Topp, M.J.L. Robin, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B.Ball Coelho and M. Payne. 2007a. Tine-influenced infiltration patterns and informing timing of liquid amendment applications suing brillant blue dye tracers. *Bisosystems engineering* 98: 235-247.

Turpin, K.M., D.R. Lapen, M.J.L. Robin, E. Topp, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B.Ball Coelho and M. Payne. 2007b. Slurry-application implement tine modification of soil hydraulic properties under different soil water content conditions for silt –clay loam soils. *Soil & Tillage Research* 95: 120-132.

Wu, B. and Y. Chen. 2009. Modeling liquid distribution in soil following pocket injection. Submitted to *Journal of Environmental Quality*.

CHAPTER 2: GENERAL LITERATURE REVIEW

2.1 Liquid manure

Manure is an inevitable natural by-product of livestock production. It primarily consists of excreted feces and urine; it may also contain bedding materials, spilled feeds, water, soil, milking centre wastewater, contaminated milk, hair, feathers, and other debris (ASAE Standards 2004). Manure is classified into four categories based on its total solids content: liquid manure, slurry, semi-solid manure, and solid manure. The corresponding ranges of total solids content are: 0-5, 5-15, 15-25, and greater than 25%, respectively, on wet basis (ASAE Standards 2004). Liquid manure is characterized by more water and urine, and less bedding material than other types of manure. This study concerned only liquid manure.

2.2 Land application of liquid manure and the concerns

Animal manure is a valuable resource. It can be applied to farmland as a fertilizer to increase crop yields. Manure provides nutrient rich organic matter that can improve soil structure. The returning of manure nutrients to the soil where they are used to produce feed crops for animal production is a cost effective and sustainable practice.

However, poorly managed manure utilization may cause environmental problems such as odour and water pollution resulting from losses of manure nutrients. Losses include gaseous ammonia emissions through volatilisation, nitrate leaching to ground water, and surface runoff of phosphorus (Rotz et al. 2007). Therefore, there is 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). A sound manure management practice, such as injecting manure into soil, minimize nutrient losses to the environment and maximize nutrient use in crop production.

2.2.1 Methods of manure application

There are two main manure application methods: surface application and injection. In surface application, manure is applied on soil surface. Surface application is further classified into broadcasting, surface banding, surface incorporation, and infiltration enhancement (Chen et al. 2001). Broadcasting is performed with a splash plate. In this method, high pressurised manure impacts an inclined splash plate creating a fan pattern which covers the entire soil surface. Surface banding is usually achieved with dribble bars. Manure with low pressure or a gravity flow is placed on soil surface as bands. The soil surface between bands is not covered with manure. Surface incorporation includes two processes: broadcasting or banding manure on soil surface, and using tillage equipment to mix the manure with soil. The two processes can be achieved with one pass of field equipment or separate passes. In the case of separate passes, the tillage operation was recommended within 24 hours of manure spreading to reduce nutrient losses. Infiltration enhancement method is discussed in detail in the section 2.2.3. Comparing with surface application and infiltration enhancement methods, injection is more environmental friendly, in terms of reducing odours, minimizing ammonia volatilization, and maximizing returns from the applied manure (Sawyer et al. 1991; Comfort et al. 1998).

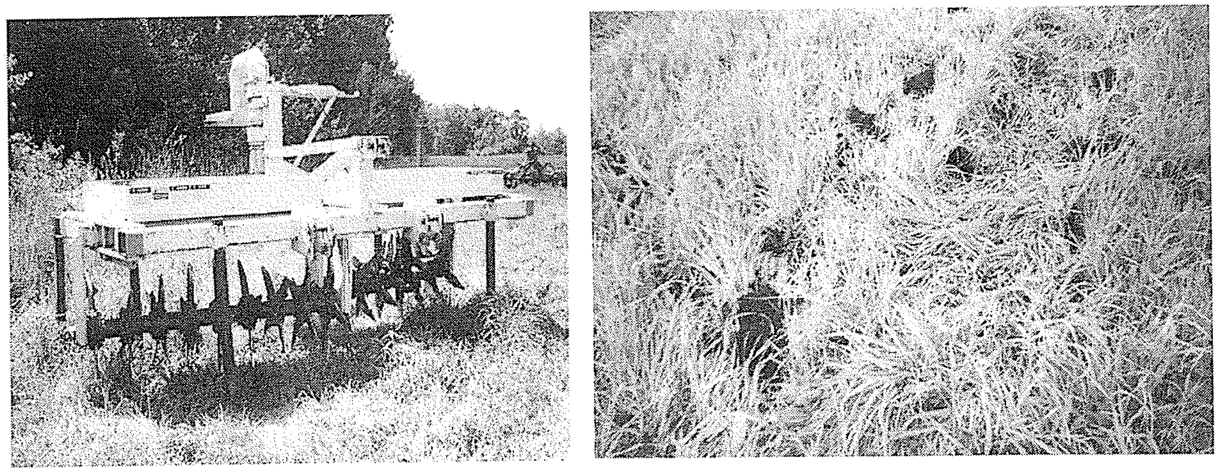
2.2.2 Manure application in forage fields

Forage crops use large quantities of nutrient, and forage fields pose less risk of leaching or runoff losses. Due to the high cost of chemical fertilizer, little or no chemical fertilizer is applied to forage crops. The lack of nutrients limits their production potential. Applying manure to forage crops will be a viable economical option. More and more producers are interested in applying manure to forage fields. Disturbance of the top layers of soil containing much of the root mass is the main disadvantage of field operations in forage fields. The crops can be harmed by tillage actions. Therefore, the criterion of low soil disturbance would be applied to any manure application equipment for forage fields.

A growing number of technologies have been tried for manure applications in forage fields. Those technologies can potentially reduce soil disturbance while incorporating manure. Again, the major performance indicator of the application equipment is minimum \soil disturbance so that the forage crops are not damaged. Low soil disturbance is also a requirement for no-till crops and growing crops (Nyord et al. 2009).

2.2.3 Infiltration enhancement

Working principle Infiltration enhancement method is classified as surface application, and it includes two processes: disturbing soil to create large soil pores and placing manure on the disturbed soil surface. Infiltration enhancement has been done with aerators, such as the AerWay aerator (Fig. 2.1A). The AerWay aerator (SAF-Holland Equipment, Norwich, ON, Canada) was originally designed for conditioning soil and enhancing the capillary action necessary for the movement of air and water. It has been used for manure application, especially in forage fields, due to its low soil disturbance feature. For manure application, the rolling tines of aerator penetrate into soil, resulting in pockets in the soil (Fig. 2.1B). Then manure is broadcast or banded on the pocketed soil surface. With this method, some manure goes into the pockets and some stays on the surface.



(A) (B)

Fig. 2.1. AerWay aerator and resultant soil surface; (a) aerator consisting of rolling tines; (b) resultant soil surface showing soil pockets.

AerWay aerators/rolling tines An AerWay aerator has one or more ground driven rollers. Each roller consists of a series of rolling wheels mounted on a shaft (Fig. 2.1A). Rolling wheels are mounted with an offset angle relative to its neighbours to balance the soil cutting forces. Rolling wheels are spaced 0.19 m apart on the shaft. Four rolling tines are distributed on a rolling wheel. As a tractor pulls the aerator along, the rolling tines dig into the ground, which make the rolling wheels rotate. The rotation of rolling tines in soil results in rows of pockets in the soil (Fig. 2.1B). The pocket row spacing is equal to the rolling wheel spacing.

AerWay manure applicators Since 1980s, the AerWay rolling tines have been used for incorporating liquid manure into soil which is the infiltration enhancement method. In the earlier models, the processes of pocket creation and manure placement were achieved in separate field operations. In the newer models, two processes are completed within one pass of the equipment. The current models include AerWay sub-surface deposition (SSD) (Fig. 2.2A) and box frame system for row crops (BF) (Fig. 2.2B). In these two systems, a rolling-tine aerator was coupled with an AerWay slurry distribution system. The SSD system has been assessed by several researchers. Harrigan et al. (2006) found that the greatest soil phosphorus concentration was in the surface to 7.6-cm soil layer at the point of tine entry, and little of the manure slurry moved below that depth within 48 h of application. Turpin et al. (2007a) found that the AerWay soil pockets had generally higher field saturated hydraulic conductivities than undisturbed soil. This effect was primarily produced by the tine's capacity to fracture surface soil especially at lower water content (Turpin et al. 2007a). Bittman et al. (2005) reported lower ammonia emissions in the two weeks following application and slightly higher orchard grass yield for manure applied with the SSD compared to broadcast. Little research was found on the evaluation of AerWay BF system.

(A) (B)

Fig. 2.2 AerWay manure applicator: (A) sub-surface deposition (SSD) system; (B) box frame system (BF) for row crops. Source: http://aerway.com.

2.3 Liquid manure injection

Injection of liquid manure is defined as placing manure into soil below the soil surface. As compared with surface application methods, such as broadcasting and banding, the advantages of injection method include:

- minimising volatilisation of nutrient;
- reducing odour emission;
- reducing surface runoff losses of nutrient.

The disadvantages of injection method include:

- high tractor power requirement;
- lower manure application rates;
- high soil disturbance.

As it is environmentally friendly, injection method has been considered as the best management practice for land application of manure. Injection method can be further classified into two categories: "*furrow injection*" and "*pocket injection*" as described below.

2.3.1 Furrow injection

Traditionally, manure is injected into soil by opening furrows and placing manure bands into the furrows, which is referred as furrow injection. The injection tools used for furrow injection are shank-types, such as sweeps, chisels, shovels, discs, and runner openers. Shank-type injectors open furrows by moving soil forward, upward, and sideways (Rahman et al. 2001). Soil surface profiles may show a depression or a mounded zone in the centre of the tool path. Creating furrows by those injection tools may cause significant soil disturbance. As compared with furrow injection, pocket injection causes less soil disturbance and is discussed in the following section.

2.3.2 Pocket injection

Definition of pocket injection Pocket injection is to place manure into soil pockets. The basic concept of pocket injection was proposed by Leafloor (2004) and Chen and Leafloor (2006). The process of pocket injection can be identified as follows:

1) Creating soil pockets using soil engaging tools, such as rolling tines;
2) Placing manure into the pockets using a manure delivery device, such as pulsing meters or valves.

Existing equipment for pocket injection A prototype pocket injector has been developed by Chen et al. (2009). In their study, the concept proposed by Leafloor (2004) and Chen and Leafloor (2006) was further developed into a pulsing meter. The prototype of the pulsing meter was adapted onto the existing AerWay rolling tine system in constructing a field pocket injector. The AerWay rolling tines created pockets on the soil surface, and the pulsing meter delivered manure in pulses with each pulse being placed into a pocket. Field tests showed that the prototype pocket injector reduced the manure exposure on soil surface when compared with the infiltration enhancement method. However, several challenges still remained for pocket injection. For field application, a pocket injector must be capable of creating pockets in soil for liquid manure to flow into; those pockets must be large enough to accommodate the target manure application rate; and the pulsing meter must have the desired pulsing function and pulse volume.

Manure application rate in pocket injection Application rates are important factors in manure injection. Many researchers (Sawyer et al. 1991; Schmitt et al. 1995; Chen 2002; Mooleki et al. 2002) have studied the effect of application rates on the performance of furrow injection. Rahman et al (2004) introduced the concept of micro-rate which is more critical in determining manure distribution in soil than manure application rates (L/ha). Micro-rate (L/m) was defined as the "volume of slurry applied by one injection tool within a unit distance" in furrow injection. In pocket injection, micro-rate would be equivalent to "pocket rate" (ml/pocket) which is the amount of manure placed in a pocket. Pocket rate, together with the number of pockets per hectare, determines the field manure application rate (L/ha).

The maximum pocket rate is determined by the volume of the pocket. The maximum pocket rate which can be placed into a pocket without manure overflowing onto the soil surface can be assumed to be equal to the volume of the pocket (Wu and Chen 2009). Under this assumption, the maximum potential application rate can be estimated by the following equation:

$$R = \frac{v\,n}{1000} \tag{2.1}$$

where

v = pocket volume (ml/pocket);

R = application rate (L/ha);

n = the number of pockets per hectare of field (pockets/ha).

In practice, the volume of pocket and number of pockets per hectare are limited due to the soil disturbance issue. This sets upper limit of manure application rate in pocket injection.

2.4 Rolling tines and their performance

2.4.1 Tine spacing

Tine spacing affects not only the number of soil pockets per hectare, but also the manure distribution in soil. Few researchers studied furrow injection of liquid manure at variable tool spacings. Mooleki et al. (2002) researched two treatments of liquid swine manure injection performed using sweep at 0.3 and 0.6 m spacings and found a higher wheat yield for the 0.6 m spacing. Whereas Assefa et al. (2007) reported that 0.3 m tool spacing had advantages over 0.6 and 0.9 m spacings, in terms of the evenness of nutrient distribution in soil and crop response. Eghball and Sander (1989) used banding spaces of 0.30, 0.45, 0.60, and 0.75 m, and concluded that it was difficult to determine the optimal band spacing for fertilizer application. Tool spacing in furrow injection affects manure distribution in soil and in turn the nutrient distribution in soil as well as the nutrient up takes by the crop. This issue exists in pocket injection, where manure is placed in pockets only. As a result, there are more nutrients within the pocket area and less in between pockets. Thus, arrangement of tine spacing is important in pocket injection. To determine appropriate tine spacing, one needs the information of how manure distributes in soil following pocket injection. This was investigated in this study.

2.4.2 Pocket characteristics

Pocket characteristics include pocket volume, dimensions of pocket opening at the soil surface, and pocket shape. As mentioned above, pocket volume determines the potential manure application rate. Larger pocket favours a higher manure application rate, which is often desired in a pocket injection. Pocket opening at the soil surface defines how easily manure can be placed into a pocket. A larger opening of soil pocket would make it easier for manure to flow in. Pocket characteristics are also important for aeration of grassland. Grassland relies heavily on aeration of its root system for proper growth. In all cases, pocket characteristics are directly related to the extent of soil disturbance. Thus, they can be used to assess soil disturbance of equipment.

2.4.3 Penetration depth and swing angle

Typically, the penetration depth of the AerWay rolling tine varies from 100 mm to 175 mm and the swing angle (the angle of the rolling shaft relative to the tool bar) can be adjusted between 0 to 10°. Knauf (2005) reported that pocket volume varied from 130 to 300 ml, depending on the penetration depth and swing angle of the rolling tines. There was no mention on how these numbers were obtained. It is obvious that swing angle will affect the pocket opening dimensions. Also, altering penetration depth may also change the dimensions of the pocket opening on the soil surface. Increasing the swing angle from 0 to 10° also increased the draft (McLaughlin et al. 2006) and soil disturbance (Turpin et al. 2007a).

2.4.4 Techniques for measurements of pocket characteristics

Measurement methods of pocket characteristics have not been established. Turpin et al.

(2007b) used beads to fill pockets all the way to the soil surface, and the volume of the pocket was assumed to be equal to the volume of the beads. The reported pocket volumes ranged between 361 and 565 ml. The size of beads would affect the measurement accuracy. A material with finer particle size and more free flowing properties would be desired for this measurement. Also, measurements of pocket shape needs to be explored.

2.5 Liquid manure movement in soil

Following injection, liquid manure will spread in soil both vertically and laterally due to the gradient of liquid content between the pocket and the surrounding soil. Due to the concern on groundwater contamination, many studies (for example, Yang et al. 2007) addressed the vertical NO_3–N movement in soil. Few studies have been done on lateral manure movement in soil. Lateral movement of manure affects the evenness of nutrient distribution in soil, therefore, the crop response to the nutrients. Many researchers have reported the importance of manure distribution in the soil (Sawyer et al. 1990; Sawyer et al. 1991; Schmitt et al. 1995; Rodhe and Rammer 2002) for furrow injection. In pocket injection, as manure is placed in pockets only, the risk of lacking nutrients in between pockets exists. Thus, manure movement in soil following pocket injection is an important issue and needs to be studied.

2.5.1 Flow characteristics of liquid manure

Flow characteristics of water have been well documented. The differences between water and liquid manure are that liquid manure contains solids and nutrients, such as nitrogen (N) and phosphorus (P). Manure with 0% to 5% solid content has consistency and flow characteristics similar to water (Extension 2008). The solid content of swine manure is normally lower than 5%; therefore, one can assume that liquid manure with low solids content has the same flow characteristics as water. Thus, manure movement in the soil can be considered to be in the same manner as water movement. Lately, Kaleta et al. (2009) measured infiltration characteristics of water and liquid hog manures with total solids contents ranging from 0.38 to 8.80%. The results showed that liquid manure, regardless of solids content, had similar infiltration characteristics represented by the Kostiakov constants, when compared to water, except for the steady state infiltration rate (often considered as saturated hydraulic conduction) which was reached after approximately 2.5 hours. The model results in Wu and Chen (2009) showed that liquid flowing in soil takes place within a much shorter time period. Therefore, low discrepancy is expected by approximating liquid manure flow in soil as water flow in soil.

2.5.2 Measurement technique

Chen and Ren (2002) manually measured the maximum lateral and vertical spreads of manure in the soil following injection. Rodhe and Rammer (2002) studied width and depth of manure distribution based on the soil cross-section after injection. Rodhe (2003) researched the placement of manure in the upper soil layer using visual assessment and image analysis. Rahman et al. (2004) quantified manure distribution in the soil by measuring the manure-soil mix zone immediately following manure injection. The accuracy of this measurement can be improved using dye tracers. Hanna et al. (1998) used dye to trace the amount of manure on the soil surface and to measure the centroid of the manure zone flow surface. Those measurements were conducted following furrow injections. Little has been done for pocket injections and in different soils.

2.6 Gaps to fill

In summary, pocket characteristics and manure movement in soil following pocket injection are important in the design and operation of a pocket injector. They also have important agronomic and environmental implications. However, there have been few studies on characteristics of soil pockets resulting from the AerWay rolling tines. The existing studies were limited to the effects of tine penetration depth and swing angle. Other factors, such as type of rolling tines and soil texture, may also have effects on the pocket characteristics. No measurements have been done on pocket shapes and descriptions of pocket shapes using mathematic equations. Measurement techniques also need to be developed for pocket characteristics, including pocket shape, volume, and pocket opening. In addition, there was lack of information on liquid movement following pocket injection. The purpose of this study was to fill these gaps.

2.7 References

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

Assefa, B.A. 2007. Measuring and modeling nitrated-nitrogen movement in soils following manure injection. Unpublished Doctor of philosophy, Department of Biosystems Engineering, University of Manitoba, Canada.

Bittman, S., L.J.P. van Vliet, C.G. Kowalenko, S. McGinn, D.E. Hunt and F. Bounaix. 2005. Surface banding liquid manure over aeration slots: A new low disturbance method for reducing ammonia emissions and improving yield of perennial grasses. *Agronomy Journal* 97(5): 1305-1313.

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

Chen, Y. and E. Leafloor. 2006. Liquid Fertilizer Injection System, Method and Apparatus. Canadian and US Patent offices: PCT/CA2005/000560.

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

Chen, Y., J. Wylde and S. Ai. 2009. Pre-commercialisation of a pulsing meter for liquid manure injection in forage fields. Project Report. Submitted to ACAAF Program Agriculture Agri-Food Canada, Ottawa, ON, Canada.

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

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.

Extension. 2008. Liquid Manure Storage Treatment Options, Including Lagoons. [Online]. Retrieved March 4, 2008, from:

http://www.extension.org/pages/Liquid_Manure_Storage_Treatment_Options,_Including_Lagoons.

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.

Hanna, H.M., D.S. Bundy, J.C. Lorimor, S.K. Mickelson, and S.W. Melvin. 1998. Evaluating land waste application machinery to meet odour and environmental objectives. Final project Report (NPPC Project No. 1851). Ames, Iowa: Iowa State University, Department of Agricultural and Biosystems Engineering.

Honeyman, M.S. 1996. Sustainability issues of U.S. swine production. *Journal of Animal Science* 76(6): 1410-1417.

Holland Hitch of Canada. 2009. AerWay SSD Manure Management Systems. [Online]. Retrieved November 17, 2009, from: http://aerway.com.

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.

Kaleta, K., Y. Chen and J. Mak. 2009. Liquid manure infiltration as affected by the solids content of manure. ASABE/CSBE Paper No. SD09-504. St. Joseph, MI: ASABE.

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.

Knauf, T.A. 2005. The AerWay SSD as a resource management tool in manure management and nutrient recycling, Prepared for Holland Equipment Ltd., Norwich, ON Canada.

Leafloor, E. 2004. Design of Machine of Grassland Injection of Liquid Manure. Undergraduate Thesis, Department of Biosystems Engineering, University of Manitoba, Canada.

McLaughlin, N.B., Y.X Li, S. Bittman, D.R. Lapen, S. Burtt and B.S. Patterson. 2006. Draft requirements for contrasting liquid manure injection equipment. *Canadian Biosystems Engineering* 48: 2.29-2.39.

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.

Nyord, T., M.H. Jorgensen and T.E. Richards. 2009. Pressurized injection of animal slurry in growing cereal crops. American Society of Agricultural and Biological Engineers. ISSN 0001-2351.

Rodhe, H. 2003. Methods of determining the presence of slurry on the crop and in the upper soil layer after application to grassland. *Bioresource Technique* 90(1): 81-88.

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, 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.

Rodhe, L. and C. Rammer. 2002. Application of slurry to ley by band spreading and injection methods. *Biosystems engineering* 83: 107-118.

Rotz, C. A., P. Kleinman, C. Dell, J. Schmidt, and D. Beegle. 2007. Environmental and Economic Comparisons of Manure Application Methods on Dairy Farms. 2007 ASABE Annual International Meeting, ASABE17 - 20 June 2007, Minneapolis, Minnesota.

Sawyer, J.E., M.A. Schmitt, and R.G. Hoeft. 1990. Inorganic nitrogen distribution and soil chemical transformations associated with injected liquid beef manure. *Journal of Production Agriculture* 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 slurry application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8: 186-189.

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.

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

Turpin, K.M., D.R. Lapen, M.J.L. Robin, E. Topp, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B. Ball Coelho and E. Payne. 2007a. Tine-influenced infiltration patterns and informing timing of liquid amendment applications suing brilliant blue dye tracers. *Bisosystems engineering* 98: 235-247.

Turpin, K.M., D.R. Lapen, M.J.L. Robin, E. Topp, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B.Ball Coelho and E. Payne. 2007b. Slurry-application implement tine modification of soil hydraulic properties under different soil water content conditions for silt –clay loam soils. *Soil & Tillage Research* 95: 120-132.

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. *Agriculture Waste Management* 87 (3): 299-306.

Wu, B. and Y. Chen. 2009. Modeling liquid manure distribution in soil following pocket injection. Submitted to *Journal of Environmental Quality*.

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

CHATER 3: CHARACTERISTICS OF SOIL POCKETS RESULTING FROM THE AERWAY ROLLING TINES

3.1 Abstract

In a pocket injection, characteristics of the soil pockets are very important because they affect the manure placement and manure application rate. A field study was carried out in two forage fields in Manitoba. One field had clay loam soil, and the other had sandy soil. An AerWay aerator with two types of the AerWay rolling tines (Shatter tine and Leaf tine) were used in the field study. Each type of rolling tine was operated at two different swing angles (0 and 5°) and penetration depths (125 and 150 mm). The characteristics of the resultant pockets, including pocket longitudinal spacing, pocket opening dimensions at the soil surface level, and pocket volume were measured. The results showed that the pocket longitudinal spacing was 0.445 m for the 125 mm penetration depth and 0.440 m for the 150 mm. Depending on treatments, the pocket opening varied between 91 and 212 mm for the length of opening, 9 and 44 mm for the width, 1,088 and 5,555 mm^2 for the area. The volume of pocket also varied with the soil type and treatments, ranging between 69 and 327 ml. Larger pockets, in terms of both pocket opening and volume, were observed in the clay loam soil than in the sandy soil. Shatter tine created larger soil pockets than Leaf tine. The larger swing angle and greater penetration depth both resulted in larger soil pockets. Thus, the largest pockets were observed when Shatter tine was arranged with the 5° swing angle and operated at the 150 mm penetration depth in the clay loam soil.

Keywords: AerWay, rolling tine, soil, pocket, depth, swing angle, forage.

3.2 Introduction

Liquid manure has been used for crop production and soil improvement (Gilley and Risse 2000; Chen and Samson 2002). Injection of liquid manure below the soil surface reduces odour emissions when compared to surface application (Hoff et al. 1981; Sutton 1994; Hanna et al. 2000; Chen et al. 2001). Researchers (Mueller et al. 1984; Gilley et al. 1999; Van Vilet and Kenney 2000; Daverede et al. 2004) have found that injection of liquid manure also reduces surface runoff and erosion due to the soil stabilizing effect of manure.

Liquid manure injection systems evolved with time, and currently, many types of liquid manure injector are being used, and most of them are for annual crops. Forage crops use large quantities of nutrients, and forage field poses less risk of leaching or runoff losses. Due to the high cost of chemical fertilizer, no or little chemical fertilizer is applied to forage crops. The lack of nutrients limits their production potential. Applying manure to forage crops can be an economical option. In fact, more and more producers are interested in applying manure to forage fields.

Several methods have been used for manure injection in forage fields. These methods included high pressure injection with disks, shallow injection with disks, coulters and sweeps (Rahman et al. 2001), and runner openers (Chen et al. 2001). These methods may cause too much soil disturbance. If this is the case, they are not suitable for injecting manure in forage fields.

SAF-Holland Equipment (Norwich, ON, Canada) developed a sub-surface deposition (SSD) and a box frame system (BF) for manure application in row crops. Both systems were developed based on their existing aerators with AerWay rolling tines. The main feature of the AerWay rolling tines is their low soil disturbance. They were originally designed for aerating grassland by creating soil pockets, which allows the movement of air and water in the soil. These rolling tines were adapted in SSD and BF systems for manure applications to improve manure infiltration (Rotz et al. 2007). Harrigan et al. (2004) stated several advantages of the aerator applicator, including improving infiltration, conserving protective crop residues, and decreasing runoff of sediment and contaminants. Studies on perennial grass showed that surface-banding manure directly over aeration pockets using the SSD applicator reduced emission of NH_3 and odours and increased yield compared with surface broadcasting (Bittman et al. 2005; Lau et al. 2003).

However, the current SSD or BF systems were not for manure injection, but for manure incorporation through infiltration. A BF or SSD system consists of manure delivery nozzles placed behind rolling tines. As a tractor pulls the system along, the rolling tines penetrate the soil, creating soil pockets, and the nozzles deliver manure in bands over the pockets. Thus, some of the manure flows into the pockets, and some is placed on the soil surface between the pockets. Placing manure into pockets is desired, as manure is incorporated into the soil; whereas placing manure between pockets on the soil surface is not desired as it may promote nutrient loss and odour emission. If one can avoid the undesired part, rolling tines would be considered the most appropriate tools to pursue for manure injection in forage fields, due to its low soil disturbance feature.

A pulsing meter has been proposed by Leafloor (2004), Chen and Leafloor (2006) for pocket injection of liquid, together with rolling tines. Lately, Chen et al. (2009) developed the prototype pulsing meter which was intended to work with AerWay rolling tines to perform pocket injection. The pulsing meter delivers manure intermittently as pulses with each pulse of manure being placed into a soil pocket, while the current nozzle system on the

SSD or BF delivers manure continuously as bands. The intention of using the pulsing meter was to ensure that manure is placed only in pockets, not on soil surface. The prototype pulsing meter has been adapted to AerWay rolling tines in a field injector (Chen et al. 2009).

The amount of manure placed in a pocket is defined as the pocket rate. Pocket rate (ml/pocket), together with the number of pockets per hectare, determines the manure application rate (L/ha). The maximum pocket rate determines how much manure can be placed into a pocket without manure overflowing onto the soil surface. The pocket rate is determined by the volume of the pocket. Larger pocket volume favours a higher manure application rate, which is often desired in a pocket injection. Thus, studying the volume of pocket is important for the design of a pocket injector. The opening of soil pocket at soil surface is another important factor for pocket injection. The size of the opening affects how easily manure can be placed into a pocket. A larger opening would make it easier for manure to flow in.

Typically, the penetration depth of the AerWay rolling tine varies from 100 mm to 175 mm and the swing angle can be adjusted between 0 to 10°. Altering the depth and angle will result in different draft force requirements (McLaughlin et al. 2006) and soil saturated hydraulic conductivities (Turpin et al. 2007). Altering these two operational parameters may also change soil disturbance and in turn the pocket characteristics (Knauf 2005; Turpin et al. 2007).

In summary, pocket characteristics, such as pocket volume and pocket opening dimensions, are important information for the design of pocket injector. Few studies (Knauf 2005; Turpin et al. 2007) were conducted on characteristics of pockets resulting from rolling tines, and they were limited to the effects of tine penetration depth and swing angle. Other factors, such as type of soil, and type of rolling tine may also have effects on the pocket characteristics. The objectives of this study were to examine the effects of soil type, type of rolling tine, swing angle, and penetration depth on the characteristics of soil pockets produced by the AerWay rolling tines in forage fields.

3.3 Materials and methods

3.3.1 Site description

Field experiments were conducted in two forage fields in October 2008 and July 2009. One field (Fig. 3. 1A) had clay loam soil and was located in Piney, Manitoba. The other (Fig. 3. 1B) had sandy soil and was located in Menisino, Manitoba. Both fields had a mix of alfalfa and timothy. Table 3.1 lists the soil composition of the two fields in depths of 0-150 and 150-300 mm.

(A) (B)

Fig. 3. 1. Forage crop growing conditions of the test fields: (A) clay loam field; (B) sandy soil field.

Table 3.1. Summary of soil composition of the experimental sites.

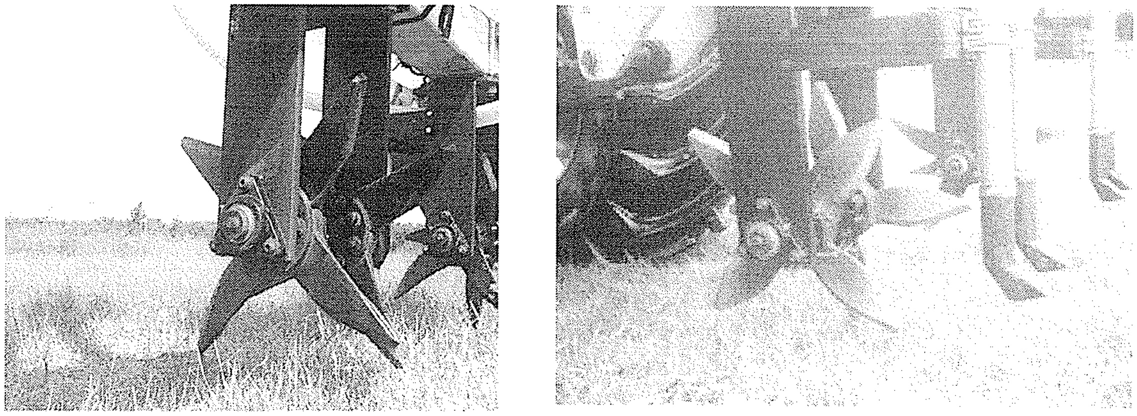
Particle	Clay loam		Sandy soil	
(%)	0-150 mm	150-300 mm	0-150 mm	150-300 mm
Sand	50.89	62.91	67.28	82.49
Silt	24.31	20.72	24.07	12.47
Clay	24.80	16.38	8.65	5.04

3.3.2 Equipment description

A field scale AerWay box frame system (BF) for row crops (Holland Hitch of Canada 2007) was used for the field experiments due to its availability. The toolbar was 4.27 m long and had conventional three-point hitch arrangement and two support wheels (Fig. 3.2). Four box frames were mounted on the toolbar at 1.17 m box spacing. The large box spacing was used to avoid interactions of soil disturbance between rolling tines. Each box had two rolling wheels spaced 0.19 m apart on the shaft. The swing angle could be adjusted between 0 and 5° only. There were no options for other swing angles in the BF system. The liquid tanks and manifold shown in Fig. 3.2 were set up for another field study, and they are not used in the field experiments because this study focused on pocket characteristics only. However, the liquid tanks were filled with water for the purpose of ballasting to facilitate the penetration of rolling tines.

Fig. 3. 2. Set up of field implement.

Two types of the AerWay rolling tines were used: Shatter tine (Fig. 3.3A) and Leaf tine (Fig.3.3B). Shatter tine had a bevelled tip, and Leaf tine had a leaf-like shape. Both tines had the same maximum length (200 mm) and width (13 mm), and thickness (2.5 mm).



(A) (B)

Fig. 3.3. AerWay Rolling tines: (A) Shatter tine; (B) Leaf tine.

3.3.3 Experimental design

Combinations of two types of rolling tines (Shatter tine and Leaf tine), two penetration depths (125 and 150 mm), and two swing angles (0 and 5°) were used as the treatments in each field. The travel speed was kept constant (5 km/h) for all treatments. The plot size was 50 m long and 6 m wide to accommodate one passage of the toolbar. Shatter tines and Leaf tines were mounted on the toolbar side by side during the operation, i.e. Shatter tine and Leaf tine treatments were applied in the same pass of the implement, meaning the experimental factor of tine type was not completely randomized. However, the factors of penetration depth and swing angle were completely randomized and replicated four times; therefore, the total number of plots was 16 (2 penetration depths x 2 swing angles x 4 replications). The plot randomization for each field is shown in Fig.3.4.

125 mm, 5°	150 mm, 5°	150 mm, 5°	150 mm, 5°	150 mm, 0°	150 mm, 0°	125 mm, 0°	125 mm, 0°	150 mm, 5°	150 mm, 0°	150 mm, 0°	125 mm, 5°	125 mm, 5°	125 mm, 5°	125 mm, 0°	125 mm, 0°

Fig. 3.4. The plot layout for the field experiment in both fields; "125 mm, 5°" stands for the treatment with the combination of 125 mm penetration depth and 5° swing angle; each plot included both Shatter tine and Leaf tine treatments.

3.3.4 Measurements

Soil background Soil properties may have effects on the characteristics of soil pockets. Thus, soil moisture content and dry bulk density were measured at the time of the field operations. Soil cores were taken using a core sampler (diameter: 11 mm) at three random locations per site to a depth of 300 mm at 50 mm intervals. For soil bulk density measurements, copper core samplers (diameter: 50 mm) were used to take soil cores at three random locations per site for two depth intervals: 0-150 mm and 150-300 mm. Soil cores were oven-dried at 105 °C for 24 hours to determine the gravimetric soil moisture content and dry soil bulk density (ASABE Standards 2006).

Longitudinal pocket spacing Longitudinal pocket spacing determines the number of pockets per hectare under a given lateral pocket spacing. Longitudinal and lateral pocket spacings are illustrated in Fig. 3.5. Lateral pocket spacing does not need to be measured, because it is equal to the tine spacing on the toolbar. To determine the longitudinal pocket spacing, the number of soil pockets in a 19.8-m distance along the travel direction was counted at five locations per plot following the passes of the AerWay rolling tines.

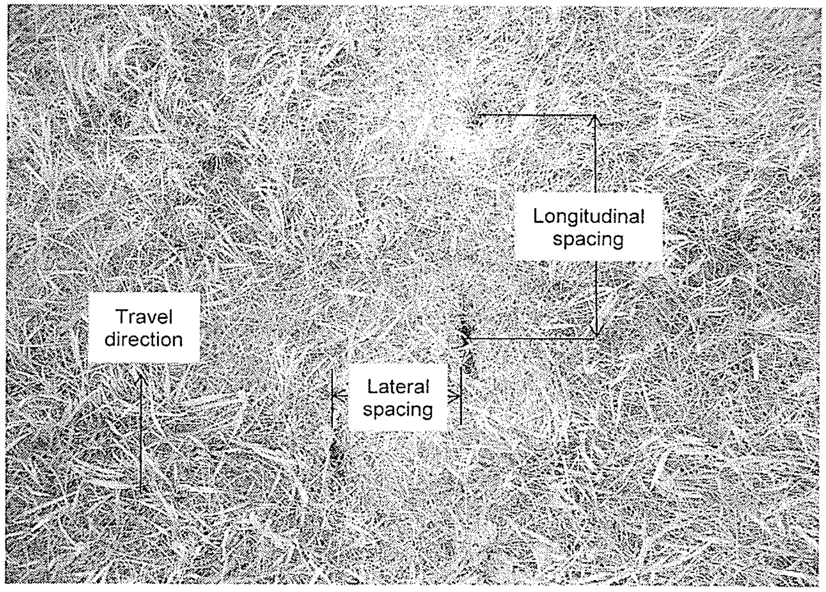
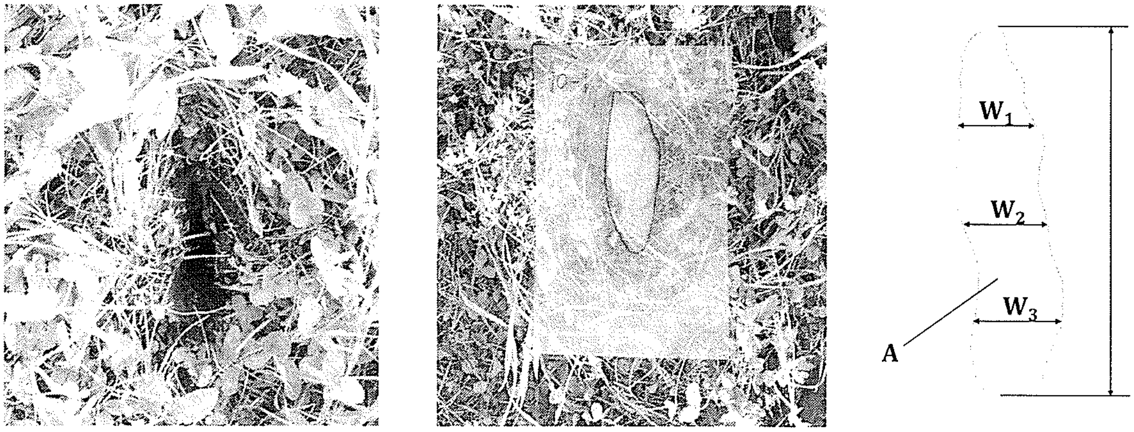


Fig. 3.5. Pockets on soil surface showing the definition of longitudinal and lateral pocket spacings, as well as the travel direction.

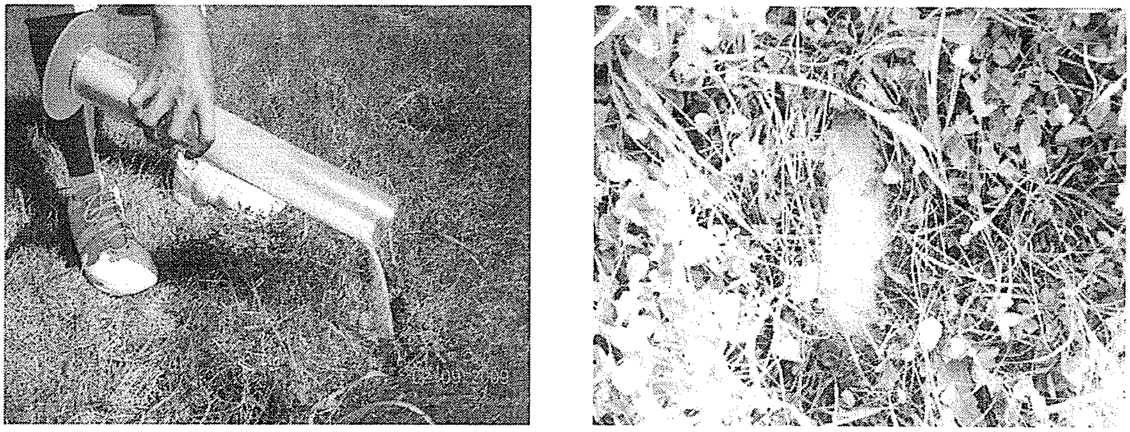
Pocket opening Pocket opening (Fig. 3.6A) was measured at the soil surface level. The boundary of the opening was manually traced using a transparency placed on soil surface (Fig. 3.6B). The boundary of the traced pocket was later digitized to determine the length (L), width (W), and area (A) of the pocket opening (Fig. 3.6C). The L was taken as the maximum distance along the implement travel direction; the W was the average of three widths (W1, W2, and W3) equally distributed lengthwise.



(A) (B) (C)

Fig. 3.6. Measurement of pocket opening at soil surface: (A) top view of soil surface showing a pocket opening; (B) transparency after the pocket opening being traced with a permanent marker; (C) the definitions of the pocket opening length (L), width (W), and area (A).

Pocket volume Pocket volume was measured by pouring dry sand (Soil Industrial Minerals Inc, grade sil-4 D. S. 2000) into a pocket. This type of sand has fine particles and excellent free flowing properties. First, sand was filled into a plastic graduated cylinder (Fig. 3.7A); then it was poured slowly and carefully into the pocket until the pocket was full (Fig. 3.7B). The volume of the pocket was estimated as the difference of graduated cylinder readings before and after pouring.



(A) (B)

Fig. 3.7. Measurement of pocket volume: (A) pouring sand into a pocket using a graduated cylinder; (B) top view of a filled pocket.

3.3.5 Data analysis

ANOVA analysis was performed on data of pocket characteristics. A mixed procedure was used since the factor of tine type was not completely randomised. Means between treatments were compared within a year using Duncan's multiple range tests. The statistical inferences were made at a 0.05 level of significance. When the interactions between the factors of penetration depth and tine angle were significant, simple effects were presented. Otherwise, main effects were presented.

3.4 Results and discussion

3.4.1 Soil background

Table 3.2 summarises the average values of soil moisture content for both soils at the time of the field experiment in 2008 and 2009. In both years, the fields were wet at the time of field operations, except the sandy soil in 2009. The field operations were manageable in all cases due to the low clay content and vegetation in both fields. The moisture content at the 0-50 mm layer of the clay loam was as high as 56% in 2008 and 55% in 2009. The top layer of the sandy soil site had a moisture content of 26% in 2008 (which was high for a sandy soil) and 18% in 2009 which was normal. Soils in both sites were dryer at the greater depths.

Table 3.2. Gravimetric soil moisture content (dry basis) at the time of field experiment.

	2008		2009	
Depth (mm)	Clay loam (%)	Sandy soil (%)	Clay loam (%)	Sandy soil (%)
0-50	56	26	55	18
50-100	40	23	52	13
100-150	48	16	48	13
150-200	31	19	42	13
200-250	41	13	41	10
250-300	33	14	35	11

Values of soil bulk density from two years were consistent within each soil (Table 3.3). For both soil types in both years, the sandy soil had higher bulk densities than the clay loam, and the 150-300 mm depth had higher soil density than the 0-150 mm. All these were expected for typical agricultural fields.

Table 3.3. Soil dry bulk densities at the time of field experiment.

	2008		2009	
	Clay loam	Sandy soil	Clay loam	Sandy soil
Depth (mm)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)
0-150	1.06	1.37	1.08	1.40
150-300	1.14	1.68	1.13	1.66

3.4.2 Longitudinal pocket spacing

Longitudinal pocket spacing was not affected by type of rolling tine, swing angle or soil type, but only by the penetration depth of rolling tine. Overall, there were 44.5 pockets within the 19.8 m measured distance when rolling tines penetrated to 125 mm depth, and there were 45.0 pockets within the same measured distance when rolling tines penetrated to 150 mm. The corresponding longitudinal pocket spacings were 0.445 and 0.440 m. Given the tine spacing was 0.19 m, the AerWay rolling tine would create 118,273 pockets/ha if it worked at a penetration depth of 125 mm, and 119,617 pockets/ha at 150 mm.

The penetration depth influenced the longitudinal pocket spacing due to its relation to the rolling radius of the roller. Increasing penetration depth decreased the rolling radius, which decreased the traveling distance per rotation of the roller. As the result, the smaller longitudinal pocket spacing was the case.

3.4.3 Pocket opening

3.4.3.1 Effects of penetration depth and swing angle

Clay loam The statistical analysis showed that the interaction effects of penetration depth and swing angle were significant for data from the clay loam field. Thus, simple effects of these two experimental factors are presented for this soil. The results of the characteristics of pocket opening were variable, ranging between 91 and 212 mm for the length (L), 12 and 44 mm for the width (W), and 1,088 and 5,555 mm^2 for the area (A), depending on the penetration depth and swing angle (Tables 3.4A and B). In 2008, Shatter tine and Leaf tine showed similar trends, in terms of the treatment effects on the characteristics of pocket opening. For both Shatter and Leaf tines, L was greater for the treatment combinations with the greater penetration depth, regardless of swing angle; whereas W was greater for the treatment combinations with the greater swing angle, regardless of penetration depth. This implied that L was mainly determined by the penetration depth, and W was mainly determined by the swing angle. The greatest L and W were observed at the combination of 150 mm penetration depth and 5° swing angle. As a result, the greatest A was also observed at this combination, since A was related to L and W.

In 2009, characteristics of pocket opening of Shatter tine showed similar trends as in 2008, and the trends of Leaf tine were less pronounced, but did not contradict those in 2008. In general, highest values of characteristics of pocket opening were observed at the combination of 150 mm penetration depth and 5° swing angle. This further confirmed that the AerWay rolling tines created the larger soil pocket opening when they worked at the greater penetration depth and swing angle in the clay loam soil.

Table 3.4A. Shatter tine - means and standard deviations (SD) of characteristics of pocket opening in the clay loam soil.

Year	Treatment		Pocket opening					
	Penetration depth (mm)	Swing angle (°)	Length, L (mm)		Width, W (mm)		Area, A (mm^2)	
			Mean	SD	Mean	SD	Mean	SD
2008	125	0	150b*	11	25c	11	2413b	765
	125	5	112c	8	30b	14	2396b	663
	150	0	182a	14	18d	8	2093b	760
	150	5	182a	14	44a	21	5555a	1761
2009	125	0	168B	14	20B	13	3326B	1113
	125	5	162B	14	25A	16	4002B	1340
	150	0	212B	18	20B	13	4128B	1382
	150	5	176A	15	25A	16	4432A	1484

*Values in the same column and the same year followed with different lower case or uppercase letters were significantly different.

Table 3.4B. Leaf tine - means and standard deviations (SD) of characteristics of pocket opening in the clay loam soil.

Year	Treatment		Pocket opening					
	Penetration depth (mm)	Swing angle (°)	Length, L (mm)		Width, W (mm)		Area, A (mm^2)	
			Mean*	SD	Mean	SD	Mean	SD
2008	125	0	110c	7	17b	5	1216c	467
	125	5	91c	6	27a	7	1703b	659
	150	0	156b	9	20b	5	1088c	421
	150	5	205a	12	27a	7	3212a	1244
2009	125	0	165B	14	12B	1	1927B	1113
	125	5	180A	14	15A	2	2383B	1340
	150	0	176A	18	15A	1	2748A	1382
	150	5	187A	15	14AB	2	2824A	1484

*Values in the same column and the same year followed with different lower case or uppercase letters were significantly different.

Sandy soil For the sandy soil, the interactions of penetration depth and swing angle were not significant; thus, the main effects are presented. Pockets in the sandy soil had also variable characteristics (149-208 mm for L, 9-22 mm for W, and 1,200-4,033 mm^2 for A), depending on the treatments (Tables 3.5A and B). In 2008, Shatter tine working at the 150 mm depth created a significantly greater L, so did Leaf tine although it was not significant. The L for the 150 mm depth was approximately 18% greater than that that for the 125 mm. Swing angle of rolling tine had no effects on L in both cases of Shatter and Leaf tines. However, swing angle significantly affected W. There was an approximately 45% increase in W when using the 5° angle as compared with using the 0° angle. In the case of W, penetration depth had no effects. In 2008, neither penetration depth nor swing angle made significant difference in A.

In 2009, the aforementioned trends of treatment effects for 2008 were also true. But L was slightly decreased when the greater depth was used, but it was not significantly different. W was slightly increased when the greater swing angle was used. No treatment differences were observed for A.

Table 3.5A. Shatter tine - means and standard deviations (SD) of characteristics of pocket opening in the sandy soil.

Year	Treatment	Pocket opening					
		Length, L (mm)		Width, W (mm)		Area, A (mm^2)	
		Mean	SD	Mean	SD	Mean	SD
2008	Penetration depth (mm)						
	125	171b*	19	19a	2	2570a	868
	150	202a	22	18a	2	2570a	942
	Swing angle (°)						
	0	196a	21	15b	2	2253a	760
	5	177a	19	22a	2	3107a	1049
2009	Penetration depth (mm)						
	125	208A	44	19A	3	3540A	1582
	150	194A	41	19A	2	3557A	1605
	Swing angle (°)						
	0	200A	43	18A	2	3145A	1378
	5	200A	42	20A	3	4033A	1518

*Values within each experimental factor followed with different lower case or uppercase letters were significantly different.

Table 3.5B. Leaf tine - means and standard deviations (SD) of characteristics of pocket opening in the sandy soil.

Year	Treatment	Pocket opening					
		Length, L (mm)		Width, W (mm)		Area, A (mm^2)	
		Mean	SD	Mean	SD	Mean	SD
2008	Penetration depth (mm)						
	125	149a*	12	12a	1	1200a	851
	150	177a	14	11a	1	1382a	979
	Swing angle (°)						
	0	171a	13	9b	1	1216a	861
	5	155a	12	13a	1	1367a	969
2009	Penetration depth (mm)						
	125	198A	63	12A	3	2435A	234
	150	190A	60	13A	3	2432A	234
	Swing angle (°)						
	0	199A	63	12A	3	2209A	234
	5	189A	60	13A	3	2428A	233

*Values within each experimental factor followed with different lower case or uppercase letters were significantly different.

3.4.3.2 Comparisons between types of rolling tine and soil

Results from 2008 Comparisons were made in L, W, and A of pocket opening between types of rolling tine within each soil. A greater L was observed for Shatter tine than for Leaf tine in both soils, although the difference was not statistically significant (Fig. 3.8A). Values of W were also greater for Shatter tine than for Leaf tine (Fig. 3.8B). This was significant in the sandy soil. As a result of greater L and W of Shatter tine, its pocket openings had significantly larger A in both soils (Fig. 3.8C). The pocket opening for both tines in the clay loam had smaller L (Fig. 3.8A), greater W and A (Figs 3.8B and C), than in the sandy soil. This indicated that pockets in the sandy soil were longer and narrower, and their openings were smaller, in terms of the area.

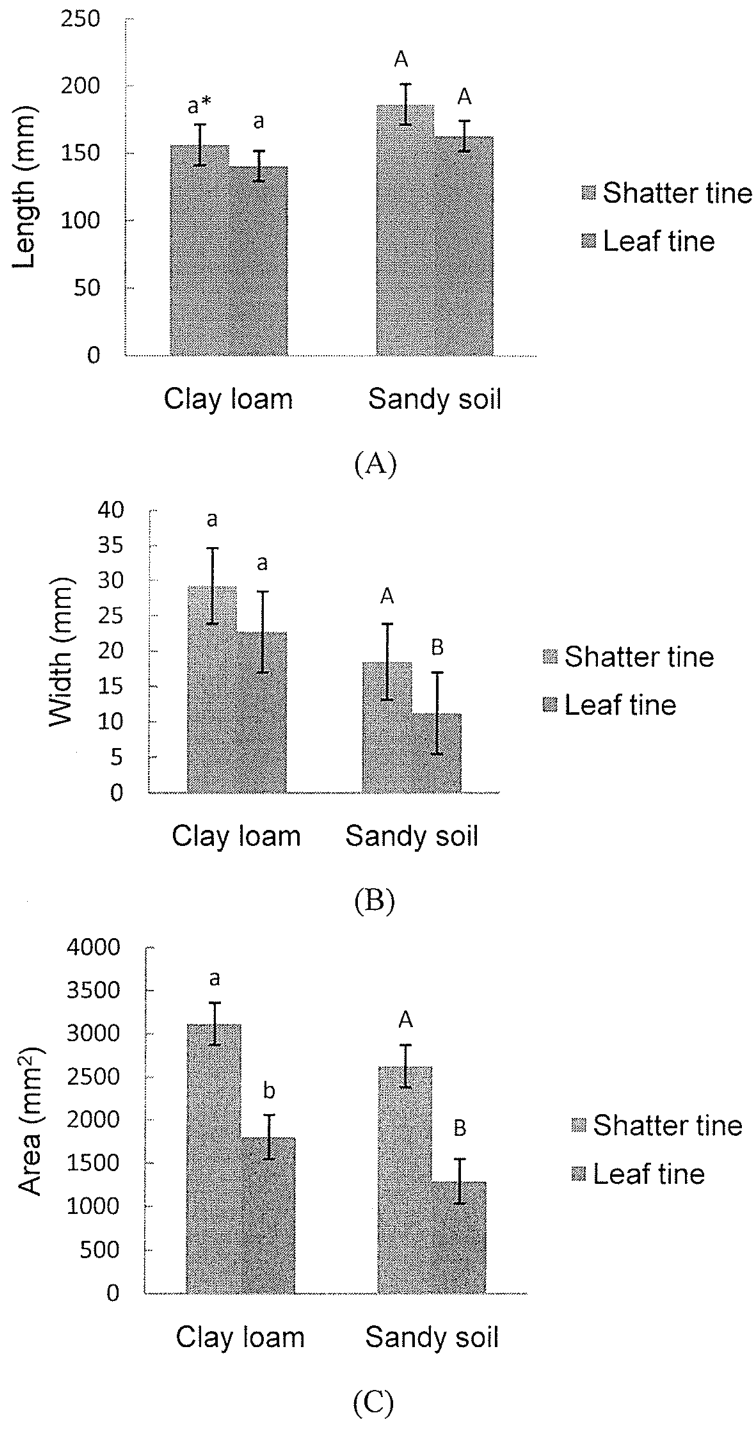
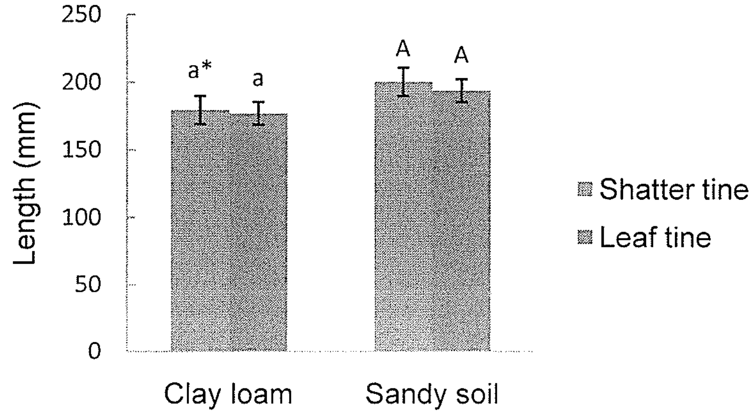
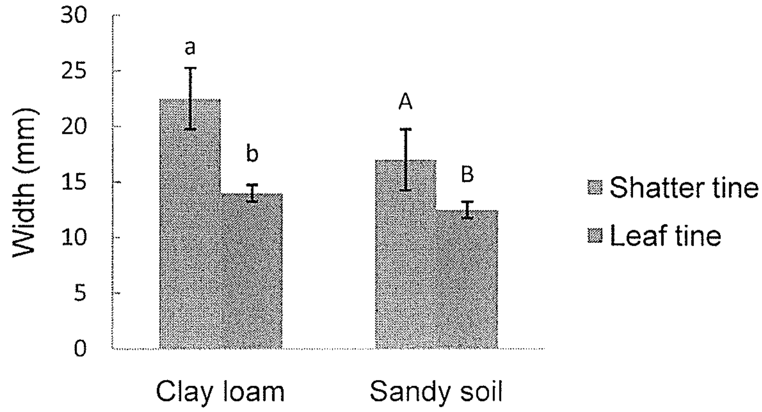


Fig. 3.8. 2008 - comparisons in pocket opening between types of rolling tine and soil: (A) length (L); (B) width (W); (C) area (A). *Means (with standard errors) followed with different lower case or upper case letters were significantly different.

Results from 2009 In 2009, slightly greater L was found for Shatter tine when compared to Leaf tine (Fig. 3.9A). Shatter tine had significantly greater W and A (Figs 3.9B and C). In regards to the effect of soil types, the sandy soil showed greater L, and smaller W and A. All of these trends were consistent with those in 2008.



(A)



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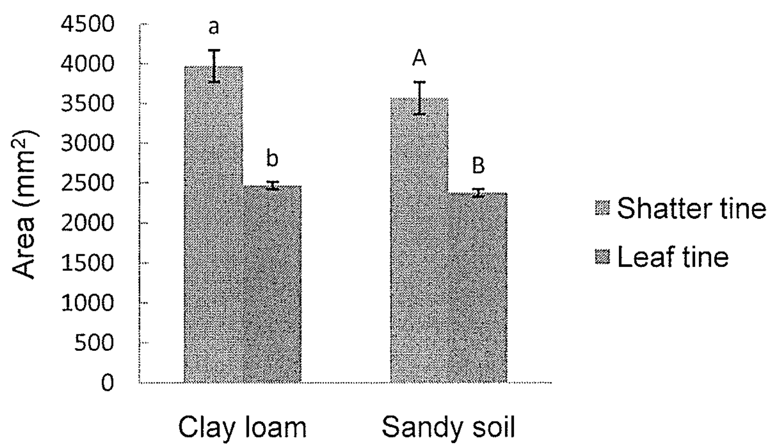


(C)

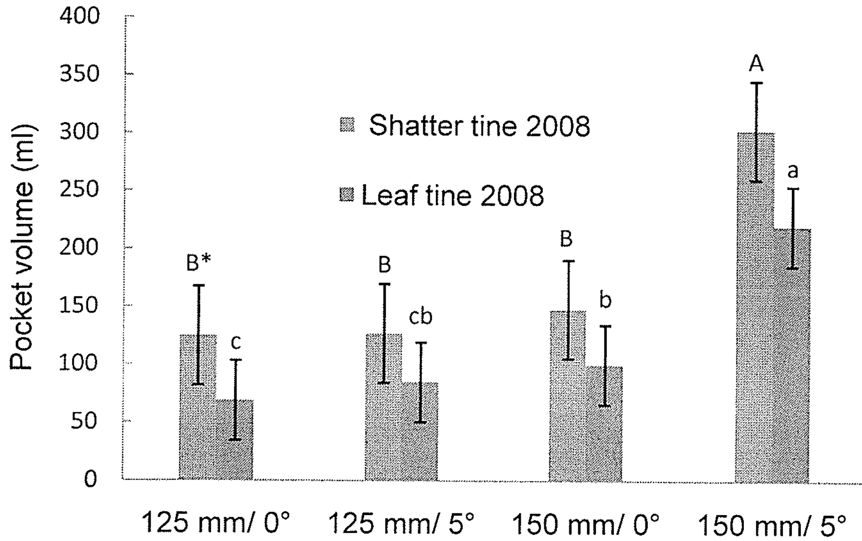
Fig. 3.9. 2009 - comparisons in pocket opening between types of rolling tine and soil: (A) length (L); (B) width (W); (C) area (A). *Means (with standard errors) followed with different lower case or upper case letters were significantly different.

The results of pocket opening have several potential implications. Greater pocket opening dimensions favour liquid placement into the pocket. More specifically, a greater W will reduce the risk of manure being placed on soil surface by the pulsing meter, and a greater L will give the pulsing meter more time to deliver manure over a pocket. Given these implications, the results from this study implied that the greater penetration depth and larger swing angle are desired for pocket injection. Shatter tine has advantage over Leaf tine, and clay loam is more suitable for pocket injection. Swing angles larger than 5° could be used in some other AerWay systems (such as the SSD system), which is expected to produce wider pocket opening.

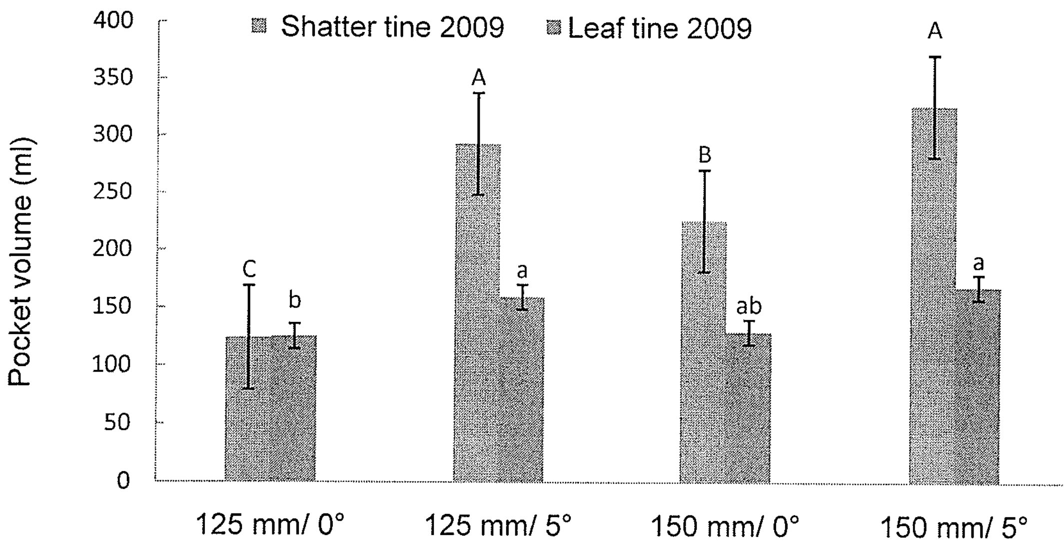
3.4.4 Pocket volume

Clay loam soil For data from the clay loam soil, simple effects of the experimental factors are presented due to the significant interactions of the experimental factors. At the combination of 150 mm/5°, the pocket volume was 303 ml for Shatter tine and was 220 ml for Leaf tine in 2008 (Fig. 3.10A). These pocket volumes were higher than those of the other three treatment combinations which had similar pocket volumes: 176 ml (Shatter tine) and 119 ml (Leaf tine) on average. Overall, Shatter tine had 48% greater pocket volume when compared to Leaf tine.

In 2009, treatment effects on pocket volume showed different trends with those in 2008. For Shatter tine, the treatments of 125 mm/5° and 150 mm/5° had the greater pocket volumes (293 and 327 ml, respectively), followed by 150 mm/5° (226 ml) and 125 mm/0° (124 ml) (Fig. 3.10B). This implied that the swing angle contributed more to the pocket volumes than the penetration depth. For Leaf tine, similar conclusions could be drawn, but the trends were less pronounced as compared with Shatter tine. Again, the overall pocket volume of Shatter tine was higher than that of Leaf tine, and Shatter tine resulted in a 67% increase in pocket volume.



(A)



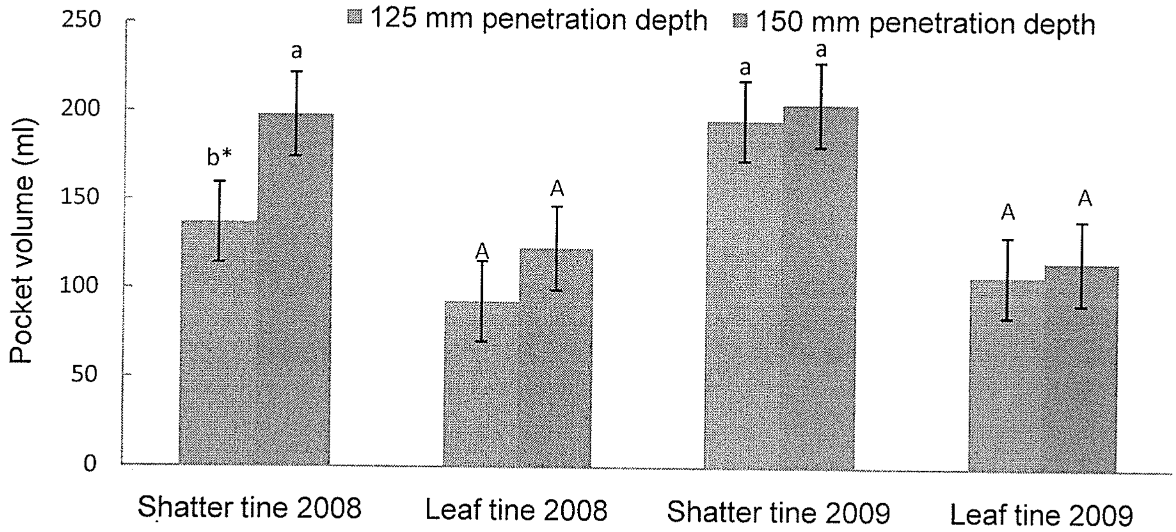
(B)

Fig. 3.10. Clay loam - pocket volumes for different combinations of penetration depth and swing angle: (A) 2008; (B) 2009. *Means (with standard errors) follow with different lower case or upper case letters were significantly different.

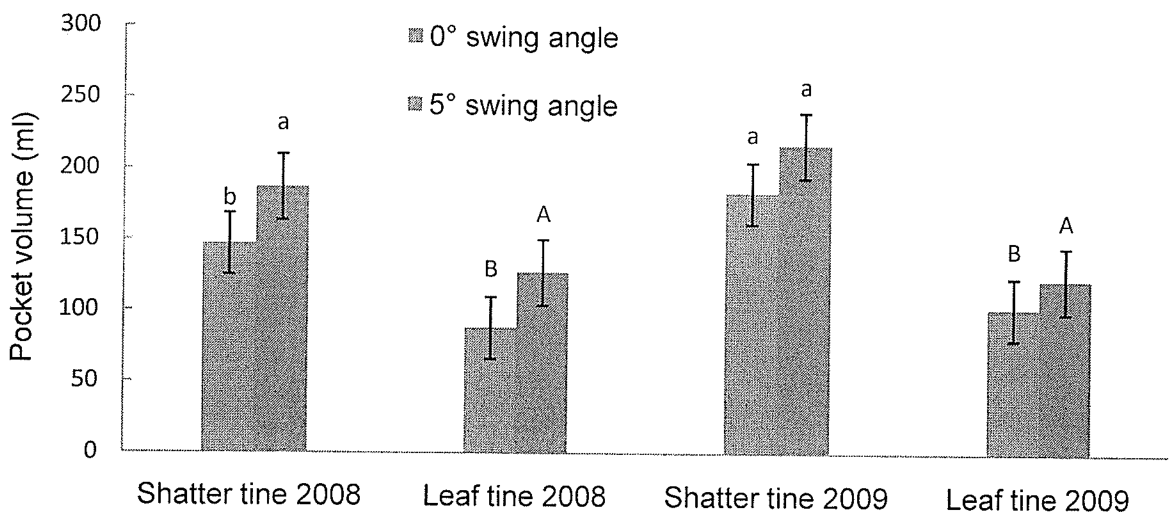
Sandy soil For the sandy soil, the interactions of the treatments were not significant, and main effects of the treatments are presented. Data from two years were fairly consistent. The mean pocket volumes in the sandy soil, varying between 93 and 205 ml, were lower than those in the clay loam (Fig. 3.11A). In both 2008 and 2009, rolling tines operated at the greater penetration depth created larger pocket volumes, as expected. With Shatter tine, 80% higher pocket volumes, averaged over two years, was observed if it worked at the 150 mm depth as compared with the 125 mm. This difference in pocket volume between the two depths was statistically significant. For Leaf tine, 10% higher pocket volume was also observed at the greater depth, although the differences were not statistically significant. With the same penetration depth and swing angle, Shatter tine created larger volume than Leaf tine.

As expected, larger swing angle resulted in higher pocket volume, observed in both 2008 and 2009 (Fig. 3.11B). Over two years, a 30% increase in pocket volume was found for Shatter tine, while a 37% increase was found for Leaf tine. Again, effects of swing angle in the case of Shatter tine were statistically significant.

The results for pocket volume were comparable with those from Knauf (2005), who reported that the pocket volume from Shatter tines varied between 130 and 300 ml for penetration depths from 100 mm to 150 mm with 0° to 7.5° swing angles on a clay loam soil. Turpin et al. (2007) reported a greater range of pocket volume (361-565 ml) for Shatter tines in a clay loam soil with a maximum swing angle setting (10°) and 130 mm penetration depth.



(A)



(B)

Fig. 3.11. Sandy soil - pocket volumes for different combinations of penetration depth and swing angle: (A) 2008; (B) 2009. *Means (with standard errors) follow with different lower case or upper case letters or different years were significantly different.

The results of pocket volume have very important implications to pocket injection. Pocket volume determines the maximum pocket rate and therefore the maximum manure application rate. Application rate can be estimated by the following equation:

$$R = \frac{v\,n}{1000} \tag{3.1}$$

where

v = pocket volume (ml/pocket);

R = application rate (L/ha);

n = the number of pockets per hectare of field (pocket/ha).

Given the pocket characteristics measured for the AerWay rolling tines in this study, the potential field application rates of the AerWay were estimated and summarized in Table 3.6. Using AerWay rolling tines for pocket injection, up to 24,521 L/ha can be applied to the sandy soil, and up to 39,115 L/ha can be applied to the clay loam soil.

Table 3.6. Estimated ranges of application rates with the AerWay rolling tines for pocket manure injection.

Soil	Pocket volume (ml)	Number of pockets (pockets/ha)	Liquid application rate (L/ha)
Clay loam			
Min.	124	118,273	14,666
Max.	327	119,617	39,115
Sandy soil			
Min.	93	118,273	10,999
Max.	205	119,617	24,521

3.5 Conclusion

The longitudinal pocket spacing resulting from AerWay rolling tines changed slightly when the rolling tines worked at different penetration depths. For both Shatter and Leaf tines, a longitudinal pocket spacing of 445 mm was found for the 125 mm penetration depth, and 440 mm was found for the 150 mm.

The length of pocket opening varied between 91 and 212 mm, the width varied between 9 and 44 mm, and the area varied between 1,088 and 5,555 mm^2, depending on the type of soil, type of rolling tine, penetration depth, and swing angle. The length of pocket opening was mainly determined by the penetration depth of rolling tine, with greater depth resulting in a longer pocket opening; the width was mainly determined by the swing angle, with larger swing angle producing a wider pocket opening. When compared with Leaf tine, Shatter tine created shorter and wider pocket opening, and larger opening area. The clay loam soil favoured larger pocket opening when compared to the sandy soil, regardless of other treatments. Among the treatments used in this study, the largest pocket openings were found when Shatter tines worked at the 150 mm penetration depth and the 5° swing angle in the clay loam soil.

Pocket volumes (between 124 and 327 ml) measusred in the clay loam soil were larger than those (between 93 to 205 ml) in the sandy soil. On average, Shatter tine created 52% higher pocket volume. In the clay loam soil, the largest pocket volumes were observed at the combination of 150 mm penetration depth and 5° swing angle for both Shatter tine and Leaf tine. In the sandy soil, the 150 mm depth resulted in larger pocket volumes than the 125mm; the 5° swing angle resulted in the larger pockets than the 0° swing angle

Characteristics of pocket opening have impact on manure placement and the environmenal consequence such as manure exposure on soil surface. Information on pocket longtudinal spacing and pocket volume determines the potential manure application rate. According to the results from this study, the AerWay Shatter tines may be a better choice for pocket injection among the two tine types studied. The Aerway rolling tines may be operated, if possible, at penetration depth and swing angle as great as practical, which will benefit higher manure application rates and reduced manure exposure on soil surface. Further research on swing angles larger than 5° and different travel speeds is recommended.

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3.7 References

ASABE Standards. 2006. ASABE Standards. St. Joseph, MI: ASABE.

Bittman, S., L. J.P. van Vliet, C.G. Kowalenko, S. McGinn, D.E. Hunt and F. Bounaix. 2005. Surface banding liquild manure over aeration slots: A new low disturbance method for reducing ammonia emissions and improving yield of perennial grasses. *Agronomy Journal* 97(5): 1305-1313.

Chen, Y. and E. Leafloor. 2006. Liquid Fertilizer Injection System, Method and Apparatus. *Canadian and US Patent offices*: PCT/CA2005/000560.

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., J. Wylde and S. Ai. 2009. Pre-commercialisation of a pulsing meter for liquid manure injection in forage fields. Project Report. Submitted to ACAAF Program Agriculture Agri-Food Canada, Ottawa, ON, Canada.

Chen, Y., Q Zhang and D.S. Petkau. 2001. Evaluation of different techniques for liquid manure appliaion on grassland. *Applied Engineering in Agriculture* 17(4): 480-496.

Daverede, I.C., A.A. Kravchenko, R.G. Hoeft., E.D. Nafziger, D.G. Bullock., J.J. Warren and L.C. Gonzini. 2004. Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. *Journal of Environment Quality* 33: 1535-1544.

Gilley, J.E., and L.M. Risse, 2000. Runoff and soil loss as efectd by the application of manure. *Transactions of the ASAE* 43(6): 1583-1588.

Gilley, J,E., B.Eghball, J.M. Blumenthal and D.D. Baltensperger. 1999. Runoff and erosion from interfill area as affected by the application of manure. *Transactions of the ASAE* 42: 975-980.

Hanna, H.M, D. S. Bundy, J.C. Lorimor, S.K. Mickelson, S.W. Melvin and D.C. Erbach. 2000. Manure incorporation equipment effects on odour, residue cover, and crop yield. *Applied Engineering in Agriculture* 16: 621-627.

Harrigan, T. M., W. Northcott, A. Kravchenko, and A. Thomas. 2004. Time-series analysis of sediment and bacterial transport from manure applied land following aeration tillage. ASAE Paper No. 042200. St.Joseph, Mich.: *ASAE.*

Holland Hitch of Canada. 2007 AerWay SSD Manure Management Systems. Holland Equipment Limited Brochure No. XL-AW290-01.

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

Knauf, T.A. 2005. The AerWay SSD as a resource management tool in manure management and nutrient recycling, Prepared for Holland Equipment Ltd., Norwich, ON Canada.

Lau, A., S. Bittman, and G. Lemus. 2003. Odor measurements for manure spreading using a subsurface deposition applicator. *Journal of Environ. Sci. Health Part B* 38: 233-240.

Leafloor, E. 2004. Design of Machine for Grassland Injection of Liquid Manure. Undergraduate Thesis, Department of Biosystems Engineering, University of Manitoba, Canada.

McLaughlin, N.B., Y.X. Li, S. Bittman, D.R. Lapen, S. Burtt and B.S. Patterson. 2006. Draft requirements for contrasting liquid manure injection equipment. *Canadian Biosystems Engineering* 48: 2.29-2.39.

Mueller, D. H., R.C. Wendt, and T.C. Daniel. 1984. Soil and water losses as affected by tillage and manure application. *Soil Science Society of America Journal* 48: 896-900.

Rotz, C.A., P. Kleinman, C. Dell, J. Schmidt and D. Beegle. 2007. Environmental and Economic Comparisons of Manure Application Methods on Dairy Farms. *2007 ASABE Annual International Meeting*, ASABE17 - 20 June 2007, Minneapolis, Minnesota.

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): 33-40.

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

Turpin, K.M., D.R. Lapen, M.J.L. Robin, E. Topp, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B.Ball Coelho and M. Payne. 2007. Slurry-application implement tine modification of soil hydraulic properties under different soil water content conditions for silt –clay loam soils. *Soil & Tillage Research* 95: 120-132.

Van Vliet, L.J.P., E.A. Kenney. 2000. Reducing the risk of surface water contamination from manure grassland using a soil aerator. 1999/2000 Final progress Report from environment Canada. March 15, 2000. Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre. Agassiz. BC.

Wu, B. and Y. Chen. 2009. Modeling liquid distribution in soil following pocket injection. Manuscript submitted to *Journal of Environmental Quality.*

CHATER 4: MEASUREMENTS OF SOIL POCKET SHAPE AND LIQUID DISTRUTION IN SOIL FOLLOWING POCKET INJECTION

4.1 Abstract

Measurements of soil pocket shape and liquid distribution in soil following pocket injection are required to assess the agronomic and environmental impact of pocket injection and to develop, improve, and validate models on manure movement in soil following pocket injection. Field measurements were carried in the experiment described in Chapter 3. The selected treatments were AerWay Shatter tines operated at 150 mm injection depth and 5° swing angle in both clay loam and sandy soils. Pocket shape was measured by pouring plaster and cement into pockets to make casts. Then, mathmatical equations were extracted from the casts which describe the pocket shapes. Liquid-soil mix zones were measured using dye tracers. Soil liquid content near a soil pocket (75 mm away from the pocket in the lateral direction) was measured at 50 and 100 mm depths, following placement of water into a pocket. The results showed that measurements of pocket shape and liquid-soil zone measurements were successful. Regardless of soil type, the top, back, and side views of the pocket were best described by an ellipse, trapezoid, and second order polynomial curves, respectively. The liquid-soil mix zone areas of the sandy soil were fairly consistent over two years, with the average zone area of 18,343 mm^2. The zone area in the clay loam was 22% larger in 2008 and 56% larger in 2009. Liquid movement around a soil pocket at both 50 and 100 mm depths as indicated by the increasing trends in soil liquid content over time. This however lasts only approximately 250 s. After that, the liquid content regained nearly

constant.

Keywords: AerWay, Shatter tine, soil, pocket, shape, dye tracer, liquid, distribution.

4.2 Introduction

Liquid manure is a valuable fertilizer resource, and land application of liquid manure is a sustainable practice. In the past, most liquid manure was applied to annual crops. Due to the high cost of chemical fertiliser, forage fields receive little or no fertilizer. This limits the production potential of forage fields. Forage crop requires large amount of nitrogen. Thus, applying some manure to forage field will be a viable alternative of manure management.

Of all liquid manure application methods, such as injection, broadcasting, surface banding, and surface spreading with incorporation, injection method is recommended to reduce odour and ammonia emissions as well as surface runoff of manure nutrient (Schmitt et al. 1995; Hanna et al. 2000; Smith et al. 2000; Van Vliet and Kenney 2000; Huijsmans et al. 2003; Daverede et al. 2004). Injection of liquid manure can be achieved using tillage tools, such as sweeps, discs, and chisels. These tools work in annual crop systems, as soil disturbance is not a concern in annual crop systems. They may not be suitable for injecting manure in forage fields due to their high soil disturbance which may damage the forage crops. Thus, low soil disturbance injectors are required for forage fields.

Among a number of methods for liquid manure injection in forage fields, pocket injection method causes relatively low soil disturbance, which is desired for forage field applications. Pocket injection method was proposed by Leafloor (2004), Chen and Leafloor (2006), and Wu and Chen (2009). Pocket injection can be performed using an aerator which creates soil pockets and a special manure delivery device, such as the pulsing meter developed for delivering manure in pocket injection by Chen et al. (2009). The pulsing meter was designed to deliver pulses of liquid with each pulse being placed into a soil pocket created by an aerator.

Nutrient distribution in soil after manure injection depends partially on how manure was distributed in the soil. Thus, manure distribution in soil affects the nutrient uptake by the crop. Since manure is placed in pockets in the pocket injection method, there is a possibility of a lack of nutrients in between pockets. Therefore, the information on manure movement in soil is important for pocket injection. Moreover, manure distribution in soil is useful information for arranging rolling tines on the toolbar, in terms of tool spacing. Appropriate tool spacings ensure even nutrient distributions in soil.

Little research has been carried out on manure movement in soil following injection. Few experimental studies were found on manure-soil mix zone following a furrow injection. Chen and Ren (2002) and Rahman et al. (2004) manually measured the maximum lateral and vertical spreads of manure-soil mix zone in clay soil following furrow injection. Rodhe (2003) studied the placement of manure in the upper soil layer using visual assessment and image analysis. These measurements had to be performed immediately following manure injection because manure zone is hard to see when the soil is wet. Also, manure zone in soil may disappear quickly. To solve this problem, dye tracers were added into manure for the measurements (Weiler and Fluhler 2004; Turpin et al. 2007). For example, Hanna et al. (1998) used dye to trace the amount of manure on the soil surface and to measure the centroid of the manure zone in soil. Rahman et al. (2005) used such a blue dye in measuring water-soil mix zone in a laboratory soil bin study. German-Heins and Flury (2000) indicated that Brilliant Blue is a good dye tracer to study water flow processes in the vadose zone in terms of toxicity, mobility, and visibility. This method should be tested in different soil types.

The literature showed that measurement of manure distribution in soil, regardless of the method used, is time consuming. Thus, modeling approach has been suggested by Rahman et al. (2008). Rahman et al. (2008) modeled liquid manure flow and redistribution in soil following furrow injection. Lately, Wu and Chen (2009) initiated modeling work for pocket injection. The model required a known volume and a known shape of pocket which was located in the model domain. As the information on pocket volume and shape was not available, an assumption of pocket shape as a triangular prism was made, which does not represent actual field pocket. In measuring manure-soil mix zone which was required to validate the model, Wu and Chen (2009) manually created pockets in fields. Those pockets would not be the same as those resulting from field rolling tines. Wu and Chen (2009) concluded that using field data of pocket shape in the model would definitely improve the model predictions.

In summary, the information of manure movement in soil has ergonomic and environmental implications. This information, together with that of pocket characteristics, is also required for setting appropriate tine spacing and for modeling of liquid movement following pocket injection. However, little research has been done in these aspects. The primary objectives of this study were to measure (1) shape of soil pocket resulting from AerWay Shatter tines, (2) liquid-soil mix zone following pocket injection, and (3) the change in soil liquid content over time following pocket injection. The secondary objective was to explore suitable techniques for these measurements.

4.3 Materials and methods

4.3.1 Field conditions and operations

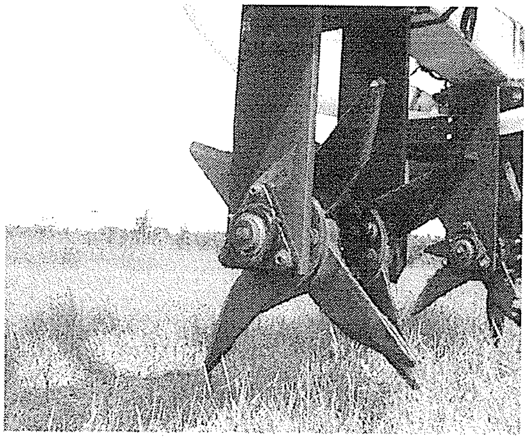
Field measurements were performed within the experiment described in Chapter 3. The following is a brief summary of that experiment. An AerWay aerator equipped two types of rolling tines (Shatter tine and Leaf tine) was operated at two swing angles (0° and 5°) and two penetration depths (125 and 150 mm). The experiment was conducted in two forage fields in October 2008 and July 2009.

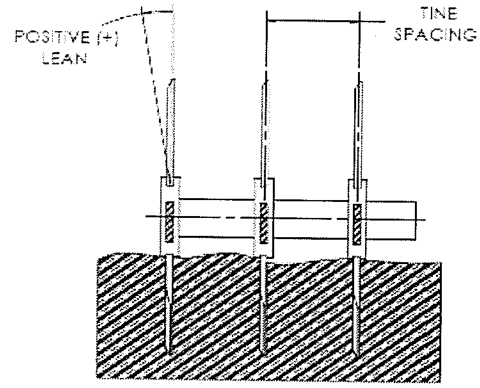
4.3.2 Scope of the measurements

The results from Chapter 3 showed that AerWay Shatter tines arranged at the 5° swing angle and operated at the 150 mm penetration depth produced the largest soil pockets among all treatments. This treatment favours pocket injection, in terms of maximizing the application rate and minimizing manure exposure on soil surface. Therefore, the field measurements described in this Chapter were conducted only on those pockets resulting from this treatment.

4.3.3 Shatter tine and its parameters

Shatter tine had a bevelled tip (Fig. 4.1A). Its rotation direction was such that the bevelled edge penetrated soil first. The maximum length of the tine (from the hub to the tip) was 200 mm and the maximum width was 80 mm, and the thickness was 13 mm. Tines were arranged on the shaft with a twist angle (tine twisted around its axis) and a lean angle (tine leaned away from the vertical line) (Fig. 4.1B). The design and operation parameters of Shatter tine are summarised in Table 4.1.





(A) (B)

Fig. 4.1. AerWay rolling tines: (A) Shatter tine; (B) lean angle (Holland Hitch of Canada 2007).

Table 4.1. Design and operation parameters of Shatter tine used in the field measurements.

Parameter	Values
Maximum tine length	200 mm
Maximum tine width	80 mm
Tine thickness	13 mm
Tine bevel angle	36°
Lean angle	2.5°
Twist angle	8°
Swing angle	5°
Penetration depth	150 mm

4.3.4 Field measurements

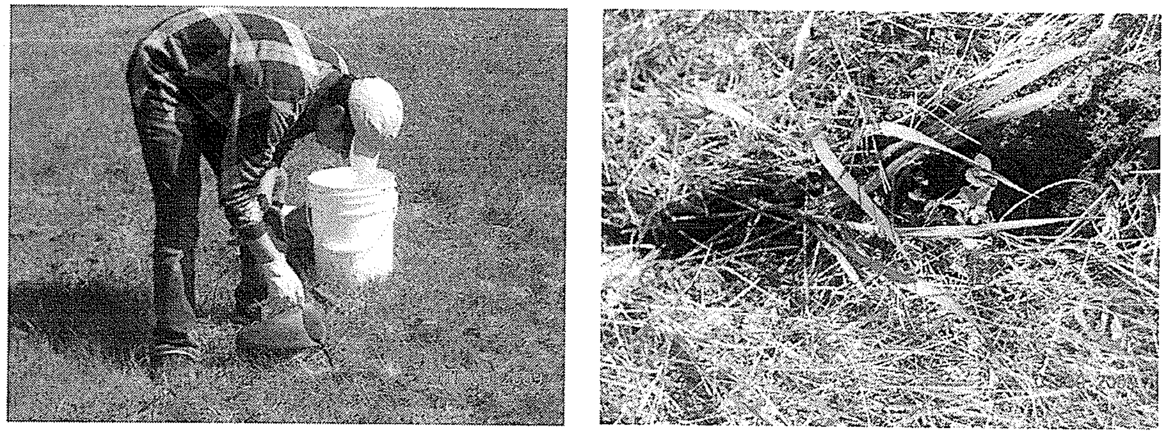
Pocket shape Pocket shape was measured by making casts using plaster in 2008 and cement in 2009. The first step was mixing plaster or cement with appropriate amount of water to obtain free flow plaster or cement slurry with free of big air bubbles (Fig. 4.2A). Immediately following rolling tine operations, the slurry was poured into pockets (Fig. 4.2B). Casts were formed after the slurry became solid; then the castes were dug out and kept for later analysis on pocket shapes. This measurement was performed in each field for 2 pockets from the plot of Shatter tine/150 mm penetration depth/5° swing angle.

(A) (B)

Fig. 4.2. Pocket shape measurements: (A) cement slurry; (B) cement slurry being poured into a pocket.

Liquid-soil mix zone Water was used to simulate liquid manure. This was supported by the following results in the literature. Flow of animal slurry was Newtonian at solids content below 5% (Kumar et al. 1972). Manure with 0% to 5% solid content has consistency and flow characteristics similar to water (Extension 2008). The solid content of liquid manure is normally lower than 5%. Thus, water flow in soil can be considered to represent manure flow in soil (Rahman et al. 2008; Assefa and Chen 2008).

Liquid-soil mix zone was measured with dyed water. The Brilliant Blue FCF dye (product no. 05601, Warner Jenkinson Co. Inc. 2526 Baldwin Street St. Louis, MO 63106) was added to water at a concentration of 5 g l^{-1}. To simulate pocket injection, dyed water was poured quickly into a pocket (Fig. 4.3A). The volume of the dyed water was predetermined to be equal to the average pocket volume of the treatment obtained from Chapter 3. The infiltration status of dyed water in the pocket (Fig. 4.3B) was watched closely. After the dyed water completely infiltrated into the surrounding soil of the pocket, a cross-section of soil (perpendicular to the travel direction) was excavated. The boundary of the liquid-soil mix zone, of the blue dye, was traced on a transparency with a permanent marker. The boundary was later analysed for the characteristics of liquid-soil mix zone. Measurements were performed for 5 pockets randomly selected from the plot of Shatter tine/150 mm penetration depth/5° swing angle.

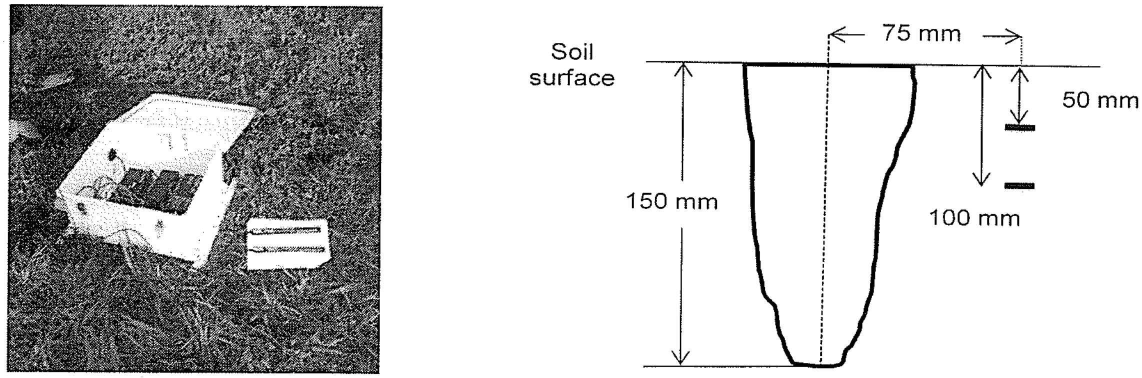


(A) (B)

Fig. 4.3. Liquid-soil mix zone measurements: (A) dyed water being poured into a pocket; (B) pocket filled with dyed water.

Change in liquid content over time This measurement was to examine liquid movement in soil following pocket injection, through monitoring the soil liquid content around a pocket over time. Soil liquid content was measured with two ECHO soil moisture sensors and a datalogger (Fig. 4.4A). The ECHO soil moisture sensor measured the water content through measuring the dielectric constant of the soil. The ECHO sensor measurement time was 10 ms with accuracy of approximately 3%; signals of the soil sensors were recorded with a Campbell data logger (CR10X, 11564 - 149th Street NW Edmonton, AB T5M 1W7 CANADA).

Immediately following the passage of Shatter tines, a random pocket from the plot of Shatter tine/150 mm penetration depth/5° swing angle was selected. Two ECHO sensors were buried 75 mm away from the centre line of a pocket at 50 and 100 mm injection depths as illustrated in Fig. 4.4B. To bury the sensors, certain amount of soil had to be excavated and back filled after. This soil disturbance was not desired, but was unavoidable. Again, water was used to simulate liquid manure. After the burial of the ECHO sensors, predetermined volume of water was poured into the pocket. Recording was commenced at the same time of water pouring and stopped approximately after 24 hours. It was expected that liquid movement in soil would be more rapid at the beginning and slow down over time. Thus, the data logger was programmed to record the data every second in the first 30 min, every minute from 30 min to 60 min, and every hour afterwards.



(A) (B)

Fig. 4.4. Measurements of soil liquid content around a pocket; (a) Data logger and two ECHO sensors; (b) diagram showing the locations of ECHO sensors relative to a pocket in a soil cross-section.

4.3.5 Data analysis

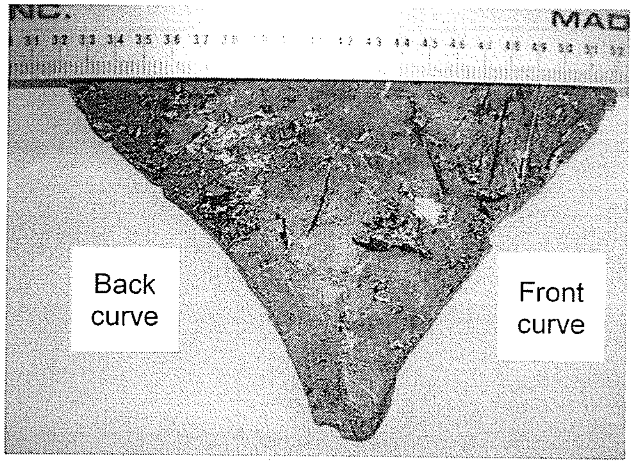
Analysis of variance (ANOVA) was performed to determine the effects of tine types within each soil. Means were compared using Duncan's multiple range tests at a significance level of 0.05. This was done only on data of liquid-soil mix zone, due to the limited numbers of the other data.

4.4 Results and discussion

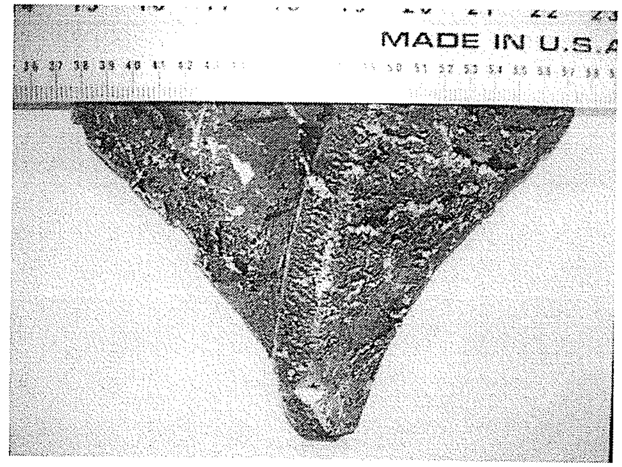
4.4.1 Pocket shape

The measurement technique using casts proved to be successful. Plaster gave smoother casts than cement, but plaster casts were easier to break. The best formed casts were obtained in the clay loam in 2008, when the soil was wet and showed plastic behaviour. Pocket shape was characterised using mathematical equations based on the shape of the casts obtained from the field measurements. Due to the irregularity of the cast shape, separate equations were used for the top, back, and side views of cast, as described below.

Side view Side view (projected from the side of the tractor) was the broad view of pocket. Fig. 4.5A shows the side view of a typical cast obtained from the field measurements. Fig. 4.5B shows the other side of the same cast, where a curved line separate the cast surface into two planes. The higher plane was the result of rolling tine compressing the soil laterally due to its lean, twist, and swing angles. The casts revealed that side curves were different on two sides of cast. The short curve was the result of the bevelled edge of the tine which penetrated the soil first. As the shorter curve was in the front relative to the direction of travel, it was named as Front curve, while the long curve was named as Back curve (Fig 4.5A).



(A)



(B)

Fig. 4.5. Side view of a typical cast from the pocket shape measurement: (A) plaster cast; (B) reverse side of the plaster cast.

In developing mathematic equations of the two side curves, the cast was first placed on a grid paper and the boundary of the cast was traced on the paper. Then, the coordinates (x, z) of the boundary were read relative to the origin which was the intercept of soil surface and the vertical centre line of the pocket. The coordinate x is the direction of travel and positive towards the front of tractor. It was found that the data for both Front and Back curves were best described by a second order polynomial equation as followings.

$$x = a_1 z^2 + a_2 z + a_3 \tag{4.1}$$

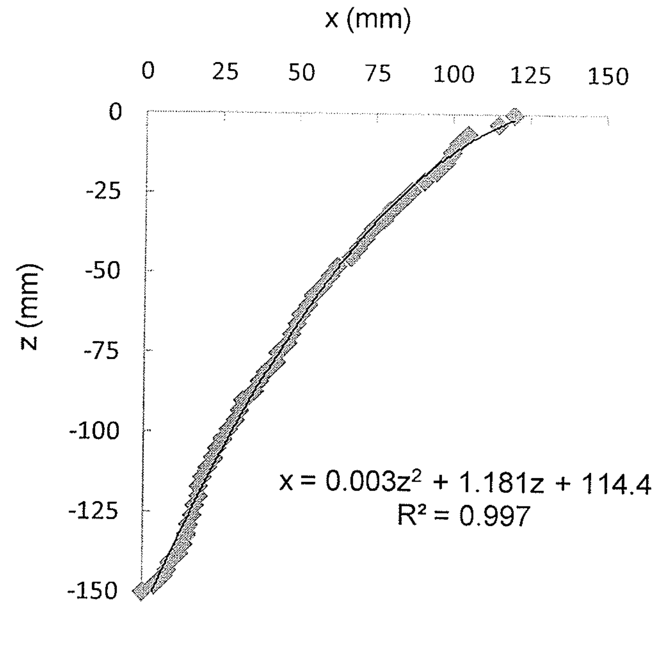
where

z = vertical coordinate along the depth (mm);

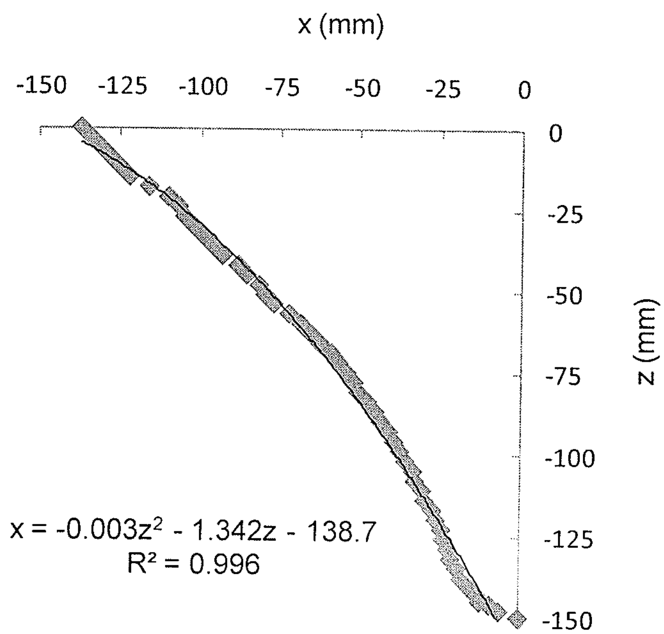
x = horizontal coordinate along the travel direction (mm);

a_1, a_2, and a_3 = regression coefficients (dimensionless).

Data extracted from a cast and the regression polynomial equations are demonstrated in Fig. 4.6A for Front curve and in Fig. 4.6B for Back curve. When combining Front and Back curve along the z axis, the regression curves would give a pointed pocket bottom, whereas the actual pocket bottom was in a narrow round shape. To better describe this feature, third order polynomial equations were tried. It was found that the regression coefficients of the third order terms in the equations were very small. The second order polynomial equations were considered to fit well the overall curves, except for the bottom part of the cast/pocket. In all cases, a strong correlation was found between the side curves and the second order polynomial equations, as demonstrated with high values of coefficients of determinations (R^2). The regression coefficients and R^2 values (between 0.98 and 0.99) for different soils and years are summarised in Tables 4.2.



(A)



(B)

Fig. 4.6. Data of side curves of pocket extracted from a cast: (A) Front curve; (B) Back curve.

Table 4.2. Regression coefficients and the coefficients of determinations of side view of pocket.

		Front curve				Back curve			
Year	Soil type	a_1	a_2	a_3	R^2	a_1	a_2	a_3	R^2
2008	Clay loam	0.004	1.255	94.66	0.988	-0.005	-1.590	-136.2	0.980
	Sandy soil	0.003	1.181	114.40	0.997	-0.003	-1.342	-138.7	0.996
2009	Clay loam	0.003	1.105	86.90	0.996	-0.001	-1.027	-115.8	0.992
	Sandy soil	0.002	1.101	116.30	0.988	-0.002	-1.293	-128.0	0.998

Top view The top view of cast represents the shape of pocket opening at the soil surface level. Fig. 4.7 shows the top view of a typical cast obtained from the field measurements. To extract data, the top boundary of cast was traced on a grid paper. It was found that this view could be described as an ellipse with the origin at the centre of the pocket opening at the soil surface. Thus, the following equation applies:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{4.2}$$

Where

a = semi-major axis (mm);

b = semi-minor axis (mm).

Values of parameters a and b were extracted from the plaster or cement casts. In the extraction, the major axis of ellipse was defined as the centre line along the direction of travel of rolling tines, and the value of 2a was taken as the maximum length of the cast along this direction. The value of 2b was the maximum width taken perpendicularly to the major axis across the middle of the major axis. The crossing point of the major and minor axis was considered as the centre of pocket on the plane of soil surface. The extracted values of 2a and 2b are summarised in Table 4.3.

The elliptical equation (Equation 4.2) with the coefficients listed in Table 4.3 was used in predicting the top views of pocket for the two soil types and years. The accuracy of using an ellipse to describe the top view of pocket was evaluated using the absolute mean difference between measured and predicted value as followings:

$$ADM = \frac{1}{N}\sum_{i=1}^{N}|M_i - P_i| \qquad (4.3)$$

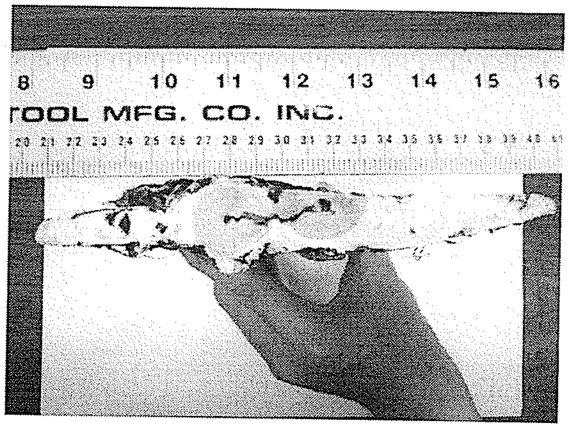
where

N = the number of data points;

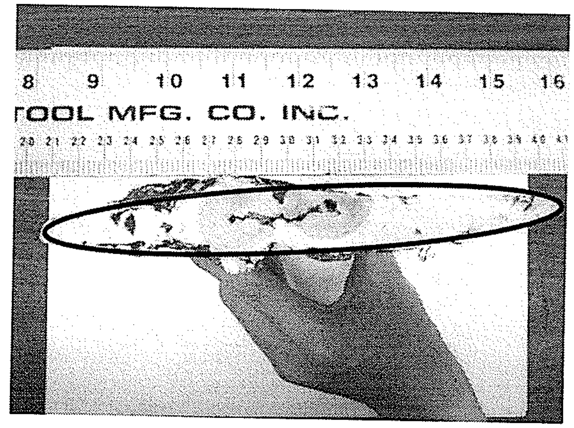
M_i = the i^{th} measurement;

P_i = the i^{th} prediction.

Predictions of y values were performed for x values varying from –a to +a at an interval of 5 mm. The corresponding measurements of y values were read off from the boundary traced from the cast at the same x. Values of AMD were calculated using Equation 4.3, and they are summarised in Table 4.3. The low values of AMD (between 1 and 2) demonstrated that the elliptical equations could reasonably well describe the top views of pocket.



(A)



(B)

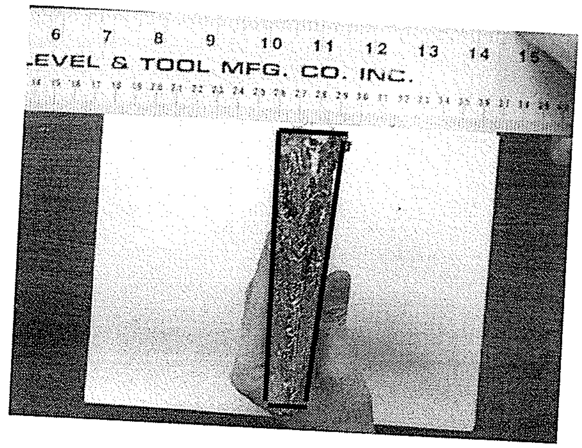
Fig. 4.7. Top view of a typical cast from the field pocket shape measurements: (A) plaster cast; (B) an ellipse on the cast.

Table 4.3 Parameters of ellipses describing the top view of pocket shape from Shatter tine working at a penetration depth of 150 mm and 5° swing angle, and the absolute mean difference (AMD) between the predictions and measurements.

Year	Soil Type	Major axis, 2a (mm)	Minor axis, 2b (mm)	AMD
2008	Clay loam	240	32	3
	Sandy soil	257	17	1
2009	Clay loam	262	32	2
	Sandy soil	223	18	2

Back view The back view (projecting from the back of tractor) is the narrow side of pocket. Fig. 4.8A shows the back view of a typical cast, which was slightly taped at the bottom of the cast. It could be simplified as a trapezoid (Fig. 4.8B).

(A)



(B)

Fig. 4.8. Back view of a typical cast from the pocket shape measurements: (A) plaster cast; (B) a trapezoid on the cast.

The top width of trapezoid was equal to the minor axis of the ellipse, 2b; the vertical dimension (height) of the trapezoid was similar to the penetration depth (d) of the rolling tine in the field operation; the bottom width of trapezoid was similar to the thickness of the rolling tine (t). Thus, the side lines of trapezoid can be described in the following linear equations:

$$y = b + \frac{\left(\frac{t}{2} - b\right)}{d} z \tag{4.4a}$$

$$y = -b + \frac{\left(b - \frac{t}{2}\right)}{d} z \tag{4.4b}$$

Given the particular values for the parameters: d = -150 mm and t = 13 mm, used in this study, values of y can be estimated for any depth, z from 0 to 150 mm. The parameters of the back view of pocket shape are summarised in Table 4.4.

Table 4.4. Parameters of trapezoid describing the back view of pocket shape from Shatter tine working at a penetration depth of 150 mm and a swing angle of 5°.

Year	Soil type	Trapezoid		
		Height, d (mm)	Top width, 2b (mm)	Bottom width, t (mm)
2008	Clay loam	150	32	13
	Sandy soil	150	17	13
2009	Clay loam	150	32	13
	Sandy soil	150	18	13

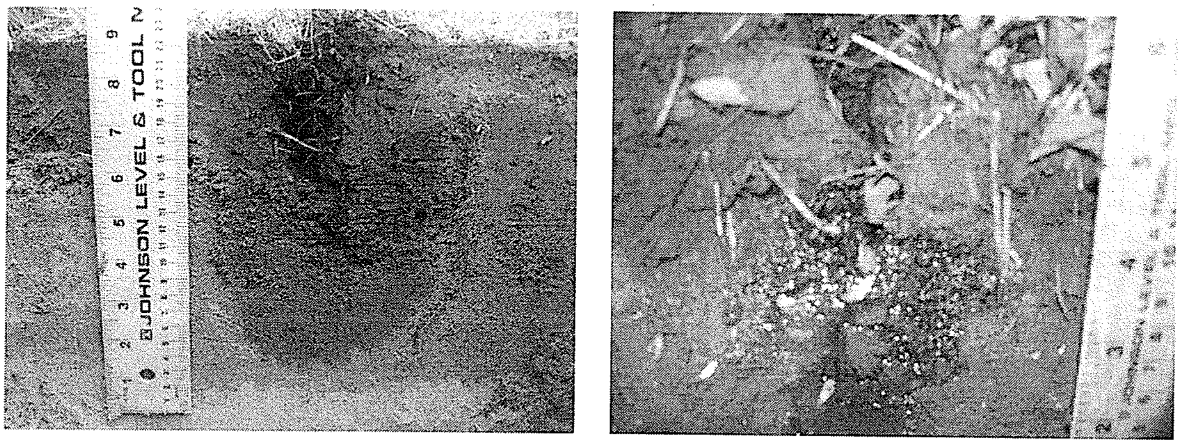
Pocket volumes The equations obtained above can be used to predict the volume of a pocket. In doing so, the pocket was envisioned as a series of vertically connected discs all having an elliptical cross-section, although the sizes of the discs vary over the soil depth. The variation of the major axis of elliptical disc, 2a, over the soil depth is determined by the two polynomial equations of the side curves. At a given z, 2a was calculated as the sum of the two absolute x values predicted from the polynomial equations (Equation 4.1) for Front and Back side curves; 2b was calculated as the sum of the two absolute y values predicted from the linear equations for the back view (Equations 4.4a,b). Each disc was arbitrarily assumed to have 5 mm thickness. Then those discs were numerically integrated over the soil depth of 0-150 mm at an interval of z=5 mm (equal to the disc thickness). The resultant volumes of pocket from the numerical integration are summarised in Table 4.5 and were compared with the measured volumes obtained in Chapter 3. All the predicted volumes were smaller than the measured ones. The smallest difference happened in the clay loam soil 2008, where the predicted volume was 13% smaller than the measured one. The greatest difference between the prediction and measurement happened in the clay loam soil 2009, where the measured volume was 38% greater than the predicted one. For the sandy soil, the differences between the predicted and measured volumes were 17% and 16% in 2008 and 2009, respectively.

Table 4.5. Pocket volumes predicted and measured.

Year	Soil Type	Volume (ml)	
		Predicted	Measured
2008	Clay loam	268	303
	Sandy soil	198	231
2009	Clay loam	240	331
	Sandy soil	190	220

4.4.2 Liquid-soil mix zone

Characteristics of liquid-soil mix zone Figs 4.9A and B show the soil cross-sections with the infiltrated blue dye around a pocket. The liquid-soil mix zone was well defined in the sandy soil (Fig. 4.9A), while the zone was not well defined in the clay loam (Fig. 4.9B) which may affect the accuracy of the measurement in this type of soil. Through some visual examinations on soil cross sections, one found that in the clay loam rolling tines resulted in some soil cracks around a pocket, while the sandy soil had a more uniform soil matrix around a pocket. This difference in soil disturbance may explain the differences in the dye distribution pattern between the clay loam and sandy soil.



(A) (B)

Fig. 4.9. Liquid-soil mix zone: (A) sandy soil; (B) clay loam soil.

Liquid-soil mix zone was characterised with three parameters: lateral spread which was the average of three widths equally distributed depth wise, vertical thickness which was the maximum dye infiltration depth, and the zone area which was the area within the blue dyed boundary in the soil. In 2008, the lateral spread of the sandy soil was 131 mm and that of the clay soil was 192 mm which was approximately 47% greater (Table 4.6). These were also true in 2009. The greater lateral spread of the clay loam may be due to its lower bulk density and the existence of soil cracks around a pocket which contributed to the greater lateral movement of the liquid within the soil. The reverse trend, in terms of effect of soil type, was found for the vertical thickness of liquid-soil mix zone. The water infiltration process was the main factor that influences the vertical thickness. Water infiltrated deeper in the sandy soil than the clay loam. The liquid-soil mix zone area in the sandy soil was 18,275 mm^2 in 2008 and was similar (18,410 mm^2) in 2009. A larger cross-sectional area was occupied by the liquid in the clay loam, as a result of its greater lateral spread. When compared to the sandy soil, the clay loam had 22% larger zone area in 2008 and 56% larger zone area in 2009. Turpin et al. (2007) reported a much larger zone area (70,000 mm^2) resulting from the same shatter tine 150 mm penetration depth. This may be due to the differences in soil conditions used in these two studies.

The lateral spread likely determines the nutrient distribution status between pockets. The lateral spread of the liquid-soil mix zone in the clay soil was greater than the lateral tine spacing, 190 mm, which ensures that the crop between pockets get nutrients. Therefore, tine spacing smaller than 190 mm is not necessary for the clay soil. However, the average lateral spread of the sandy soil (133 mm) implied that liquid-soil mix zones from the adjacent tines were not connected to each other. Thus, the 190 mm tine spacing could be too large for the sandy soil, depending on the nutrient movement in soil over time.

Table 4.6. Liquid-soil mix zone in 2008 and 2009.

Year	Soil type	Lateral spread (mm)		Vertical thickness (mm)		Zone area (mm^2)	
		Mean	SD	Mean	SD	Mean	SD
2008	Clay loam	192a*	24	167a	6	22,320a	2579
	Sandy soil	131b	25	190a	11	18,275a	2805
2009	Clay loam	198A	29	170A	12	28,638A	1943
	Sandy soil	135B	16	185A	5	18,410B	1506

*Values in the same column and year followed with different lower case or uppercase letters were significantly different.

The non-symmetric feature of the liquid-soil mix zone It was found that liquid-soil mix zones was not symmetric. One side was larger than the other relative to the centre line of the tool path (Fig. 4.10). The non-symmetric liquid distribution in soil may be explained by the following facts. The lean, twist, and swing angles all contributed to a lateral motion of the tine, relative to the travel direction, when the tine moved through the soil. This lateral motion may fracture the soil and/or compress the soil. The more lateral compression on one side than the other can be seen when Figs. 4.6 A and B are compared. This resulted in different sets of soil disturbance characteristics acting on two sides of the pocket, i.e. non-symmetric soil disturbance, and in turn the non-symmetric liquid distribution in soil. Fok et al. (1982) pointed out that field tillage operations may introduce an anisotropy that gave faster flow in certain direction.

To quantify the non-symmetric feature, liquid-soil mix zone area was further divided into two parts along the tine path: "*Leeward*" and "*Windward*" (Fig. 4.10). Windward was the side where the tine had more impact on the soil. The areas of these two parts (A_l and A_w) were determined separately and the results are shown in Table 4.7. Overall, the A_w was approximately 60% larger than A_l.

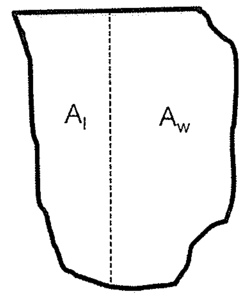


Fig 4.10 A transparency showing the traced liquid-soil mix zone: Leeward (A_l) and Windward (A_w)

Table 4.7. Non-symmetric characteristics of liquid-soil mix zone.

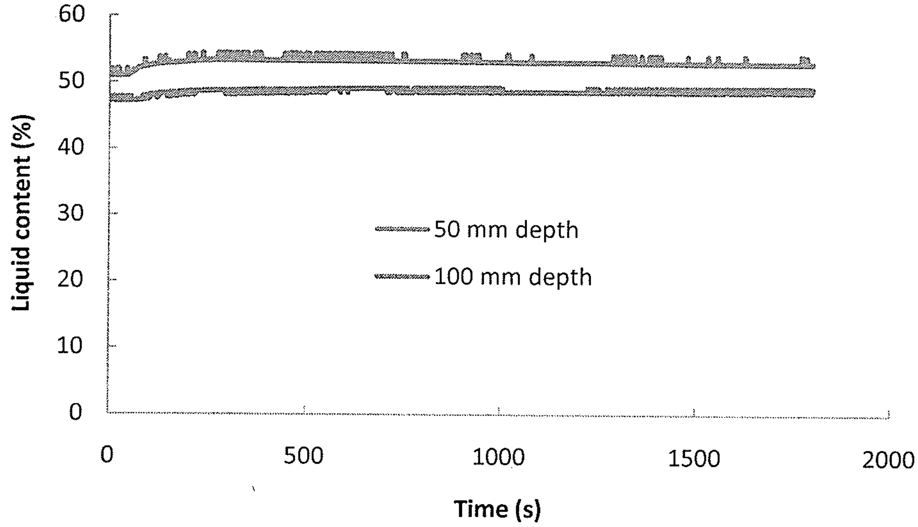
Year	Soil type	Windward zone area, A_w (mm^2)		Leeward zone area, A_l (mm^2)	
		Mean	SD	Mean	SD
2008	Clay loam	12,590a*	1,107	9,731a	1,977
	Sandy soil	10,868a	1,705	7,407a	1,583
2009	Clay loam	20,378A	1,086	8,260a	2,691
	Sandy soil	10,293B	1,475	8,117a	975

*Values in the same column and year followed with different lower case or uppercase letters were significantly different.

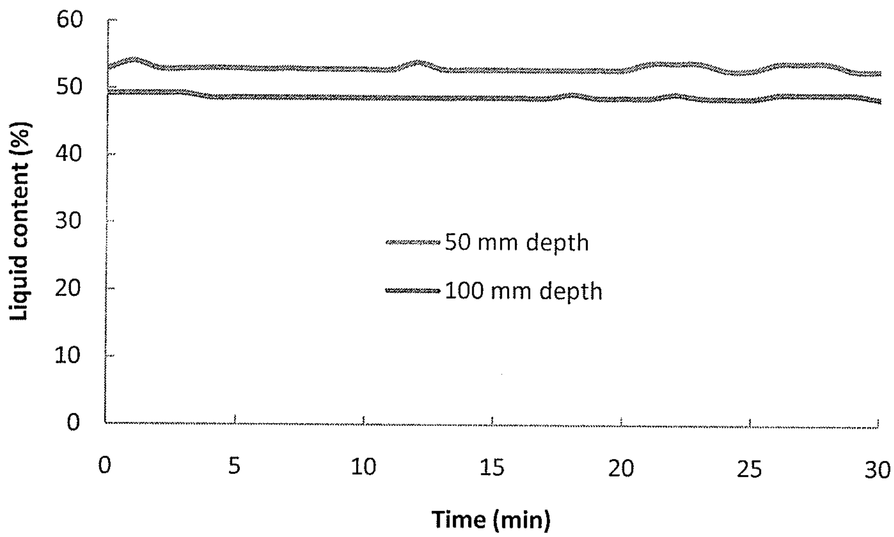
4.4.3 Liquid content around a pocket

Liquid content data were obtained only in 2008 for the clay loam site. For the other cases, data were not recorded due to failures of the moisture sensors or datalogger, The data showed that soil liquid contents fluctuated over time. This was expected for any type of moisture sensors. Only the general trends are discussed here. The data recorded at three different time intervals are presented in three separate graphs. Data for the first 1800 seconds (30 min) showed a general trend that the soil liquid content at both 50 and 100 mm increased from the beginning to approximately 250 s (Fig. 4.11A). This increase was more rapid at the 50 mm than at the 100 mm. Then, the liquid content remained nearly constant afterwards at both depths. The constant liquid contents persisted during the next 30 min (Fig. 4.11B) as well as the rest of the recording period (Fig. 4.11C).

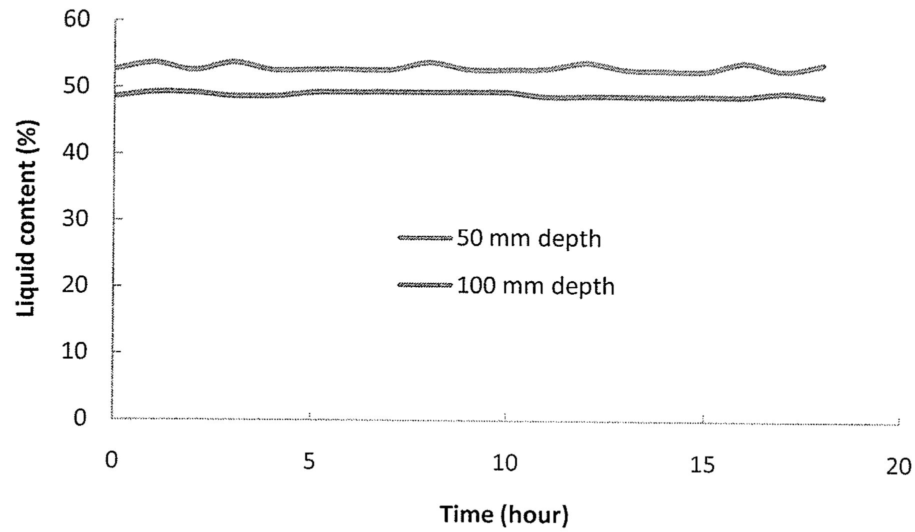
From the time of water being poured into the pocket, liquid flowing occurred due to the gradient of soil liquid content and the preferential flow through soil cracks. Liquid flowed into the surrounding soil of the pocket both laterally and vertically. At one point of time, the movement of the liquid stopped due to the equilibrium of liquid content around the pocket with the initial water content of the soil. Thus, no further change in soil liquid content was observed. The time from liquid being placed in the pocket to the equilibrium was approximately 250 s for the given soil condition. In other cases, this distribution time would depend on the soil conditions.


Liquid content (%)
60
50
40
30
20
10
0
50 mm depth
100 mm depth
0
500
1000
1500
2000
Time (s)

(A)


Liquid content (%)
60
50
40
30
20
10
0
50 mm depth
100 mm depth
0
5
10
15
20
25
30
Time (min)

(B)



(C)

Fig. 4. 11. Liquid content around a pocket over time for the clay loam soil in 2008: (A) during the first 1,800 seconds; (B) during the second 30 min; (C) during the second hours and after.

4.5 Conclusions

For both the clay loam and sandy soils, the top view of the pocket shape fitted an ellipse; the back view fitted a trapezoid shape; and the side view curves were best described by a second order polynomial regression equation with coefficients of determination ranging from 0.98 to 0.99.

The liquid-soil mix zone areas of the sandy soil were fairly consistent in two years. The clay soil did not produce consistent liquid-soil mix zone areas within two years. The average zone area of the sandy soil was 18, 275 mm^2 in 2008 and 18,410 mm^2 in 2009. When compared to the sandy soil, the clay loam had 22% larger zone area in 2008 and 56% larger zone area in 2009. The soil liquid content around a pocket increased after water was placed in the pocket. A more rapid increase was observed at the 50 mm depth than the 100 mm depth. Approximately 250 s after, the soil liquid content at both depths became constant over a period of approximately 24 hours.

The method of using casts to measure field soil pocket shapes was feasible, with a better result in the wet clay loam soil. The liquid-soil mix zone area was successfully measured using dye tracer with a better result in the sandy soil. This study explored some new measurement techniques as an initial step and the focus was more qualitative. Further development of the measurement techniques are suggested for future studies. In addition, further exploration on 3D mathematical equations for pocket shape is recommended.

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4.7 References

Assefa, B. and Y. Chen. 2008. Simulation of the lateral movement of NO_3-N in soils following liquid manure injection. *Canadian. Biosystems Engineering* 50: 2.17-2.26.

Chen, Y. and E. Leafloor. 2006. Liquid Fertilizer Injection System, Method and Apparatus. *Canadian and US Patent offices*: PCT/CA2005/000560.

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

Daverede, I.C., A.N. Kravchenko, R.G. Hoeft, E.D. Nafziger, D.G. Bullock, J.J. Warren and L.C. Gonzini. 2004. Phosphorous runoff from incorporated and surface-applied liquid swine manure and phosphorous fertilizer. J. *Environ. Quality* 33: 1535-1544.

Extension. 2008. Liquid Manure Storage Treatment Options, Including Lagoons. [Online]. Retrieved March 4, 2008, from: http://www.extension.org/pages/Liquid_Manure_Storage_Treatment_Options,_Including_Lagoons

Kumar, M., H.D. Bartlett, and N.N. Mohsenin. 1972. Flow properties of animal waste slurries. *Transactions of the ASAE* 15(4): 718-722.

Rahman, S., Y. Chen, J. Paliwal, and B. Assefa. 2008. Models for manure distribution in soil following liquid manure injection. *Transactions of the ASAE* 51(3): 873-879.

Fok, Y. S., S. O. Chung and C. C. K. Liu. 1982. Two-dimensional exponential infiltration questions. Journal of Irrigation and Drainage, 108, 231-241.

German-Heins, J. and H. Flury. 2000. Sorption of brilliant blue FCF in soils as affected by pH and ionic strength. Geoderma, 97, 87-101.

Hanna, H. M., D.S. Bundy, J. C. Lorimor, S. K. Mickelson and S. W. Melvin. 1998. Evaluating land waste application machinery to meet odour and environmental objectives. Final project Report (NPPC Project No. 1851). Ames, Iowa: Iowa State University, Department of Agricultural and Biosystems Engineering.

Hanna, H.M., D.S. Bundy, J.C. Lorimor, S.K. Mickelson, S.W. Melvin, and D.C. Erbach. 2000. Manure incorporation equipment effects on odour, residual cover, and crop yield. *Applied Engineering in Agriculture* 16: 621-627.

Huijsmans, J.F.M., J.M.G. Hol and G.D. Vermeulen. 2003. Effect of application method, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to arable land. *Amorphous Environment* 37 (1): 3669-3680.

Kumar, M., H.D. Bartlett and N.N. Mohsenin. 1972. Flow properties of animal waste slurries. *Transactions of the ASAE* 15(4): 718-722.

Leafloor, E. 2004. Design of Machine for Grassland Injection of Liquid Manure. Undergraduate Thesis, Department of Biosystems Engineering, University of Manitoba, Canada.

Rodhe, H. 2003. Methods of determining the presence of slurry on the crop and in the upper soil layer after application to grassland. *Bioresource Technique* 90(1): 81-88.

Rahman, S., Y. Chen, J. Paliwal and B. Assefa. 2008. Models for Manure Distribution in Soil Following Liquid Manure Injection. *Transactions of the ASABE* 51(3): 873-879.

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

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.

Rotz, C.A., P. Kleinman, C. Dell, J. Schmidt and D. Beegle. 2007. Environmental and Economic Comparisons of Manure Application Methods on Dairy Farms. *2007 ASABE Annual International Meeting*, ASABE 17-20 June 2007, Minneapolis, Minnesota.

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

Smith, K.A., D.R. Jackson, T.H. Misselbrook, B.F. Pain, and R.A. Johnson. 2000. Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research* 77: 277-287.

Turpin, K.M., D.R. Lapen, M.J.L. Robin, E. Topp, M. Edwards, W.E. Curnoe, G.C. Topp, N.B. McLaughlin, B. Ball Coelho and M. Payne. 2007. Slurry-application implement tine modification of soil hydraulic properties under different soil water content conditions for silt –clay loam soils. *Soil & Tillage Research* 95: 120-132.

Van Vliet, L.J.P. and E. A. Kenney. 2000. Reducing the risk of surface water contamination from manure grassland using a soil aerator. 1999/2000 Final progress Report from Environment Canada. March 15, 2000. Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre. Agassiz. BC.

Weiler, M. and H. Fluhler. 2004. Inferring flow types from dye patterns in macroporous soils. *Geoderma* 120: 137-153.

Wu, B. and Y. Chen. 2009. Modeling liquid distribution in soil following pocket injection. Manuscript submitted to *Journal of Environmental Quality.*

CHATER 5: SMMARY AND RECOMMENDATIONS

In this study, AerWay rolling tines were used in field experiments conducted in two forage fields in Manitoba in 2008 and 2009. Field treatments included the combinations of two types of soil (clay loam and sandy soil), two types of rolling tine (Shatter tine and Leaf tine), two tine penetration depths (125 and 150 mm), and two tine swing angles (0 and 5°). For each treatment, pocket longitudinal spacing, pocket opening dimensions, and pocket volume were measured. Measurements on field pocket shape and liquid distrution in soil following pocket injection were performed for the treatment combination of Shater tine, 150 injection depth, and 5° swing angle. Measured pocket shapes were characterised using mathematical equations. Measurement techniques were also explored in this study.

Results showed that for both soil and tine types, the longitudinal pocket spacing was slightly smaller when the rolling tines worked at a greater penetration depth. The characteristics of pocket opening (length, width, and area) varied, depending on the type of soil, type of rolling tine, penetration depth, and swing angle. The length of pocket opening was mainly determined by the penetration depth of rolling tine, with greater depth resulting in a longer pocket opening; the width was mainly determined by the swing angle, with larger swing angle producing a wider pocket opening. On average, Shatter tine created higher pocket volume than Leaf tine. Pockets in the clay loam had larger opening than in the sandy soil. The rolling tines produced larger pocket volumes when worked at the greater penetration depth or swing angle. Among all the treatments, soil pockets had the greatest opening and volume when using AerWay Shatter tine opeated at the 150 injection depth and 5° swing angle in the clay loam soil. The larger pocket opening and pocket volume would favour a better pocket injection performance, in terms of maxmising manure application rate and minimising manure exposure on soil surface.

The pocket shape was irregular. Its top view could be described as an ellipse, its back view could be simplified as a trapezoid. The side views of the pocket consisted of two curves both of which could be fitted to a second order polynomial equation with high coefficients of determination.

Liquid-soil mix zones in the clay loam soil had greater lateral spread and zone area than those in the sandy soil. Liquid distribution in soil was non-symmetrical relative to the centre line of the tine path. This was due to the non symmetrical soil disturbance characteristics of the rolling tine. Liquid placed in a pocket moved in the clay loam soil over a period of approximately 250 s, as indicated by the increasing liquid content around the pocket at 50 and 100 mm depths. Little liquid movement was found after 250 s.

The methods of using sand to measure pocket volume and using casts to measure field soil pocket shapes were feasible. Using dye tracer to measure liquid-soil mix zone was more successful in the sandy soil when compared to the clay loam.

The information on pocket characteristics and liuqid distribution in soil has important implications to pocket injection of liquid manure. According to the results from this study, the AerWay Shatter tines may be a better choice for pocket injection than Leaf tines. Rolling tines may be operated, if possible, at penetration depth and swing angle as great as practical, which will benefit higher manure application rates and reduced manure exposure on soil surface. More trials are suggested to further approve these measurement techniques. Further research on swing angles larger than 5° and different travel speeds is recommended.