

**STUDIES ON DIFFERENT LIQUID MANURE INJECTION TOOLS UNDER
LABORATORY (SOIL BIN) AND GRASSLAND CONDITIONS**

BY

SHAFIQR RAHMAN

A thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba

© August 2000



National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file *Voire référence*

Our file *Notre référence*

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-53212-7

Canada

**THE UNIVERSITY OF MANITOBA
FACULTY OF GRADUATE STUDIES

COPYRIGHT PERMISSION PAGE**

**Studies on Different Liquid Manure Injection Tools Under Laboratory (Soil Bin) and
Grassland Conditions**

BY

Shafiqur Rahman

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of
Master of Science**

SHAFIQUR RAHMAN © 2000

Permission has been granted to the Library of The University of Manitoba to lend or sell copies of this thesis/practicum, to the National Library of Canada to microfilm this thesis/practicum and to lend or sell copies of the film, and to Dissertations Abstracts International to publish an abstract of this thesis/practicum.

The author reserves other publication rights, and neither this thesis/practicum nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

ABSTRACT

In this study, five different existing liquid manure injection tools (three sweep-types and two disc-types) were evaluated both in the soil bin and at three prairies with heavy clay, coarse sandy loam with stone, and fine sand soil. In the soil bin, the effects of injection depths and tool forward speeds on soil cutting forces and soil disturbance were investigated. While in the field studies, the effects of injection depths and manure application rates on soil disturbances, odor and ammonia concentration, and agronomic response by crop damage and yield were studied.

In the soil bin conditions, among the sweeps, sweep A injection tool required the lowest draft force due to its smallest cutting width and rake angle. On the average, sweep B and sweep C required 12 and 97% more draft force than sweep A sweep due to their wider cutting width. For the sweep A, on the average, addition of a flanged coulter in front of a sweep required 27% more draft force. Higher soil disturbance in terms of soil disturbance width and height was observed at deeper injection depth for all the tested tools rather than speeds. Highest soil surface disturbance was observed for the sweep C due to its wider cutting width than other sweeps. On the average, sweep C disturbed 44% and twice as much than the sweep B and sweep A injection tool, respectively. While for sweep A, the presence of flanged coulter produced 10 and 12% higher value in soil surface disturbance width and height, respectively. For the given soil bin condition, all sweep injection tools could effectively reduced bulk density from 50 to 100 mm depth and can create up to 29% new soil pores. These new pores would be potentially available for absorbing injected manure.

In the field study, highest soil disturbance occurred in clay soil due to its wet soil

condition. No significant differences in odour concentration were observed between two selected treatments. Similarly, no ammonia concentration was detected from the surface except for higher application rate ($112 \text{ m}^3/\text{ha}$) combined with shallow injection depth (80 mm) in clay soil. Injection can slightly damage crops due to action of the injectors themselves and from soil compaction associated with a heavy manure injection system such as self propelled tankers. Injection of manure at a greater depth ($> 90 \text{ mm}$) resulted in higher crop yields than shallow depth possibly due to better and quick utilization of manure nutrient by the grass roots.

ACKNOWLEDGEMENTS

First, I thank Dr. Ying Chen, my thesis advisor, for her invaluable guidance and painstaking advice both in thesis work and professional development activities. I would like to thank my thesis committee members Dr. Q. Zhang and Dr. N. Sepehri for their time and effort.

My sincere gratitude to Mr. Dale Bourns, Matt McDonald, and Jack Putnam for setting up the testing tools and fabrication of a wind tunnel and tool connectors. My acknowledgement to Dr. J. Liu, Mr. X. Ren, J. Gratton and T. Belsham for extending their help in laboratory and as well in fieldwork.

Unbounded thanks to my family members, especially to my elder brother and my wife, for their encouragement and support for higher studies.

Last but not least, I thank the Triple S Hog Manure Management Initiative for funding this project.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENT	iv
TABLE OF CONTENTS	v
LIST OF TABLES	ix
LIST OF FIGURES	x
1. INTRODUCTION	1
2. LITERATURE REVIEW	4
2.1. Manure as fertilizer	4
2.2. Injection of liquid manure	5
2.2.1. Importance of injection	5
2.2.2. Types of injection tool	6
2.2.3. Effects of injection tool on soil cutting forces	9
2.2.4. Importance of injection depth and speed on soil cutting forces	10
2.3. Soil disturbances and manure covering	11
2.4. Odor concentration and ammonia volatilization	12
2.4.1. What causes odor	12
2.4.2. Characteristics of agricultural odor sources	13
2.4.3. Options for odor reduction	14
2.4.4. Factors affecting ammonia volatilization form land application	15

TABLE OF CONTENTS (Contd.)

2.4.5. Purpose of odor measurement	15
2.4.6. Methods of odor evaluation	16
2.4.7. Odorous air sampling methods	16
2.5. Yield response	17
2.6. Soil compaction	18
3. MATERIALS AND METHODS	19
3.1. Soil bin studies.....	19
3.1.1. Experimental design	19
3.1.2. Injection tools	19
3.1.3. Testing facilities and soil bin preparation	22
3.1.4. Soil moisture content and bulk density measurement	23
3.1.5. Measurement and prediction of soil cutting forces	25
3.1.6. Soil surface disturbance measurement	27
3.2. Field studies.....	28
3.2.1. Experimental design	28
3.2.2. Field locations and physical properties	28
3.2.3. Injection unit	29
3.2.4. Manure samples collection and analysis	29
3.2.5. Odorous concentration measurement	31
3.2.6. Ammonia concentration measurement	34
3.2.7. Yield measurement	34

TABLE OF CONTENTS (Contd.)

3.2.8. Soil compaction	34
3.3. Data analyses	36
4. RESULTS AND DISCUSSION	37
4.1. Soil bin studies.....	37
4.1.1. Soil cutting forces	37
4.1.1.1. Comparison of draft force among the sweeps for a single injection tool	38
4.1.1.2. Comparison between predicted and measured force in the soil bin conditions for sweep tools	38
4.1.1.3. WC vs. WOC for sweep A	41
4.1.1.4. Disc A vs. disc B	43
4.1.2. Soil surface disturbance and changes of bulk density	43
4.1.2.1. WC vs. WOC for sweep A	43
4.1.2.2. Sweep B vs. sweep C	45
4.1.2.3. Disc A vs. disc B	49
4.1.3. Specific draft force for sweep tools	53
4.2. Field studies	54
4.2.1. Soil disturbances and manure exposure	54
4.2.2. Odor concentration following liquid manure application to land	55

TABLE OF CONTENTS (Contd.)

4.2.3. Ammonia volatilization	57
4.2.4. Yields response	58
4.2.4.1. Crop damage	58
4.2.4.2. Crop yield	60
5. CONCLUSIONS	61
6. RECOMMENDATIONS AND FUTURE WORKS	63
7. REFERENCES	64

LIST OF TABLES

Table I	Classification of manure by moisture content	5
Table II	Geometrical parameters of the manure injection tools	22
Table III	Soil physical properties of the three fields used for the field tests	28
Table IV	Manure properties used for the field tests	31
Table V	Injection depths, manure application and harvesting dates for different fields	37
Table VI	Inputs for the universal equation to predict draft force	40
Table VII	Odor concentration following the application of manure at two different treatments	57

LIST OF FIGURES

Fig. 1.	Different types of injection tools; (a) chisel or knife injector, (b) sweep injector, (c) s-tine cultivator, and (d) disks injection tool	7
Fig. 2.	Distribution of manure (a) sweep type tool and (b) simple tine/chisel type injection tool	8
Fig. 3	Sweep type liquid manure injection tool used in this study; (a) sweep A, (b) sweep B, and (c) sweep C	20
Fig. 4.	Disc type injection tool used in this study; (a) disc A and (b) disc B ...	21
Fig. 5	Indoor soil bin facilities located in the Department of Biosystems Engineering, at the University of Manitoba	24
Fig. 6.	Three dimensional force and moment dynamometer and injection tool	25
Fig. 7.	The liquid manure injection unit used for field studies	30
Fig. 8.	Semi-cylinder chamber (left) and vacuum chamber (right) used to collect air samples for odor concentration measurements	32
Fig. 9.	AC'SCENT international olfactometer used for odor concentration measurement	33
Fig. 10.	Alfa-Omega forage harvester used for crop harvesting	35
Fig. 11.	Comparison of draft force requirement for different sweep injection tools averaged over two forward speeds	39
Fig. 12.	Comparison between predicted and measured draft force among sweep injection tools using the three dimensional soil cutting equations (McKyes and Ali 1977)	41

LIST OF FIGURES (Contd.)

Fig. 13.	Comparison of draft force versus injection depths for the sweep A injection tool at two different forward speeds	42
Fig. 14.	Comparison of draft force averaged over two forward speeds; versus injection depths for the disc A and disc B injection tool	44
Fig. 15.	Soil surface disturbance profile for a single sweep A sweep injection tool in the soil bin conditions	44
Fig. 16a.	Comparison of soil surface disturbance width averaged over two working speeds versus injection depth for the sweep A injection tool; values with the same letter are not significantly different at 0.1 level with each depth	46
Fig. 16b.	Comparison of soil surface disturbance height averaged over two working speeds versus injection depth for the sweep A injection tool; values with the same letter are not significantly different at 0.1 level with each depth	46
Fig. 17.	Changes of soil dry bulk density versus injection depth averaged over two forward speeds	47
Fig. 18.	Soil surface disturbance profiles for a) sweep B, and b) sweep C	47
Fig. 19.	Comparison of soil surface disturbance width averaged over two forward speeds versus injection depths for the sweep B and sweep C .	48

LIST OF FIGURES (Contd.)

Fig. 20.	Changes of soil dry bulk density averaged over two forward speeds for the sweep B and sweep C injection tools	49
Fig. 21.	Soil surface disturbance profile for the disc A	51
Fig. 22.	Soil surface disturbance width versus injection depth for the disc A at two different forward speeds	51
Fig. 23.	Soil surface disturbance profiles for the disc B at a) 40 mm and b) 110 mm depth	52
Fig. 24.	Soil surface disturbance width versus injection depth for the disc B at two different forward speeds	52
Fig. 25.	Specific draft force versus injection depth for the sweep injection tools; averaged over two forward speeds	54
Fig. 26.	Soil surface disturbance profile for a single sweep injection tool in the field condition	55
Fig. 27a.	Comparison of field soil disturbance width averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level	56
Fig. 27b.	Comparison of field soil disturbance height averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level	56

LIST OF FIGURES (Contd.)

Fig. 28	Comparison of field soil disturbance width averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level	59
Fig. 29.	Soil dry bulk density versus soil sampling order, showing the effects of change in load on the extent of soil compaction at the Headingley site	59
Fig. 30.	Injection depth effects on crop yields; values with the same letter within each site are not significantly different at 0.1 level	60

1. INTRODUCTION

Manure is an excellent source of nutrient and organic matter that can be used for crop production and to improve the soil structure and water holding capacity of an agricultural field. However, surface application of manure is a major environmental concern because it causes nutrient losses (by volatilization of ammonia) and odour emissions. Studies show that agricultural practices are the major source of ammonia emissions into the atmosphere and contribute to about 90% of the total ammonia emissions in Western Europe. Land application of manure itself contributes to about 46% of the total ammonia emission (Phillips and Pain 1998, cited by Meisinger and Jokela 2000). In addition, over-application of manure can lead to phosphorous accumulation and nutrient imbalances within the soil system (Danesh et al. 1999). Therefore, many efforts have been focused on reducing ammonia losses, resulting from land application of manure (Meisinger and Jokela 2000). This has led to the adoption of liquid manure incorporation techniques, including manure injection (Warner et al. 1991), which can reduce odour and ammonia emissions up to 95% (Phillips et al. 1988). However, existing manure incorporation tools require a great deal of draft force or tractor power, cause potential damage to grass and may not cover completely manure with soil (Hultgreen and Stock 1999; Warner and Godwin 1988).

In western Canada, hogs are often raised within close proximity to pastureland or prairies (referred as grassland hereafter). Thus applying the manure to grassland would be an inexpensive practice because of the nearby manure source. Furthermore, grassland is often not fertilized due to high costs of chemical fertilizer (Chen and Rahman 1999). However, surface application of manure on grassland may cause poor palatability,

pathogen contamination of grazing cattle and fouling or burning of grass (IGER 1995; Jokela and Côté 1994). As compared with surface spreading of manure, injection of manure into soil results in lower odour emissions, nutrient losses by volatilization, and grass damage by burning or grass contamination in a much shorter no-grazing period in grassland (Kempainen 1986; Warner and Godwin 1988).

Despite the potential benefits, injection of liquid manure has not been widely used due to high power requirement, slower operation, lower spreading capacity, and higher equipment costs (Jokela and Côté 1994; Laguë 1991). Most existing manure incorporation tools were derived from tillage tools (Hall 1986). Cutting forces, soil disturbance patterns, odour emissions, crop damage due to action of the injectors, and soil compaction from heavy injection systems, are important parameters for evaluating the performance of manure incorporators. These above parameters have not been well documented, therefore, it is important to evaluate injection tool based on these.

Evaluation of any equipment depends on both laboratory and field studies. The main advantage in a laboratory study is the ability to control the experimental factors such as soil moisture content and bulk density, working depths, and speeds of the testing unit. It also allows the measurement of forces and other parameters under uniform conditions and a comparison of performance. Field studies show large variation of forces due to soil types and moisture contents. As a result, it is difficult to compare performances of the testing unit. Given above, it is necessary to validate the laboratory study with the field study.

This study was focused on the performance evaluation of different existing liquid manure injectors under laboratory and as well in different soil and field conditions. Three

sweep-types and two disc-types injection tools were tested under laboratory conditions. A whole injection unit was tested in the field. The objectives of this study were:

- To investigate the effects of injection depths and forward speeds on soil cutting forces and soil disturbance under a soil bin;
- To study soil disturbance under the field conditions as influenced by injection depth;
- To determine the crop damage as influenced by injection depth and wheel traffic;
- To determine the effects of injection depth and manure application rate on grass yields; and
- To measure odour and ammonia concentrations in the air following the manure injection to grassland.

2. LITERATURE REVIEW

With the expansion of swine industry across the North America, there is more and more concern for manure management. This is a challenge to the environmentally sustainable use of manure. Studies show that land application of manure is the most cost-effective practice to control odour when compared with other manure management practices, such as aerobic or anaerobic treatments (Warner et al. 1990; Chen and Rahman 1999). In addition, the application of manure to agricultural land is recognized as the best practical environmental option (Chambers and Rudd 1995, cited by Moseley et al. 1998)

2.1. Manure as fertilizer

Livestock manure is a valuable source of organic fertilizer for field crops since it contains useful amounts of the plant nutrients: nitrogen (N), phosphorus (P) and potassium (K) (Scotford et al. 1998; Bayne 1999). Application of manure to agricultural land provides not only nutrients required for plant growth, but also improves its structure (porosity) (MacLean et al. 1983). In addition, application of manure also increases the available water holding capacity. Manure may be solid, semisolid, or liquid depending upon the proportion of bedding (straw, hay wood, corn etc. used as a bedding materials), and water it contains. Classifications of manure by moisture content are listed in Table I.

Solid manure usually characterized by the presence of bedding in the manure. Semi-solid manure is difficult to handle by being too thick to pump and too thin to handle with a tractor and front-end loader. Liquid manure results when almost no bedding is used, when the urine is contained, and where extra water is added.

Carefully managed application of manure on pasture and cropland will effectively utilize the plant nutrients in manure without any environmental threats (Chescheir III et

al. 1985). However, if mismanaged, land application of manure (spreading) becomes a practice of waste disposal rather than one of nutrient utilization, thus increasing the risks of air, water, and soil pollution (Scotford et al. 1998).

Table I. Classifications of manure by moisture content

Type of manure	Moisture content	Ease of pumping
Solid manure	< 80%	cannot be pumped
Semisolid manure	80-90%	may be difficult to pump
Liquid manure	>90%	easy to pump

Source: Bayne (1999)

2.2. Injection of liquid manure

2.2.1. Importance of injection Injection may be defined as the application of manure by method, which incorporate the manure into the soil by some physical means (i.e. tillage operation). In 'direct incorporation', manure is directly incorporated into the soil by the injection tool itself without a separate tillage operation (Jokela and Côté 1994).

Traditional surface application of manure is low in cost and plug resistance, but requires high power, produces odour and ammonia losses by drift, and non-uniform application of manure (Hilborn 2000). In addition, surface application of manure causes smothering and scorching of the grass (Prins and Snijders 1987, cited by Misselbrook et al. 1996). In the prairies, major concerns are odour emissions and nutrient losses associated with surface spreading. Injecting manure below the soil surface can minimize odour and ammonia emission (Kempainen 1986; Hall 1986; Jokela and Côté 1994). It can also prevent the contamination of cattle grazing, which most often is the case with

surface application of manure (IGER 1995). Studies show that injection of manure can reduce odour emission and ammonia volatilization by about 85 and 90%, respectively (Wouters and Verboon 1993, cited by Jokela and Côté 1994; Pain et al. 1991). However, poor injection can still result in manure exposure on the soil surface, which causes odour emissions and nutrient losses by volatilization (Chen et al. 2000).

2.2.2. Types of injection tool The most common injection tools used include the knife, chisel, sweep, and discs (Fig. 1). Knives (Fig. 1a) often cannot create sufficient manure holding capacity for the manure application rates required by crops. The chisel-type injector cuts a slot into soil and allows the manure to flow down the slot (Goodrich 1994). As a result, they leave manure stripes in vertical bands (Fig. 2b) (Godwin et al. 1986). In addition, they penetrate deep into soil, therefore requiring more energy and often cannot create sufficient manure holding capacity for the manure application rates required by the crops (Chen and Rahman 1999).

Sweep type injectors (Fig. 1b) lift the soil and allow the manure to flow in a wide horizontal band (laterally) (Fig. 2a) at a shallower depth, and allows the soil surface to come back down over the liquid manure (Goodrich 1994; Godwin et al. 1986). Sweeps can be used for apply higher application rates in one pass than a knife injector can apply in several passes. Sweep-type (winged) injection tool demonstrate the best performance for manure injection in terms of mixing soil with manure (Moseley et al. 1998). Under certain application rates, sweep injectors can work at shallower depths and significantly reduce draft force compared to a simple tool (Warner and Godwin 1988). However, crop root damage may be a concern for sweep type tools due to their wide cutting widths (Chen and Rahman 1999).

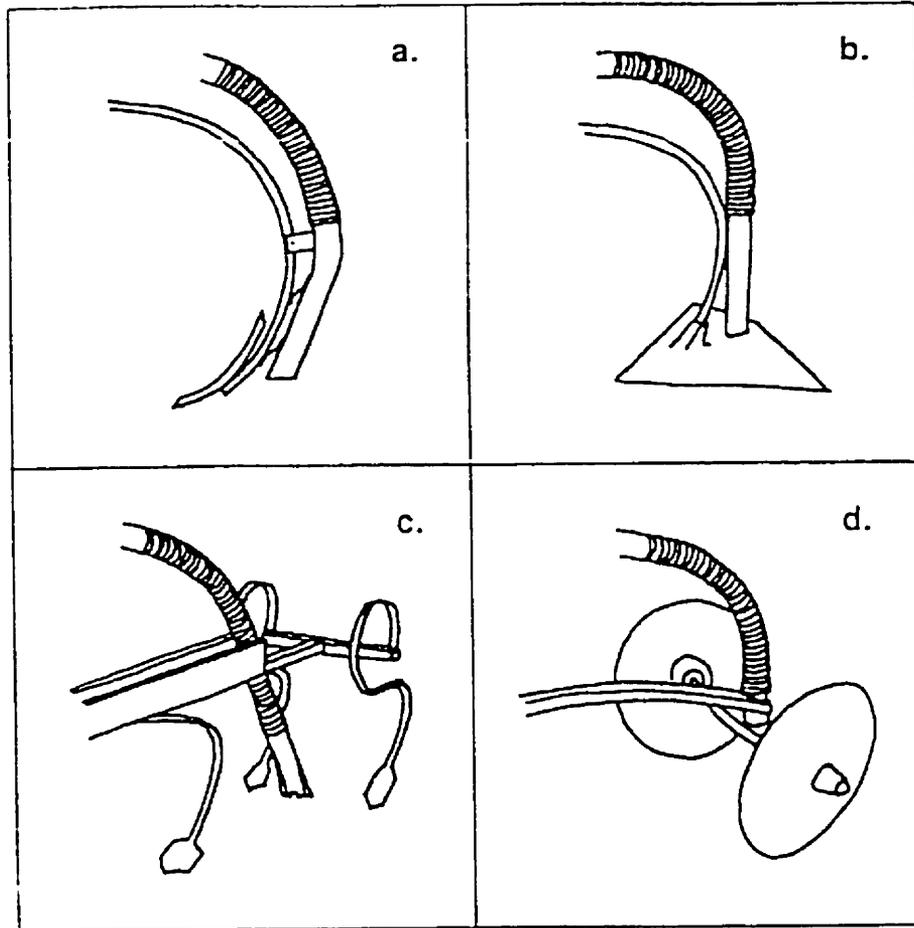


Fig. 1. Different types of incorporation tools; (a) chisel or knife injector, (b) sweep injector, (c) s-tine cultivator, (d) disc injection tool (Jokela and Côté, 1994)

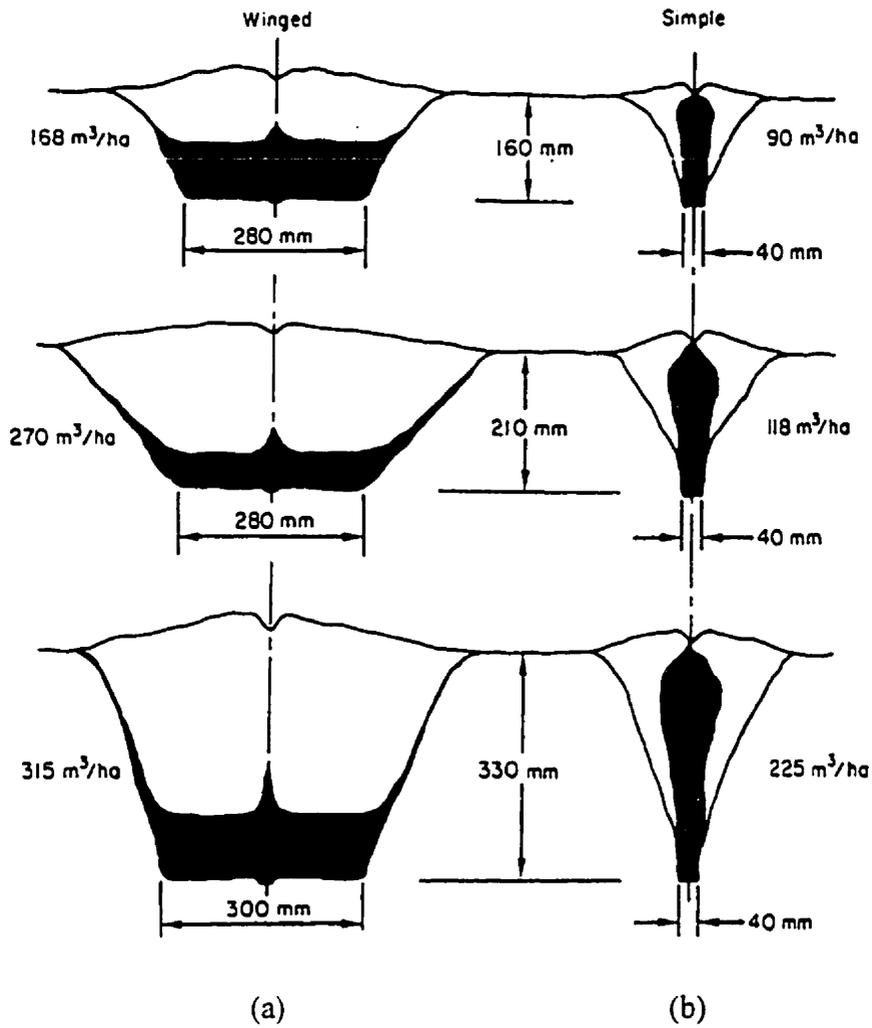


Fig. 2. Distribution of manure; (a) sweep-type injection tool and (b) simple tine/chisel type injection tool (Godwin et al., 1986).

Discs have also been used for manure injection (Fig. 1d). However, discs do not actually inject the manure, but mix and cover the injected manure with the surface soil layer (Jokela and Côté 1994; Reaves et al. 1981). The rolling motion of a disc helps to cut through the soil surface (Tice and Hendrick 1992) at the same time tend to compact the soil and reduce pore size, thus decreasing infiltration rate (Geohring and VanEs 1994).

2.2.3. Effects of injection tool on soil cutting forces The draft force requirement and soil disturbances, in terms of soil volume disturbed and bulk density changes, vary with types of injection tools and their design parameters. McKyes et al. (1977) found that, to cut a specified volume of soil, a wide tine working at a shallow depth required less draft force than a narrow tine working at a deeper depth. Similarly, a winged injector can incorporate a larger volume of manure with adequate soil cover at a shallower depth than a simple non-winged tine (Warner and Godwin 1988). They also found that a winged injector required 35% more draft force than a simple non-winged tine for the same injection depth, but could incorporate twice the volume of manure. Schmitt et al. (1995) found that a horizontal sweep injector that operates at a shallower depth (100 to 150 mm) required less power, provides more even distribution of manure, and improves nitrogen availability for the crops. A similar conclusion on draft forces has been drawn by Rahman and Chen (2000) for sweep type injection tools. In addition, orientation of tines (backward or forward inclined) also leads to an increase in draft force requirements (Warner and Godwin 1988).

A coulter in the front of a sweep injection tool is known for its effectiveness in cutting the grass sod or residue and preventing residue from collecting on the implement (Tice and Hendrick 1992). However, different opinions exist on how coulter affects the

total draft force. Huijismans et al. (1998) suggested that a coulter in the front of a sweep injection tool should help in reducing the total draft force requirement. However, Kepner et al. (1987) had previously found that draft force of a coulter increases with penetration depth since the rolling coulter must always be forced into the soil. A similar conclusion was drawn by Morrison et al. (1996) as the draft and vertical force on rolling coulters generally increase with soil penetration depth. On the contrary, Schaaf et al. (1980) found that penetration ability was inversely and vertical force was directly proportional to the diameter of the coulter and coulter shape or style had no significant effect on draft or vertical force, but influence the furrow formation and amount of soil disturbed. Similarly, a laboratory study by Harrison and Thivavarnvongs (1976) indicated that the soil reaction forces are largely insensitive to differences in disk shape and diameter. Kushwaha et al. (1986) found that the vertical force of a coulter increased with increased coulter size and depth of penetration.

Draft and vertical force on a rolling disc generally increases with soil penetration depth and increased soil strength (Morrison et al. 1996). The rolling motion of a disc helps to cut through the soil surface residue (Tice and Hendrick 1992). Disk angle also affects the soil cutting forces significantly.

2.2.4. Importance of injection depth and speed on soil cutting forces Injection depth is an important working parameter since it influences power requirements, soil disturbances and manure covering performance (associated with odour emission) of an injector (Chen and Rahman 1999; Gill and Hendrick 1976). Collins and Fowler (1996) and Huijismans et al. (1998) draw similar conclusions, whereas the draft force of tillage tools increases significantly when the depth of operation is increased. The shallow

injection depth (50 mm) required less power but produce odour and ammonia emission and crop damage (Pain and Misselbrook 1997, cited by Meisinger and Jokela, 2000). Deep injection (150 to 300 mm) can effectively reduce ammonia losses, but produce root damage and yield reduction (Thompson et al. 1987). In Europe shallow injection of manure (50 mm) is very common. However, in Canada, due to municipal requirements and environmental awareness (odour production and nitrogen loss), deep injection (100 to 200 mm below soil surface) is practiced (Danesh et al. 1999).

The draft requirement of a tillage tool is also a function of operating speed and an important criterion for evaluating the performance of a tillage tool either in field and/or laboratory conditions (Kushwaha and Linke 1996). Collins and Fowler (1996) found that speed produce a small but significant linear increase in draft force requirement. While, Stafford (1979) found that draft force is influenced by speed and moisture contents. For example, at low moisture content, draft force increased with speed, while at high moisture content, the draft force decreased with speed. In addition, he also concluded that draft force becomes virtually independent of speed above 5 m/s.

2.3. Soil disturbances and manure covering

Soil surface disturbance profiles are important performance indicators for manure injection tools, particularly under grassland conditions. An injection tool must create enough pore space to contain manure and cover it up with sufficient amounts of loose soil with minimum soil disturbance (McKyes et al. 1977; Parkinson et al. 1994). Failure to accomplish these requirements result in exposure of manure to the soil surface (McKyes et al. 1977). To meet agronomic requirements, manure should be placed in an aerobic soil environment and mixed with the soil to favor the biological stabilization of manure

(Godwin et al. 1976; McKyes et al. 1977). Moseley et al. (1998) found that a narrow channel within the disturbed soil volume indicated poor soil manure mixing, whereas a shallow and wide cross-section of disturbed soil suggested better mixing. Disturbing larger volumes of soil usually creates more voids (Chen et al. 1998). Hanna et al. (1993) concluded that a higher speed and larger rake angle on a sweep resulted in more soil disturbances. Similarly, Rahman and Chen (2000) found that soil disturbance significantly increased with injection depth and tool size. However, high disturbance injection is unacceptable for pasture or forage crops (Hultgreen and Stock 1999). Injection tools should create minimum surface disturbance to prevent excessive grass damage (Hann et al. 1987). Great surface disturbance by an injection tool causes extensive root damage for perennial crops (Warner et al. 1991).

2.4. Odour concentration and ammonia volatilization

2.4.1. What causes odour The biological breakdown of manure produces ammonia, hydrogen sulfide, NH_3 , CO_2 , and other volatile compounds (Koelsch 1994). Of the gases, only NH_3 and H_2S have odours (McQuitty and MacLean 1983). Combination of these gases can produce offensive odours at very small concentrations ppb (parts per billion). Volatile fatty acids are the most important group and usually reported as the major indicators of the offensiveness of odours from livestock slurries. Many of the odourous gases are produced in an anaerobic environment. The types of compounds produced depend on the types of biological processes which take place. The following physical factors influenced the level of odour produced by manure (Koelsch 1994):

1. **Temperature** Controls the rate of biological action. The higher the temperature, the faster the biological process takes place and therefore

increases the gas production.

2. **Moisture** Liquid manure promotes anaerobic conditions and increased odours. The bacterial activity slows down and can be stopped as manure is dried.
3. **pH** A pH of 8 or more begins or slow down anaerobic activity. High pH levels also speed up the release of ammonia. Manure pH above 8 will cause substantial ammonia release while a pH below 7 results in very little ammonia loss.

2.4.2. Characteristics of agricultural odour sources Gas emission from a storage facility or building is relatively constant and varies only with seasonal temperature. In contrast, land application of manure emits large amounts of gas periodically throughout the years (Schmidt and Jacobson 1995). The emissions from agricultural sources are different than industrial sources due to (Smith 1993):

- a) the odour source is at or near the ground
- b) the source may be of relatively large and areal extent
- c) the important receptor zone may be relatively close to the source of emission
- d) the relatively low intensity of emission
- e) lower density of a mass flow of warm gas
- f) difficulty in measurement of odour emission rate and
- g) spatial and temporal variability in emission rate.

2.4.3. Options for odour reduction Odour reduction is an important issue for hog farmers. Lindvall et al. (1974) demonstrated that odour reduction could be achieved by injecting slurry into land, adding additives to manure, or an aerobic treatment during

storage. However, chemical control of odour and existing aeration is expensive (Goodrich and Petering 1999; Lindvall et al. 1974). So the most effective method to reduce an odour is to inject the manure into the soil surface.

Anaerobic manure storage is known to be a large source of odours (Riskowski et al. 1991). To control unwanted odour emission, manure should be properly incorporated, distributed widely as possible, and covered adequately. An injector must provide sufficient cavities to contain applied manure. For example, Negi et al. (1978) found that for complete injection, the volume of newly formed voids must exceed the volume of slurry to be applied. Aerobic treatment is expensive due to its mechanical power requirement to add air to the slurry. However, due to this treatment, odour emission is lower than anaerobic manure (Riskowski et al. 1991). The main advantage of this process is that during the aerobic treatment, aerobic bacteria convert the organic materials into carbon dioxide, an odourless gas. However, if oxygen level is not maintained properly then losses of ammonia by volatilization due to the biological breakdown of manure occur. This reduces the nutrient value of the manure. Biofiltration has potential for removing odours from enclosed structures (animal housing and covered manure storage) and it has been using in many countries (Koelsch 1994). Biofiltration involves moving of odour-fouled air through a filter consisting of soil, organic residues (i.e. tree trimmings and leaves), compost, or other appropriate media. Odourous compounds are removed by combination of adsorption, absorption, and aerobic degradation.

2.4.4. Factors affecting ammonia volatilization form land application The main factors affecting ammonia volatilization can be categorized as: (Meisinger and Jokela 2000; Pain et al. 1990; Svensson 1994)

- i) Manure characteristics (dry matter, pH, NH₄-N content),
- ii) Soil conditions (soil moisture, soil properties, plant/residue cover),
- iii) Environmental factors (temperature, wind speed, rainfall), and
- iv) Application management (injection, zone application, timing).

In addition, either insufficient injection depth or excessive manure application rate can result in manure exposure and volatilization (Thompson et al. 1990). For example, slurries with higher dry matter content has greater ammonia loss because slurries with lower solids tend to have greater fluidity and therefore infiltrate more readily into the soil where ammonium is protected from volatilization by absorption onto soil colloids (Meisinger and Jokela 2000). Similarly, initial pH significantly influence ammonia emission because of the rapid increase in slurry pH after application (Sommer and Hutchings 1997; Sommer and Sherlock 1996). A pH above 8 increases ammonia volatilization, while a pH lower than 6.5 and lower TS (due to higher infiltration rate), have potential to reduce ammonia volatilization (Stevens et al. 1992; Pain et al. 1990).

2.4.5. Purpose of odour measurement The most odour causing gases are formed when liquid manure is stored in anaerobic environment and applied to the field (Janni 1982). Therefore, evaluation of odour emissions from land application, by quantifying odour, is important to develop an effective injection method for reducing odour emission (Pain et al. 1991). Odour intensity and odour threshold values are usually used to describe the odour concentration of gases (Lindvall et al. 1974). An olfactometer is commonly used to measure the concentration of odour (Hobbs et al. 1995). The perception of manure odour is a consequence of simultaneous exposition of large amount of odourants (Lindvall et al. 1974). Evaluation of an odour can be accomplished either in the

laboratory or in the field. Odour emission from land application can affect the neighbor and create an environmental problem. The purpose of odour evaluation in the laboratory or in the field is to quantify the air sample in terms of human olfactory perception.

2.4.6. Methods of odour evaluation Odour strength (intensity or concentration), odour quality (nature), and odour persistence parameters are commonly used to characterize the odour (Qu et al. 1999; Spoelstra 1980). Odour intensity and odour offensiveness are also odour parameters and measurable, but are considered as more subjective (Hobbs et al. 1995). The odour intensity is the relative strength of the odour above the threshold value and a function of the odour concentration (Qu et al. 1999). While odour offensiveness is a measure of the acceptability of an odour. Odour concentration (OC) can be objectively and quantitatively measured and defined as the number of dilutions at which 50% of the panel members can just detect an odour and is expressed as odour units (OU). Of these, odour concentration is the most widely used parameter to describe the odour concentration of gases (Lindvall et al. 1974). This value is measured by odour panel with a “olfactometer” on a collection of representative samples of air (Pain et al. 1990; Pain et al. 1991).

2.4.7. Odourous air sampling methods To estimate odour and ammonia emission under field conditions, reliable methods are required (Génermont and Cellar 1998; Sommer et al. 1995). There are some techniques to collect odourous air from the enclosure and field conditions. Enclosing methods have been used in the past for sampling odourous air in early days (Pain et al. 1991). The enclosures or hoods are placed over the land spread with manure and air is drawn directly to dilution apparatus or collected in bags for olfactometer assessment. Most recently, a system of a wind tunnel

and micro-meteorological techniques are used in the measurement of odour emission (Pain et al. 1991). However, the wind tunnel has been considered as a convenient tool to measure ammonia emissions over a small surface area of 1 m² of natural soil in the field (Lockyer 1984).

2.5. Yield response

Injection of manure can either increase or reduce yield. For example, Tunney and Molley (1986) and Warner et al. (1991) found that injection of slurry could increase grass yield, while Larsen (1986), Hall (1986), and Misselbrook et al. (1996) found that injection could reduce the yield by as much as 30%, depending on timing of injection, soil type, and soil moisture level. Similarly, Guest (1981) and Beauchamp (1983) observed that injection of cattle manure in corn at either pre-plant or side dress time increases yield compared to surface application. The primary reason for reduced yield was crop root damage from the action of injectors, as also noted by Jokela and Côté (1994). Crop damage can also be incurred from soil compaction with heavy equipment (manure spreader or tanker) wheel traffic, especially on heavy clay soil with high moisture (Frost 1988; Bédard et al. 1997; Tessier et al. 1991; Jokela and Côté 1994).

2.6. Soil compaction

Use of heavy equipment (manure spreader or tanker) over a crop field can cause soil compaction, especially on a heavy clay soil with high moisture (Frost 1988; Bédard et al. 1997; Tessier et al. 1991; Jokela and Côté 1994). From an agronomic point of view, compacted soils impede plant root development (Threadgill 1982), delay overall plant growth, and reduce yields (Gameda et al. 1985). Tessier et al. (1995) observed that, of the many reasons (odours, water pollution, soil compaction etc.), farmers or producers are

reluctant to use liquid manure due to soil compaction during application. In field situations, soil bulk density depends on land use (Carter 1990). For example low bulk density may influence manure storage capacity, while at high bulk density soil strength, air and water permeability could reduce root growth and plant productivity (Carter 1990).

3. MATERIALS AND METHODS

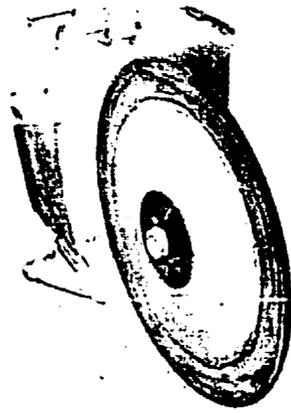
Tests were conducted both in the laboratory (hereafter referred as soil bin) and field conditions. Therefore, the following discussion is focused on both aspects.

3.1. Soil bin studies

Due to the limitation of the indoor test facility used, manure was not applied during the testing. However, investigations made on tool draft forces and soil disturbance are independent of manure application. Moseley et al. (1998) and Rahman and Chen (2000) have successfully used an indoor soil bin to evaluate the performance of an injection tool on draft forces and soil disturbance characteristics.

3.1.1. Experimental design A (3x2) completely randomized factorial experiment with three injection depths (50, 100, and 150 mm) and two tool forward speeds (0.6 and 1.4 m/s) was designed. The selected injection depths and forward speeds are commonly used by producers for manure incorporations. Speeds higher than 1.4 m/s could not be achieved by the soil bin carriage. To examine the effect of coulter, two different tool-arrangements were tested for the sweep A: sweep with coulter (WC) and without coulter (WOC). Each of the six treatments was replicated three times within each tool-arrangement. Thus a total of 108 test runs were conducted in the soil bin for five different injection tools.

3.1.2. Injection tools Five different types of injection tools were tested in the soil bin. Three of them were sweep-types (Fig. 3) and the remaining were disc-types (Fig. 4). Sweep A included a flanged coulter in the front of the sweep. The coulter helps to cut the soil and vegetation or crop residue, and the flanged of the coulter functions as a depth control. A coulter can be optionally used in the front of sweep C, however the coulter was



(a)

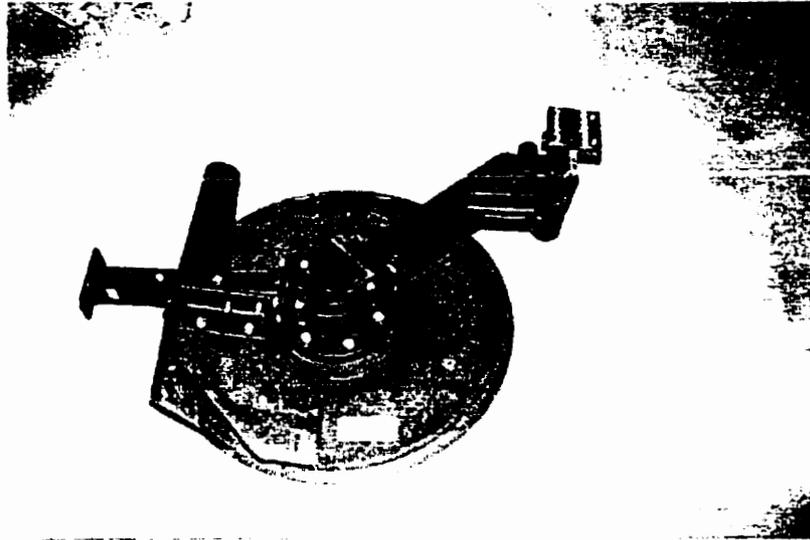


(b)

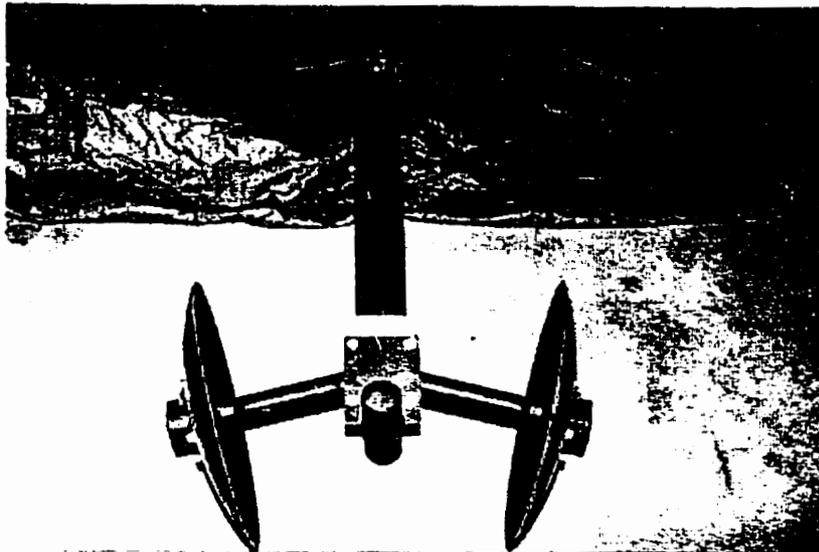


(c)

Fig. 3. Sweep type liquid manure injection tools used in this studies; (a) Sweep A, (b) sweep B, and (c) sweep C.



(a)



(b)

Fig. 4. Disc type injection tools used in this studies; (a) disc A, and (b) disc B.

removed to compare the performance with the sweep B. The disc A features a single vertical disc, whereas the disc B consists of two concave discs mounted on a flexible spring shank (Figs. 3 and 4) and their geometric parameters are listed in Table II.

Table II. Geometrical parameters of the manure injection tools

Parameters	<u>Injection tools</u>				
	Sweep A	sweep B	sweep C	Disc A	disc B
Sweep width (mm)	220	330	570		
Sweep length (mm)	200	240	490		
Sweep angle (°)	58	67	63		
Rake angle (°)	3	21.5	18.5		
Coulter dia. (mm)	620				
Flanged dia. (mm)	470				
Disc dia. (mm)				635	560
Disc angle (°)				0	6
Tilt angle (°)				0	18

Except for the disc B, all the other tools were designed for liquid manure injection where manure would be placed into the soil and covered by a layer of soil. The disc B is a surface injection tool and manure is dropped on the soil surface at the middle of the two concave discs and then covered with the loose soil produced by two discs during application. Therefore, the term manure injection refers to both manure injection and surface incorporation.

3.1.3. Testing facilities and soil bin preparation

The main advantage of using

soil bin to test injection tools is the ability to control soil properties and other testing parameters (i.e. speed and depth). The soil bin, located in the Department of Biosystems Engineering at the University of Manitoba, is 1.5 m wide, 15 m long and 0.6 m deep, filled with loamy sand soil (86% sand and 10% clay, by weight) (Fig. 5). A variable speed motor is connected to the soil bin carriage to control the tool forward speed. Similarly, injection depths were controlled by adjusting the vertical position of the tool bar on the bin carriage. The soil bin preparation steps were as follows:

1. The soil was first tilled at a greater depth than the design depth to allow uniform loosening of the subsurface soil for uniform compaction. To do this, the rotary tiller was operated at the slowest forward speed of 0.28 m/s.
2. To simulate field soil moisture conditions throughout the tests, water was sprayed over the entire length of the soil bin 24 h before the test.
3. Then soil was conditioned using a rotary tiller to allow uniform mixing of soil.
4. The soil was leveled with a leveler to get a uniform and smooth soil surface.
5. The soil was compacted with a 162 kg smooth roller to achieve consistent bulk density throughout the soil bin.
6. A plastic covering was used to maintain the same moisture level in between the tests. The above steps were followed for each soil preparation prior to any test run.

3.1.4 Soil moisture content and bulk density measurement Before each test run, three random soil cores (52 mm diameter) were taken for measuring initial soil moisture content and dry bulk density. Similarly, three random soil cores were also taken after the

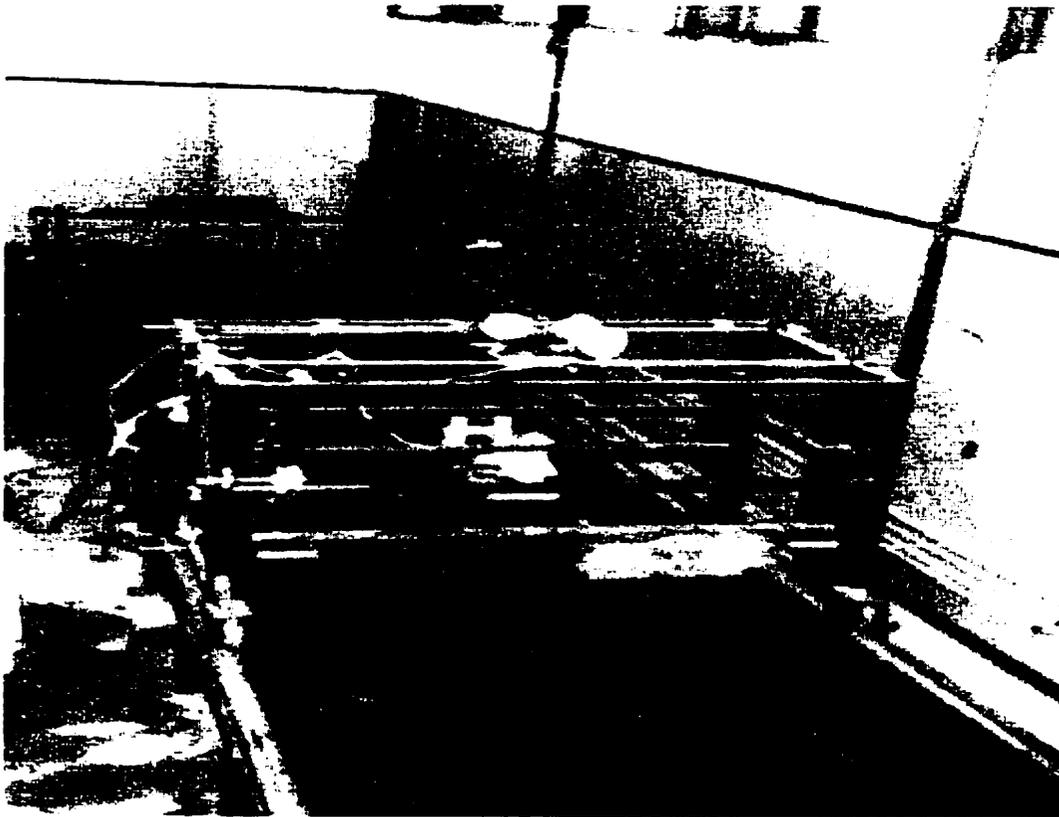


Fig. 5. Indoor soil bin facilities located in the Department of Biosystems Engineering, the University of Manitoba

test run along the tool's passage to examine the changes of bulk density. Soil bulk density and cross-sectional dimensions were measured only for the sweep injection tools to calculate the specific draft force. Soil samples were weighted and oven dried for 24 h at 105 °C. After drying, it was re-weighted to calculate the moisture content and bulk density.

3.1.5. Measurement and prediction of soil cutting forces The testing tool was mounted on a three dimensional force and moment dynamometer (Fig. 6). The three-dimensional force measuring setup was made up of three subassemblies: an active frame, passive frame and six force transducers (Kitson 1987). The testing tool was attached to the active frame and active frame was held solidly in place by six force transducers. The transducers were arranged so as to determine the draft (F_x), vertical (F_z) and side (F_y) forces as well as moments (M_x , M_y and M_z) about the respective axis.

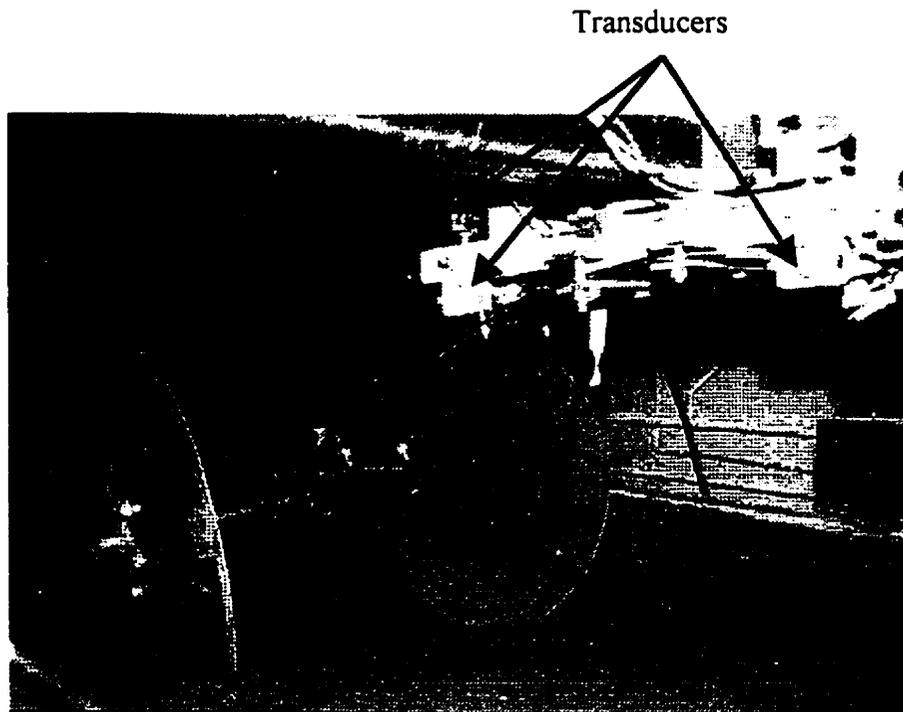


Fig. 6. Three dimensional force and moment dynamometer and injection tool

The testing tool was lowered to the experimental design depth and the design speed was achieved by adjusting the variable speed motor. The data acquisition system was attached to the three dimensional force and moment transducer to record data for every second.

Different theoretical models are available for calculating soil-cutting force. In this study the three dimensional soil cutting model of McKyes and Ali (1977) (Equation 1) was used to estimate the cutting forces of a single tool. The internal friction angle (ϕ) and cohesion of soil (c) (Table VI) were measured with a square shear box of 60 mm length for three different vertical loads (210, 480 and 745 N). The values of soil adhesion (c_a) and soil-tool friction angle (δ) were taken from the study by Godwin et al. (1984) for a similar soil condition. The rakes angle (α) was measured between the foot face and the direction of travel.

$$P = (\gamma g d^2 N_\gamma + cdN_c + c_a dN_{ca} + qdN_q + \gamma v^2 dN_a) w \quad (1)$$

Where. P = total tool force (N)

γ = total soil density (kN/m³)

g = acceleration due to gravity (m/s²)

d = tool working depth below the soil surface (m)

c = soil cohesion strength (kPa)

q = surcharge pressure vertically actin on the soil surface (kPa) and

w = tool width (m)

N_γ , N_c , and N_q are factors which depend on the soil frictional strength, tool geometry and tool to soil strength property (McKyes, 1985). These parameters can be determined as follows:

$$N\gamma = \frac{\frac{1}{2} \left[\cot \alpha + \cot \beta \left\{ 1 + \frac{2d}{3w} \{ \cot \alpha + \cot \beta \} \left\{ 1 - \left(\frac{\cot \alpha}{\cot \alpha + \cot \beta} \right)^2 \right\}^{\frac{1}{2}} \right\} \right]}{\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta + \phi)} \quad (2)$$

$$N_c = [1 + \cot \beta \cot(\beta + \phi)] / [\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta + \phi)] \quad (3)$$

$$N_a = \frac{\tan \beta + \cot(\beta + \phi)}{[\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta + \phi)] [1 + \tan \beta \cot \alpha]} \quad (4)$$

Where, N_a = an additional factor comprised in soil cutting forces, which accounts for the acceleration forces in the soil with varying tool speeds. The angle, β , is determined for each combination of tool geometry and soil strength properties by making $N\gamma$ term minimum using equation (2) with respect to β by trial and error basis (McKyes and Desir, 1984). The value of β varied from 0 to 90°.

The draft force (F_x) and the vertical force (F_z) comprises the sum of the total cutting force, P , and the adhesive force on the blade face as follows (McKyes, 1985):

$$F_x = P \sin(\alpha + \delta) + c_a d w \cot \alpha \quad (5)$$

$$F_z = P \cos(\alpha + \delta) - c_a d w \quad (6)$$

3.1.6. Soil surface disturbance measurement After each test run, soil surface disturbance profile was measured by a ruler and measuring tape. The ruler was placed over the disturbed soil surface to measure the disturbance height. At the same time, disturbance width was also measured at the same location. This was recorded at five random locations for each treatment.

3.2. Field studies

3.2.1. Field locations and physical properties The field study was conducted in three forage fields located in Headingley, Libau and Tolstoi, Manitoba, Canada, in 1999. Of the three fields, one was a heavy clay soil (in Headingley) and the others were coarse sandy loam with stone (in Libau) and fine sand (in Tolstoi). The fields featured crops of alfalfa in Headingley and mixed stands of timothy and alfalfa in Libau and Tolstoi (Table III). At the time of the field tests, the soil at Headingley site had high moisture content (39%) and the other two sites were relatively dry (9 and 16% in the Tolstoi and Libau, respectively). The soil and crop conditions are summarized in Table III.

Table III. Soil physical properties of the three fields used for the field tests

Parameters	Field locations		
	Headingley	Libau	Tolstoi
<u>Soil texture</u>	Heavy clay	Coarse sandy loam with stone	Fine sand
Sand (%)	3	76	94
Silt (%)	22	22	2
Clay (%)	75	12	4
Soil moisture content (% db)	39	16	9
Soil bulk density (Mg/m ³)	0.849	N/A*	1.1
<u>Crop type</u>	Alfalfa	Mixed timothy and alfalfa	Mixed timothy and alfalfa

* Soil samples could not be taken by a core sampler due to presence of stone in the field.

3.2.2. Experimental design A (3x2) factorial completely randomized design (CRD) was conducted with three manure application rates: R1=28 m³/ha (2500 gallons/acre), R2=56 m³/ha (5000 gallons/acre), and R3=112 m³/ha (10 000 gallons/acre)

and two injection depths (D1=80 to 90, D2=110 to 150 mm). The injection depth and manure application rate were chosen based on common practice. As it was difficult to achieve the design injection depths, the actual injection depth varied among the sites. A control plot (C) was included to investigate crop yield response to the effects of injection depth and manure application rate. To further differentiate the effects between manure and crop damage associated with the soil cutting on crop yield, two additional control plots (CD1 and CD2) were included. No manure was applied to those control plots. Out of the control plots, C was undisturbed, CD1 and CD2 subjected to injector pass at depth D1 and D2, respectively. Each treatment and control plot was repeated three times. Thus, a total of 27 plots were formed for each site. The length of the plot was 30 m with a width of 5 m allowing for one pass of the injector. Manure was injected on different dates for each site and measurements were performed within the same day of manure injection.

3.2.3. Injection unit The liquid manure injection system used was a six-wheel drive, center articulated truck riding on six 788 mm wide by 1499 mm tall Trelleborg flotation tires (Fig. 7). The total weight of the truck was about 40 tons with a full tank capacity of 22.7 m³ (5000 imperial gallons) of liquid manure. Manure was delivered to eight injection tools mounted to the system through flexible hoses. The maximum flow rate was about 7.6×10^{-3} m³/s (1000 gallons per minute). A tool spacing of 0.48 m was used forming a total working width of 4.30 m. The injection depths and application rates were controlled by hydraulic systems. The injection tool (Fig. 3a) featured a sweep arranged behind a flanged coulter. Their geometric parameters are listed in Table II.

3.2.4. Manure samples collection and analyses Three manure samples were collected in a plastic container from each manure tank before being applied to the plots

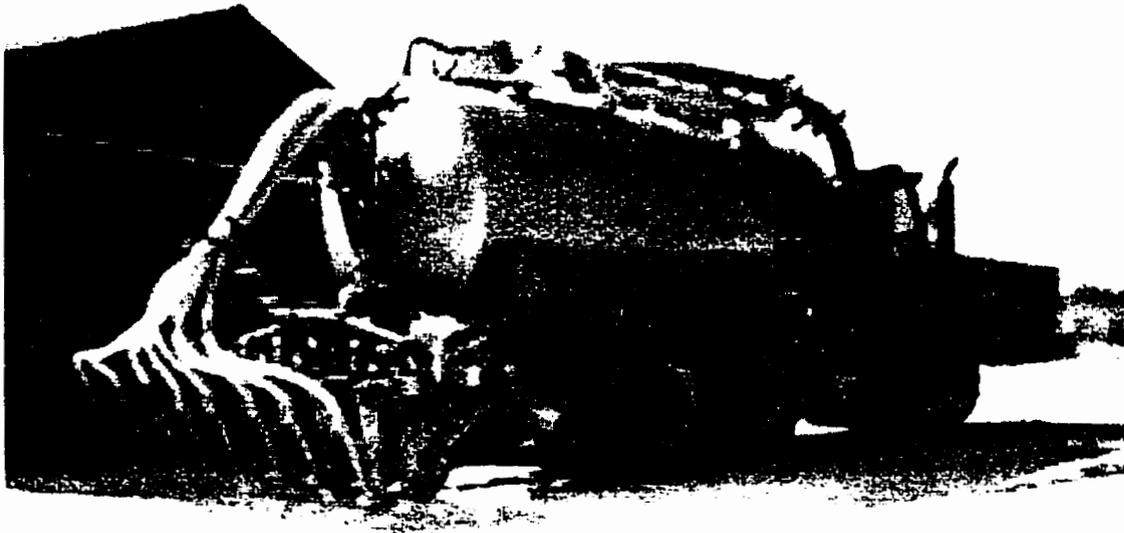


Fig. 7. The liquid manure injection unit used for field studies

and were stored in a freezer at $-4\text{ }^{\circ}\text{C}$ until being analyzed. Manure properties were measured by the Norwest Labs (Winnipeg, Manitoba) and listed in Table IV.

Table IV. Manure properties used for the field tests

Parameters	Field locations		
	Headingley	Libau	Tolstoi
Total Solids (%)	0.60	1.2	1.5
pH	7.8	8.0	7.5
Total Nitrogen (kg/1000 L)	1.2	1.0	3.10
Phosphorus (kg/1000 L)	0.03	0.08	0.16
Potassium (kg/1000 L)	0.70	0.46	1.79
Sodium (kg/1000 L)	0.28	0.14	0.41
EC (mS/cm)	10.9	7.90	21.3

3.2.5. Odour concentration measurement To determine odour concentration, odourous air samples at soil surface were collected through an airtight semi-cylindrical chamber (here after referred as “hood”) (Fig. 8) designed after Lockyer’s (1984). The hood was fabricated from a single transparent sheet of polycarbonate ($2.0 \times 1.2 \times 0.002\text{ m}$) mounted on a steel frame ($2.0 \times 0.5\text{ m}$) to cover a 1 m^2 area. An outlet consisted of steel and Teflon tube inserted in the middle of the hood was connected to a vacuum chamber (AC’SCENT vacuum chamber, St. Croix Sensory, Inc., Stillwater, MN) which pumped gas from the hood to Tedlar bags.

Two background gas samples were first collected at two random locations over the entire field before manure was applied. Immediately after manure was applied, the hood was randomly placed over the selected plots and sampling commenced. Due to very

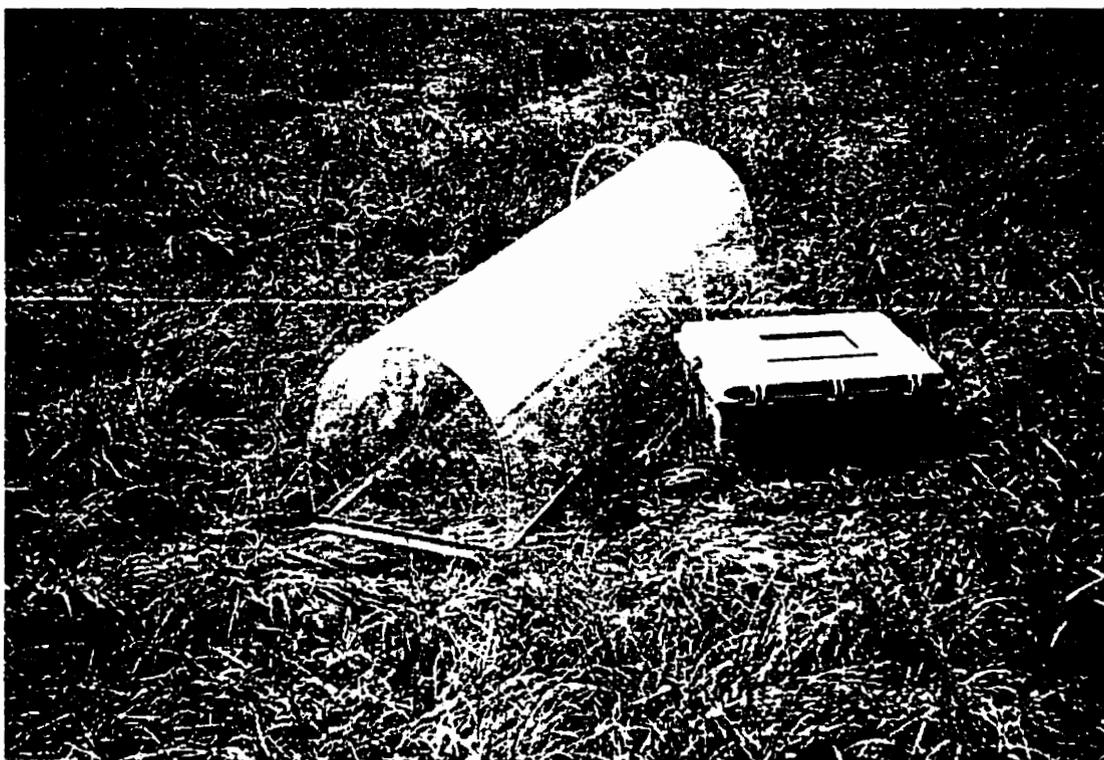


Fig. 8. Semi-cylinder chamber (left) and a vacuum chamber (right) used to collect air samples for odor concentration measurement

tedious nature of gas sampling and odour measuring with panels, gas samples were collected only from selected treatments: R2D2 and R3D1, medium and highest application rates at different injection depths. These two treatments represented the intermediate and the worst scenario in terms of odour potentials, respectively. Sampling was made for all the three replications. After collected, bags were brought back to the laboratory for subsequent analysis by using the olfactometer (Fig. 9) (AC'SCENT international olfactometer, St. Croix Sensory, Inc., Stillwater, MN) within 24 h. Odour concentration values were measured by a triangular forced choice method (Pain et al. 1991) with six panelists.

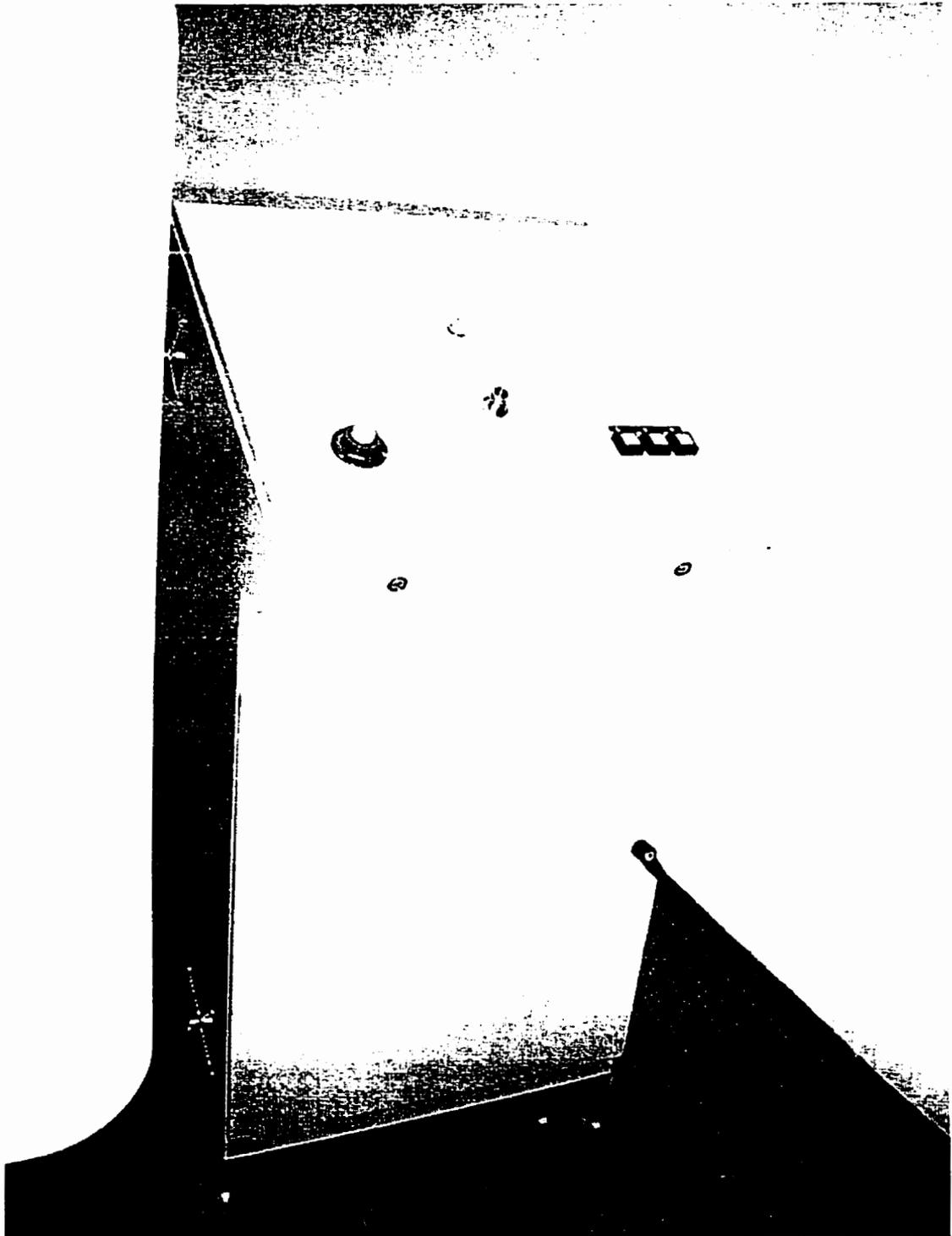


Fig. 9. AC'SCENT international olfactometer used for odour concentration measurement

3.2.6. Ammonia concentration measurement Ammonia concentration was measured by a colorimetric method using Dragger tubes and small cylindrical chambers. Small cylinder chambers, 170 mm high and 160 mm diameter (Chen et al. 2000), were used to trap the emitted ammonia from the land surface. On the top of the chamber a hole of diameter 5 mm was provided with rubber sealing to prevent air leakage and to insert the Dragger tube. When air is passed through the hole, it is trapped into the Dragger tube and after 15 minutes ammonia concentration was recorded in ppm. The chamber was placed over the plot at two random locations following the manure application.

3.2.7. Yield measurement A plot forage harvester (Fig. 10) (SE Forage and Livestock Center, Vita, Manitoba, Canada), was used for yield harvesting. The harvester mowed a stripe of 0.8 m wide along the entire length of the plots and collected the crop in a bag. Care was taken to avoid sampling over the wheel tracks for the injector. At the end of each plot, exact harvesting length was recorded and the grass collected in the bag was weighted. A sample of about 200g was also hand harvested from 10 random locations for each plot and oven dried at 60 °C for 72 h (ASAE 1993) to determine the dry matter yield. Yield harvesting was performed on October 7th and September 22nd in 1999 for the Headingley and the Libau sites, respectively. The Tolstoi site was not harvested due to an early frost.

3.2.8. Soil compaction Soil compaction in agricultural soil is commonly characterized by soil bulk density (ρ_b) and cone index (CI) value (Chen and Tessier 1996). They further explained that CI is easier to measure than ρ_b , but CI is more dependent on soil moisture content. Therefore, in this study, only ρ_b was measured to characterize the soil compaction.



Fig. 10. Alfa-Omega plot forage harvester used for crop harvesting

Ruts were observed along the injector wheel's track in the Headingley site having a clay soil with high moisture content (Table III). Therefore, soil cores were taken in this site to measure soil compaction, in terms of changes in soil bulk density. Four soil cores were taken from each of six plots following the manure injector at a depth of 100 mm along the wheel tracks of injector for varying manure tank loads. Tank or axle load was not measured, but tank capacity was visually observed (full tank to about empty tank). Soil samples were labeled in a chronological order account for varying tank load as manure tank was emptied while injecting. Soil cores were also taken from four random locations where no traffic passed to obtain the background bulk density.

3.3. Data analyses

In the soil bin tests, data were recorded in a data acquisition system for each treatment at an interval of one second and files were imported to Microsoft Excel. For each treatment, average value was taken for plotting graphs and interpretation of data. The draft force and specific resistance for the sweep tools were compared among the sweeps, while in other cases sweep B was compared with sweep C. Similarly, disc A was compared with disc B. For sweep A, a comparison was made between sweep with coulter and without coulter (WOC and WC).

Analyses of variance were used to test the main effects of the variables and their interaction effects. When interaction occurred the simple effects were tested. The means of the variables were obtained by using the DUNCAN multiple range option. Statistical inferences were made at the 0.1 level of significance.

4. RESULTS AND DISCUSSION

In the soil bin tests, the actual injection depth for the disc B was always lower than the experimental design depth due to its flexible spring shank. Similarly, in the field trials, the actual injection depths (D1 and D2) turned out to be different among sites even though the same depth setting was used, due to field and crop variability. The Headingley site had a shallower injection depth in both D1 and D2 than the other two sites, which had the same injection depths (Table V). Manure was injected on a different dates (Table V) for each site and measurements were performed within the same day of manure injection. Crop harvesting was done in the fall on two sites (Headingley and Libau sites) only. The Tolstoi site was not harvested due to an early frost.

Table V. Injection depths, manure application and harvesting dates for three sites.

Parameters	<u>Field location</u>		
	Headingley	Libau	Tolstoi
Injection depths (mm)			
D1	80 ± 9	90 ± 5	85 ± 5
D2	110 ± 10	150 ± 5	150 ± 10
Date of manure injection	25 th Aug., 1999	1 st Sep., 1999	27 th Sep., 1999
Date of yield harvesting	7 th Oct., 1999	22 nd Sep., 1999	N/A*

* Field was not harvested due to an early frost

4.1. Soil bin studies

4.1.1. Soil cutting forces Draft force (F_x) requirement is an important factor in selecting an injection tool for a particular farm situation. Because, draft and power requirement of an injection tool under a specific soil and crop conditions determine the

size of tractor required. Similarly, the vertical force (F_z) is important for tractor stability resulting from tractor weight transfer to the rear wheel (Kepner et al. 1987). Therefore, the following discussion deals only with the F_x and F_z .

4.1.1.1. Comparison of draft force among sweeps for a single injection tool

Comparison of draft force among the sweep injection tools showed that an increased injection depth resulted in an increased draft force for all the tools tested (Fig. 11) and the sweep A required the lowest draft force due to its smaller cutting width and rake angle. The F_x for the sweep A increased approximately at a constant rate with increased depth. For the sweep B, the draft force slightly increased from 100 to 150 mm than 50 to 100 mm. While, for sweep C, the F_x increased linearly from 50 to 150 mm. For the sweep A and B, the draft force requirement from 50 to 100 mm depth were about same and it was slightly increased for sweep B as the depth increased from 100 to 150 mm. As compared to the sweep A, on the average, sweep B and sweep C required 12 and 97% more draft force, respectively, since the later two sweeps have a wider cutting width (Table II). For all sweeps tested, draft force significantly increased with injection depths irrespective of travel speeds. Therefore, injection depth should be as shallow as possible in order to reduce power requirement, yet deep enough to cover the manure. Therefore, based on power requirement, it is suggested that the injection depth should be selected under 100 mm to reduce draft force requirement for all tested sweeps.

4.1.1.2. Comparison between predicted and measured draft force for sweep tools

To compare the theoretical draft force with the measured values, the three dimensional soil cutting model of McKyes and Ali (1977) (Equations 1 to 6) was used.

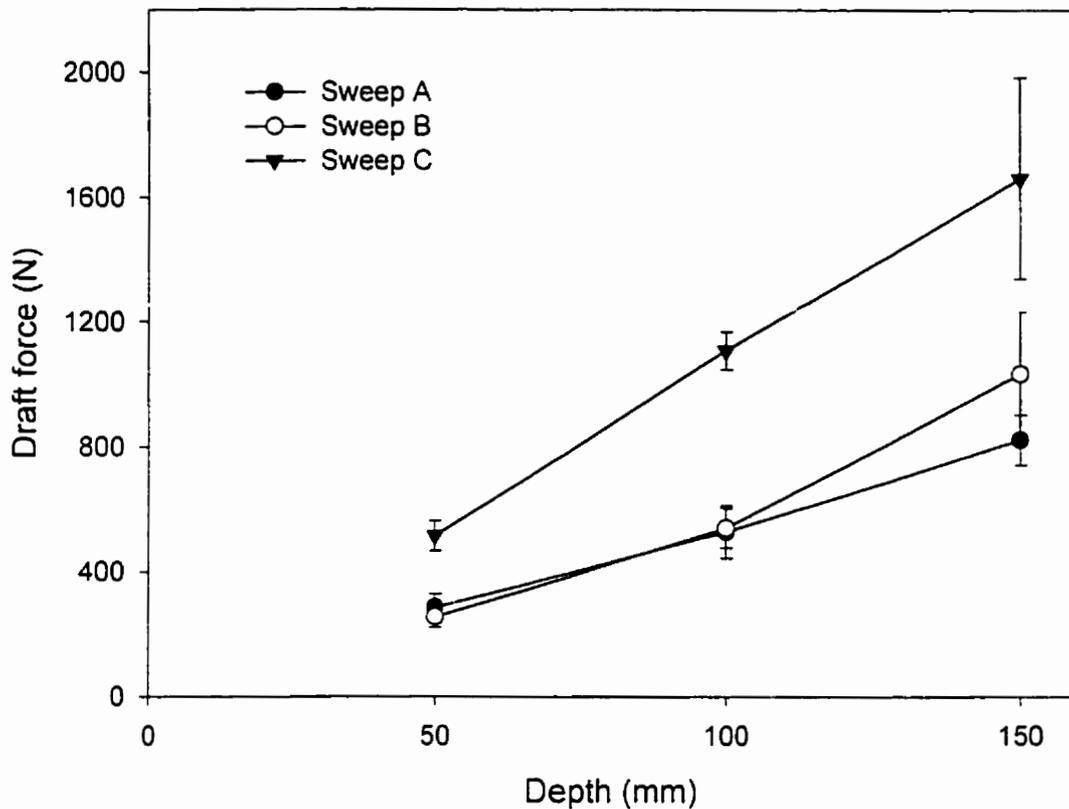


Fig. 11. Comparison of draft force requirement for different sweep injection tools averaged over two forward speeds.

The internal friction angle (ϕ) and cohesion of soil (c) (Table VI) were measured with a square shear box of 60 mm length for three different vertical loads (210, 480 and 745 N). The values of soil adhesion (c_a) and soil-tool friction angle (δ) were taken from the study by Godwin et al. (1984) for a similar soil condition (Table VI). The rake angle (α) was measured between the foot face and the direction of travel. Other input parameters for the model are presented in Table VI.

Table VI. Inputs for the universal equation to predict draft force

Symbol	Description	Values
θ	Soil moisture content (% db)	16
ρ_b	Dry bulk density (Mg/m^3)	1.35
ϕ	Soil internal friction angle ($^\circ$)	29
c	Soil cohesion (kPa)	9.23
c_a	Soil adhesion (kPa)	0
δ	Soil-tool friction angle ($^\circ$)	22
α	Tool cutting angle ($^\circ$)	Sweep A: 3; Sweep B: 21.5; Sweep C: 18.5
γ	Soil gravity (kN/m^3)	13.23
w	Tool cutting width (m)	Sweep A: 0.22, Sweep B: 0.33; Sweep C: 0.57
d	Cutting depth (m)	0.05, 0.10 and 0.15
q	Soil surface surcharge pres. (kPa)	0
v	Tool travel speed (m/s)	1.4

The degree of agreement between the predicted and measured draft forces for the sweep tools are shown in Fig. 12. The predicted draft forces (Fig. 12) and vertical forces (data not shown) agreed well with the measured values for the sweep A with a coefficient of determination (R^2) of 0.92 and 0.88, respectively. Similarly, the predicted draft forces for the sweep B agreed with the measured values with a coefficient of determination (R^2) of 0.95, while they were slightly lower than the measured values for the sweep C with a coefficient of determination (R^2) of 0.92. However, the predicted vertical force agreed with the measured values with a coefficient of determination (R^2) of about 0.58 and 0.97 for the sweep B and C, respectively (data not shown).

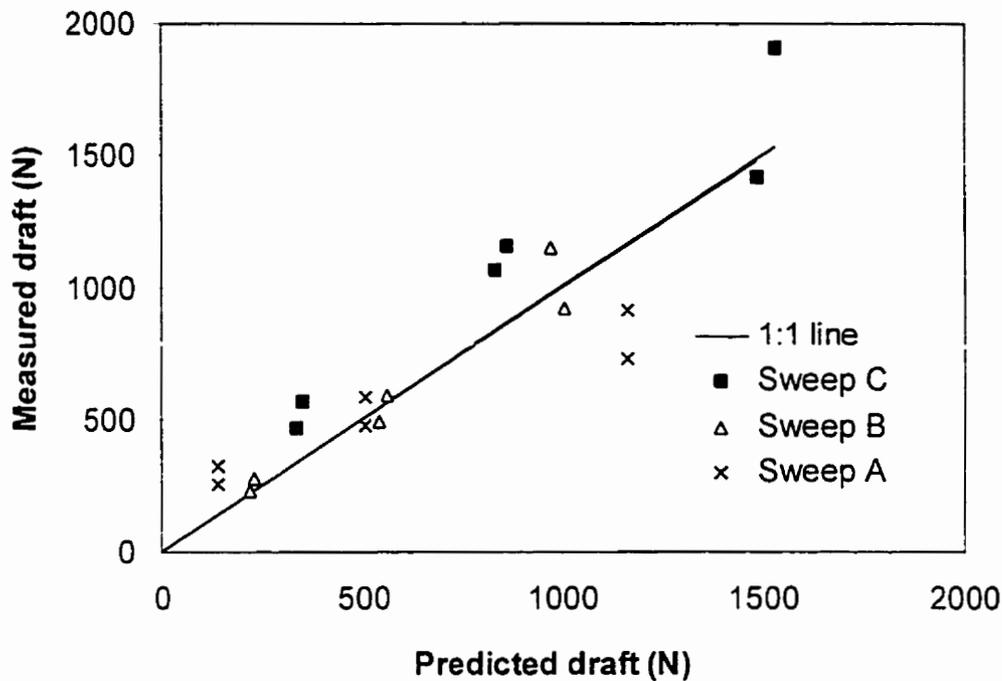


Fig. 12. Comparison between predicted and measured draft force among sweep injection tools using the three dimensional soil cutting equations (McKyes and Ali 1977)

4.1.1.3. WC vs. WOC for sweep A For the two tool-arrangements, both injection depth and forward speed significantly affected the F_x (Fig. 13). No interaction was found between these two parameters. For the WC tool-arrangement, F_x increased more steeply from 100 to 150 mm depth (57%) than from 50 to 100 mm (19%) (Fig. 13) due to higher rolling resistance resulting from flanged coulter at higher depths. For both tool-arrangements, higher speed required significantly more draft force. It is generally expected that arranging a coulter in front of the sweep would help to reduce the draft force requirement (Huijsmans et al. 1998). However, the results from this study showed that coulter required additional draft (38%) when injection at depths of 100 and 150 mm, regardless of forward speed (Fig. 13). Therefore, coulter effects on the draft force of a system are significant when used ahead of sweeps. The arrangement of coulter in the

front of the sweep was for the purpose of cutting crop residue or roots when applying manure or stubble or pasture. However, a coulter may not be necessary when injecting manure into tilled soil to reduce draft force.

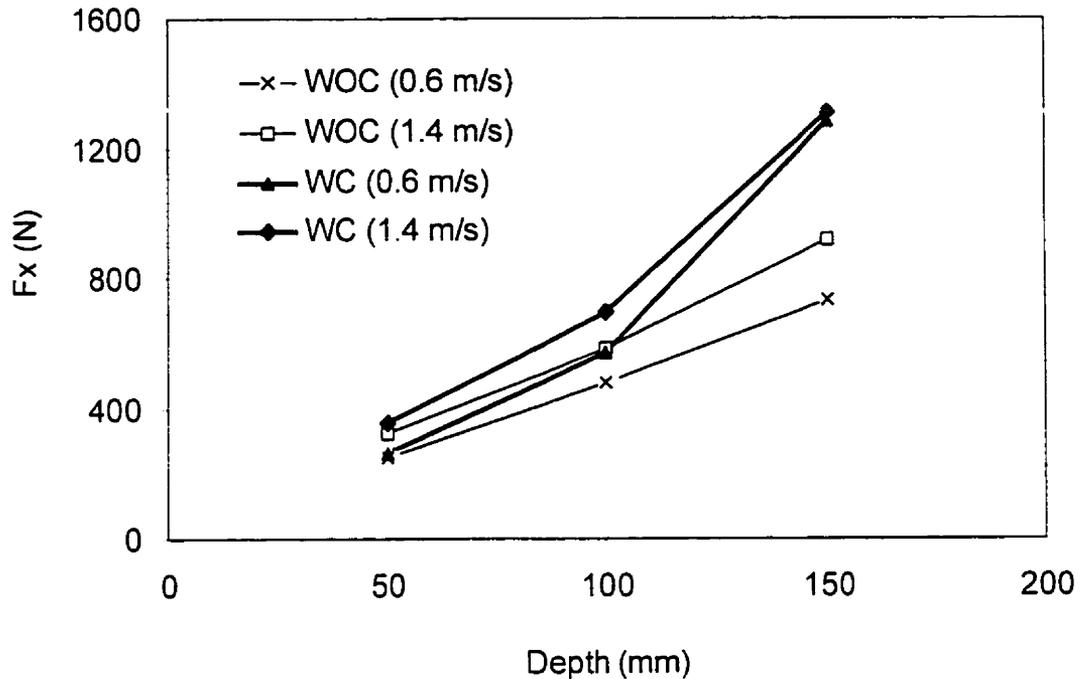


Fig. 13. Comparison of draft force versus injection depths for the sweep A injection tool at two different forward speeds

The vertical force, F_z , was significantly affected by injection depth but not by speed for the WC. F_z was not significantly related to any parameters for the WOC in any cases. No interactions were found for WC or WOC. It is generally expected that the vertical force of a sweep tool would increase with the injection depth. However, the F_z obtained with WC decreased from 50 to 100 mm and then increased because of the flanges on the coulter (data not shown). On the average, the WC required less vertical force than the WOC (252 and 344 N, respectively) as the flanged coulter support load at higher injection depth.

4.1.1.4. Disc A vs. disc B Except for the disc B, precise experimental depths was obtained with the same tool bar position. The actual injection depths for the disc B was always shallow due to its flexible spring shank and the upward soil force. Therefore, in field conditions, additional force might be needed to keep an appropriate downward pressure to ensure penetration to a target depth.

Figure 14 shows the variation of draft force with the actual injection depth, which was in the case of disc B, different from the depth designed for the experiment. Its actual three injection depths were measured as 40, 80, and 110 mm. For both the discs, F_x significantly increased with injection depth (Fig. 14) but not with speed (data not shown). The trend showed that the disc B requires more draft force than the disc A at similar injection depths. This is because the disc B has two discs penetrating into the soil, and a large disc and tilt angle (Table II).

Unlike the sweep type tools, F_z for disc-type tools decreased with increasing depths. On the average, F_z decreased from 545 to 222 N for the disc A, and from 620 to 20 N for the disc B. According to Kepner et al. (1987), increased speed would help to improve the soil penetration by discs. However, this was not the case in this study. Increasing speed from 0.57 to 1.4 m/s didn't significantly change values of F_z (415 to 370 N and 345 to 310 N for disc A and B, respectively).

4.1.2. Soil surface disturbances and changes of bulk density

4.1.2.1. WC vs. WOC for sweep A In soil bin condition, the injection tool loosened a strip of soil surface (width: W_1) along the center of the tool path and moved soil sideways, forming two mounds (Height: H_1) (Fig. 15). W_1 and H_1 were significantly

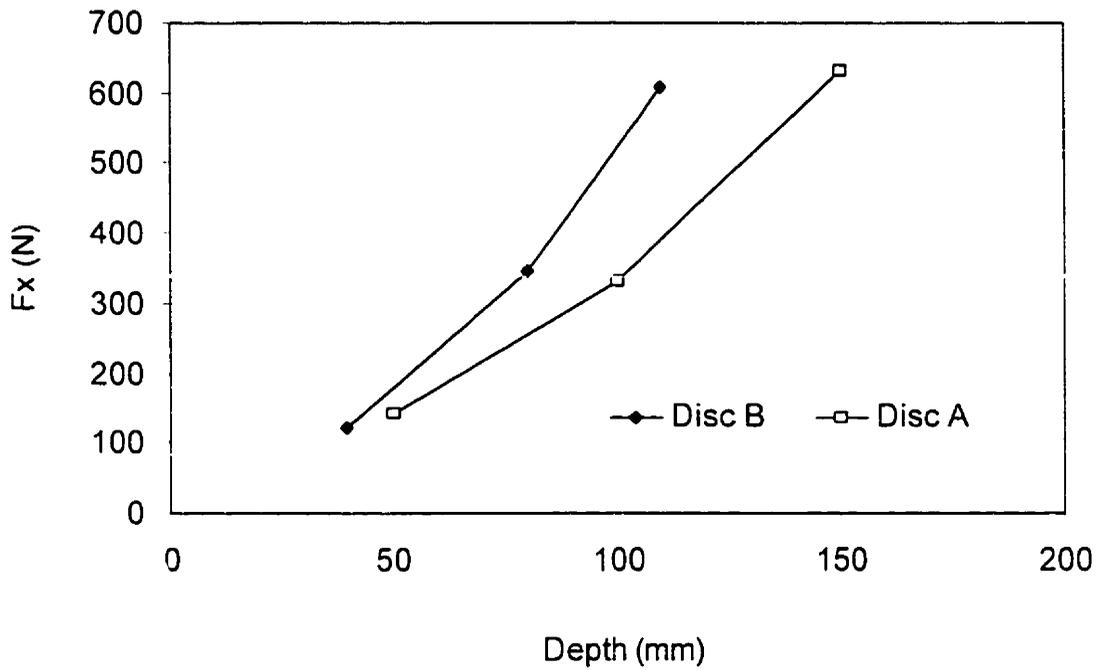


Fig. 14. Comparison of draft force averaged over two forward speeds; versus injection depths for the disc A and disc B injection tool

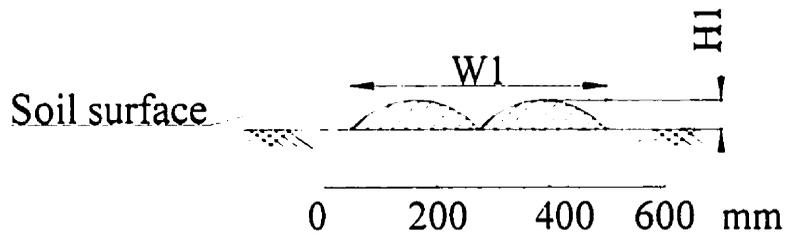


Fig. 15. Soil surface disturbance profile of a single sweep A injection tool in the soil bin conditions

affected by injection depth but not by speed and their interaction. Higher soil disturbance in terms of W1 and H1 was observed at higher depth for both tool arrangements (Figs. 16a, b) due to crescent type soil failure continued with increased injection depth (Spoor and Godwin 1978). Addition of a coulter caused a significantly wider W1 at two shallower depths (Fig. 16a), while it produce higher H1 at the two deeper depths (Fig. 16b). On the average, W1 and H1 were 10 and 12% higher for the WC relative to the WOC. Use of a coulter might thus cause rougher soil surface due to higher soil disturbance. A coulter may prevent the injection tool from braking down under adverse conditions such as heavy residue and old pasture, but when using for grassland, it might cause more crop root damage due to the higher soil disturbance.

No significant differences in bulk density were observed between the two-tool arrangement at any depth and speed (Fig. 17). On the average, bulk density at 100 mm depth decreased about 29% from initial density. This implies that the injection tool created about 29% new soil voids. According to Negi et al. (1978), these new voids would be available to absorb injected liquid manure. No significantly further decreased in bulk density when increasing injection depth from 100 to 150 mm. Therefore, injecting manure to a depth deeper than 100 mm might not be able to provide more available voids for absorbing manure.

4.1.2.2. Sweep B vs. sweep C Soil cross-sections disturbed by both the sweep B and sweep C were of a trapezoidal shape (Figs. 18a, b). The bottom of trapezoid was close to the sweep width and the height of trapezoid to the injection depth. The sweep C disturbed a larger cross-section area, consequently this should favor a higher manure application rate (Chen et al., 1999), compared to the sweep B. The sweep B created a

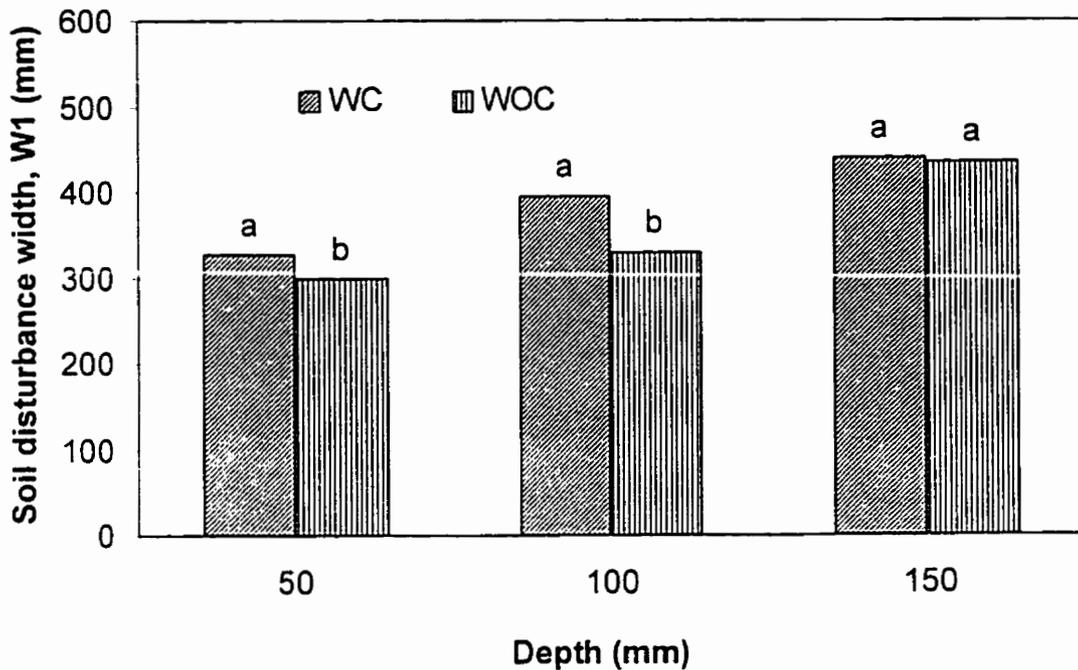


Fig. 16a. Comparison of soil surface disturbance width averaged over two forward speeds versus injection depth for the sweep A injection tool; values with the same letter are not significantly different at 0.1 level with each depth

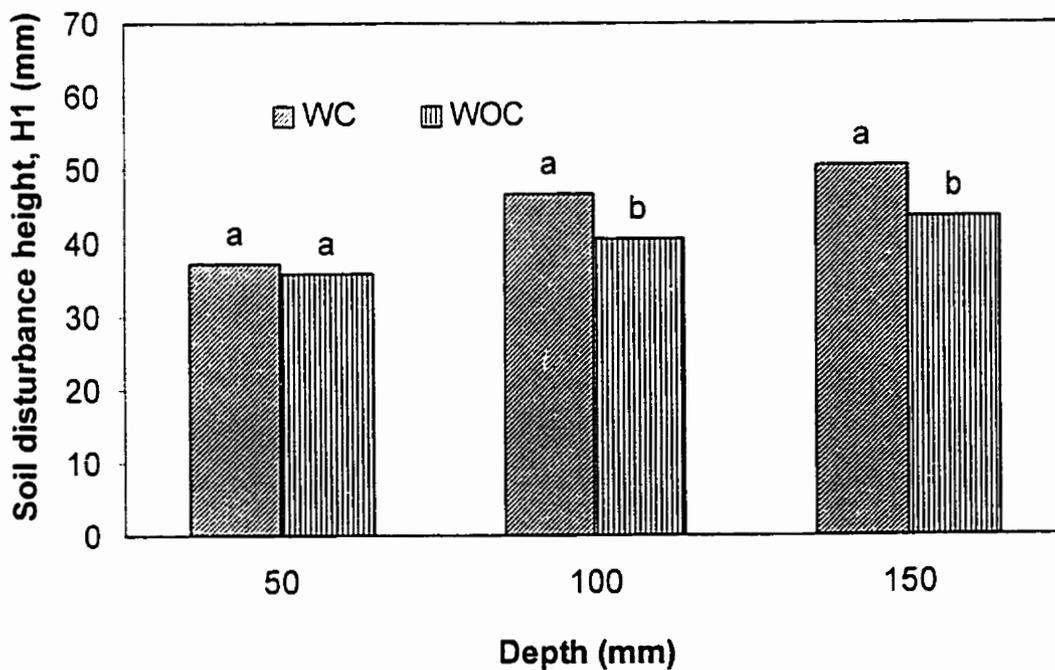


Fig. 16b. Comparison of soil surface disturbance height averaged over two forward speeds versus injection depth for the sweep A injection tool; values with the same letter are not significantly different at 0.1 level with each depth

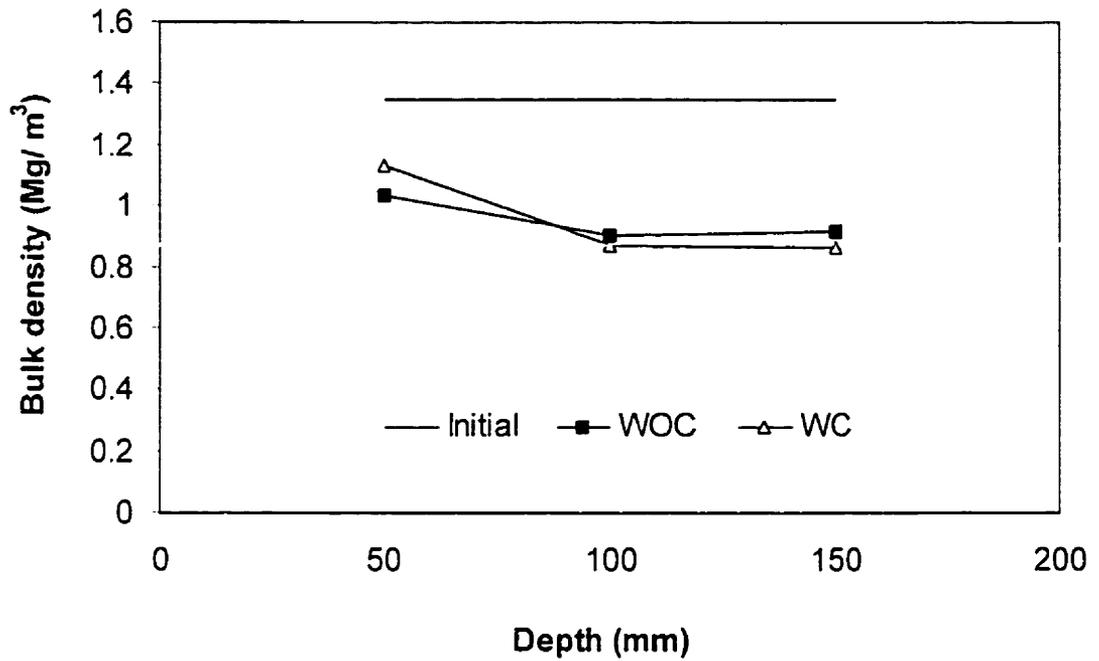


Fig. 17. Changes of soil dry bulk density versus injection depth averaged over two forward speeds

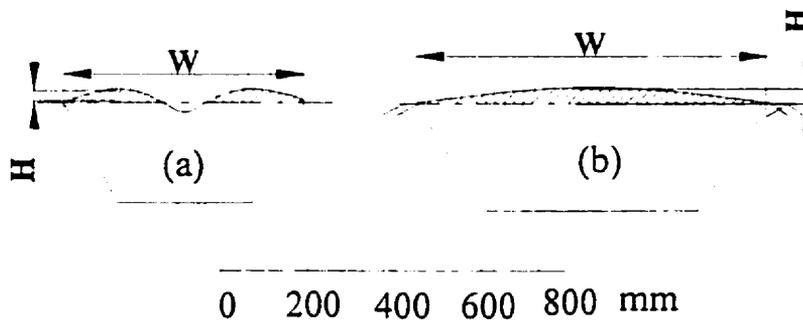


Fig. 18. Soil surface disturbance profiles for a) sweep B and b) sweep C

shallow narrow channel in the center of tool path and mounds soil to the side (Fig. 18a) while the sweep C spread soil more evenly over the cutting width of the surface (Fig. 18b).

Soil surface disturbance for the sweep B indicated that soil moved towards the sides during the cutting, which may not favor manure coverage but consume extra power. Surface disturbance was characterized as width (W) of the loose soil mound and height (H) shown in Fig. 18. The effects of forward speed on soil disturbance were not detected. Increased injection depths significantly increased W (Fig. 19), H, and cross-section disturbed (data not shown). A 44% higher W with the sweep C was found since it has a 72% larger cutting width than sweep B. Higher surface disturbance of soil might require additional tillage operations for seedbed preparation. A larger W may also imply greater crop damage for grassland application of manure.

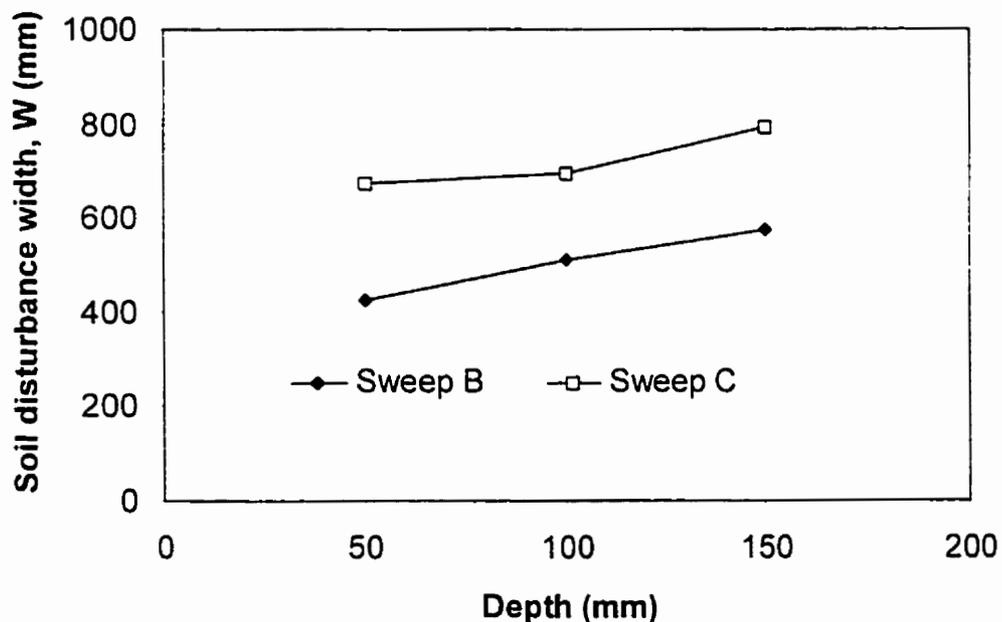


Fig. 19. Comparison of soil surface disturbance width averaged over two forward speeds versus injection depths for the sweep B and sweep C

Differences in bulk density between the two sweep type tools were insignificant. For both sweeps, on the average, bulk density decreased from the initial value of 1.35 to about 0.84 Mg/m³ as the depths increased from 50 to 150 mm (Fig. 20). However, the change of bulk density from 100 to 150 mm is slowdown than 50 to 100 mm. On the average, both sweeps created about 27% new soil pores. According to Negi et al. (1978), these new pores would be available to absorb injected liquid manure. This information can be used for selecting injection depth (Chen et al. 1999).

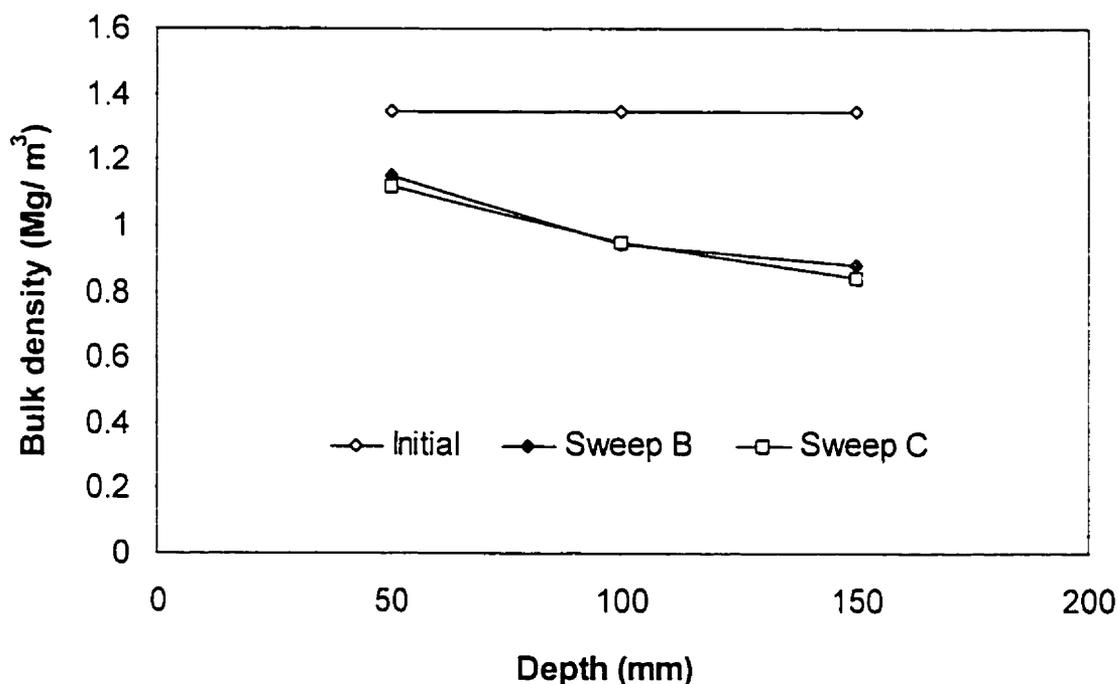


Fig. 20. Changes of soil dry bulk density averaged over two forward speeds for the sweep B and C injection tools.

4.1.2.3. Disc A vs. disc B The disc A created a clear-cut furrow in the soil cross-section and moved soil to one side forming a mound (Fig. 21). The furrow was of a triangular shape with a width of W₂ on the soil surface and a depth equal to the injection

depth (d). Manure would be placed into the furrow in the case of manure injection. An increased W_1 may indicate that more manure can be placed as larger cross-sectional area of the furrow would favor higher manure application rates (Chen et al. 1999). There were no particular trends observed for W_1 which ranged from 20 to 96 mm. The overall width of surface disturbance, W_2 , increased significantly with increased injection depth and speed (Fig. 22) but not by their interaction. Deep injection depth (150 mm) and higher speed would favor soil-manure mixing since the furrow was refilled with disturbed soil. and consequently. nutrient losses and odour emissions could be reduced. There were no particular trends observed for the mound height H_1 which ranged from 23 to 54 mm.

The disc B inverted soil to the surface. forming two mounds at 40 mm depth and one mound at 110 mm depth (Fig. 23a. b). At a depth of 40 mm, an area between the two discs. represented by a width W_3 (Fig 23a). was not covered by loose soil and manure would be dropped within that uncovered area. As a result, manure would not be incorporated adequately at this depth. increasing risks for nutrient losses and odour emissions. As the injection depth increased, the magnitude of W_3 was reduced significantly with depth and speed (Fig. 24) but not with their interaction. At greater injection depth (110 mm), the entire area between two discs was covered with loose soil up to a depth of (H_2) (Fig. 23b). At this depth, values of W_3 reduced to zero for the two forward speeds (Fig. 24), where complete manure incorporation could be expected. No consistent trend was observed for H_2 which varied from 39 to 64 mm. Values of W_4 were similar to the distance between the two discs, regardless of forward speed and depth.

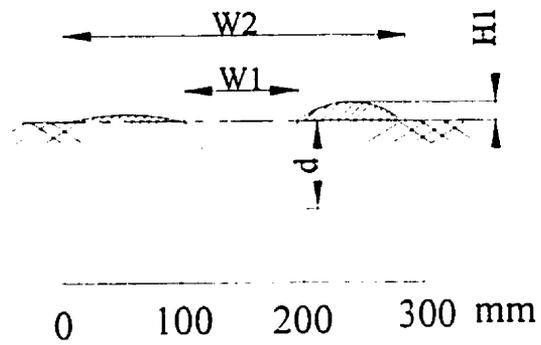


Fig. 21. Soil surface disturbance profile for the disc A

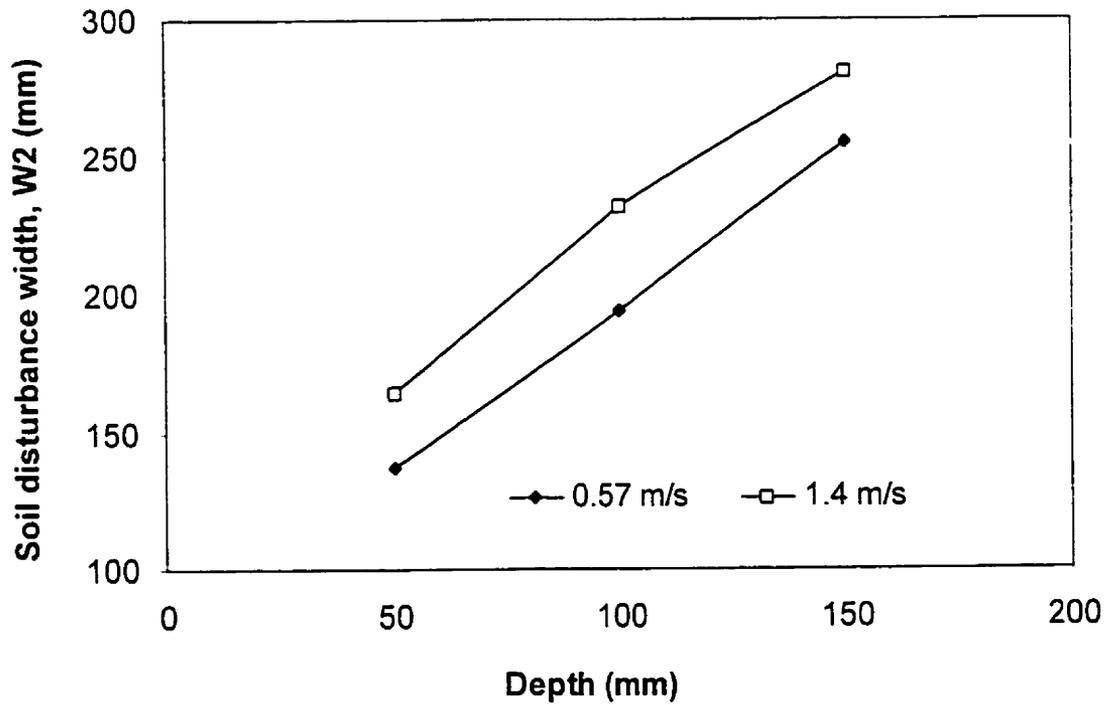


Fig. 22. Soil surface disturbance width versus injection depth for the disc A at two different forward speeds

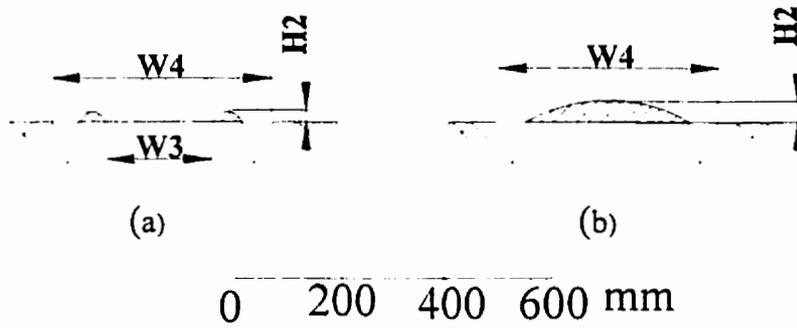


Fig. 23. Soil disturbance profiles for the disc B at a) 40 mm and b) 110 mm depth

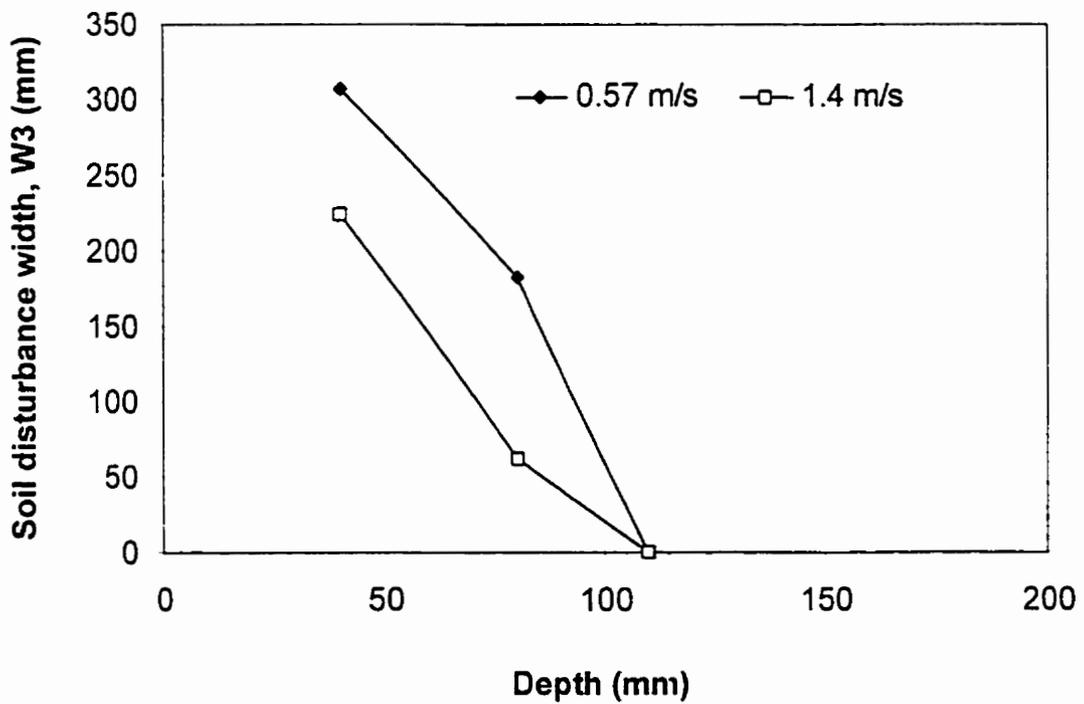


Fig. 24. Soil surface disturbance width versus injection depth for the disc B at two different forward speeds

4.1.3. Specific draft force for sweep tools Performance of an injection tool can be determined in terms of the draft force, the cross-sectional area and the specific draft force (draft force per unit area of soil disturbance) (Spoor et al. 1978). The field efficiency of a manure injection tool needs to be evaluated for both the draft force requirement and the amount of manure that can be injected (Ren and Chen 1999). Magnitudes of cross-sectional areas of disturbed soil reflect the maximum amount of manure which soil can potentially absorb (Godwin et al. 1976). Therefore, specific draft force (draft force per unit cross-sectional area of soil disturbed) can be used to evaluate the loosening performance of the sweep-type manure injection tools theoretically.

In terms of specific draft force, sweep A (WOC) resulted in the highest specific draft force due to least soil disturbance compared to other sweeps. Specific draft force significantly decreased with increased injection depth for the sweep A. Although the sweep C disturbed a larger soil cross-sectional area than other sweeps but, on the average, required 19% lower and 23% higher specific draft force than sweep A and B, respectively (Fig 25). As the injection depth increased from 100 to 150 mm, the specific draft force for the sweep C was about the same level. While, the specific draft force for the sweep B slightly increased beyond 100 mm. As the specific draft force should be minimized (Godwin et al. 1984), any injection depth from 50 to 150 mm could be selected for the sweep C. But for the sweep C, the draft force requirement was higher from 100 to 150 mm than 50 to 100 mm (Fig. 11). Therefore, an injection depth 50 to 100 mm is suggested for the sweep C. For the same reason, injection depth less than 100 mm is suggested for sweep B. While an injection depth greater than 100 mm could be chosen for the sweep A to minimize power requirement.

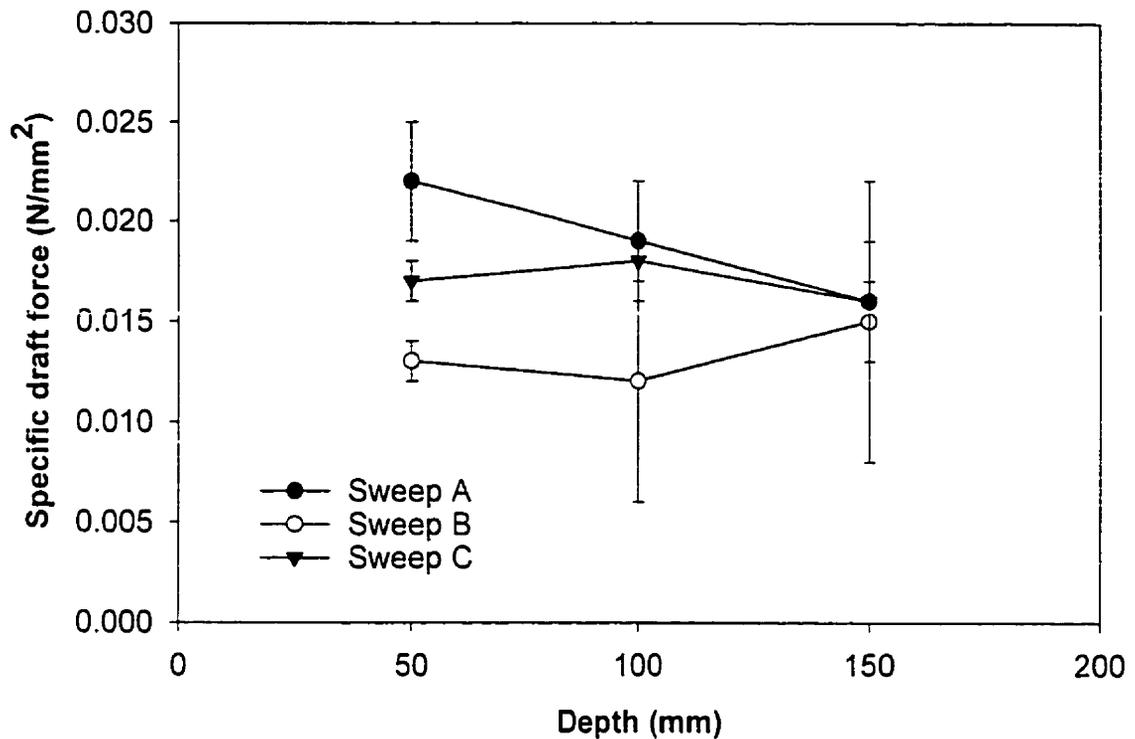


Fig. 25. Specific draft forces versus injection depth for the sweep injection tools; averaged over two forward speeds

4.2. Field studies

4.2.1. Soil disturbances and manure exposure The surface disturbance profile of the field (Fig. 26) was of different shape from that of the soil bin. due to the presence of vegetation. A clear cut was first created by the coulter on the surface layer which was then lifted up by the sweep resulting in a slot opening (W_2) in the center of tool path. The surface layer was lifted up by the sweep to a certain height (H_2), which reflects the surface roughness. Obvious soil disturbance width on the surface, previously mentioned for the soil bin situation, could not be located since the soil of surface layer was held together by grass roots. Therefore, instead of surface disturbance width, slot opening (W_2) was used to characterize the field situation. The width of slot-opening (W_2) plays a

key role in controlling the odour and ammonia emissions from injected manure into established forage fields.

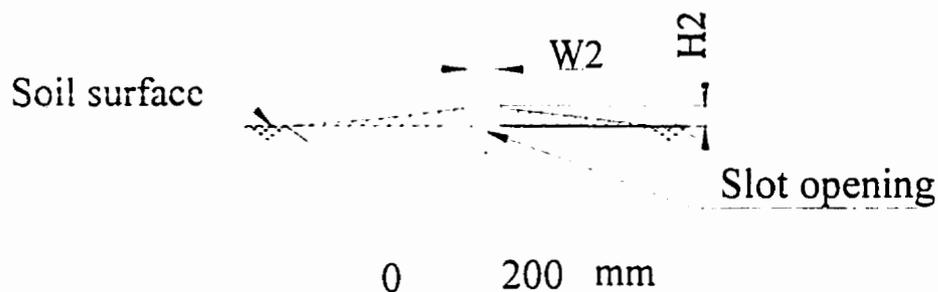


Fig. 26. Soil surface disturbances profile of a single sweep injection tool at the field conditions

The W2 and H2 significantly increased with injection depth at Libau and Tolstoi (Figs. 27a, b). This trend was similar at Headingley although it is not statistically significant. Under the same soil and crop conditions, shallow depth had advantage in terms of reduction in soil disturbance, especially in the Tolstoi where soil was extremely sandy and dry. The highest H2 and W2 were recorded at Headingley regardless of injection depth. This may be the result of its heavier soil texture and higher soil moisture content (Table III).

Big chunks of sod were inverted at some locations at the Headingley site as the injector passed. As a result, the manure injected at such locations was exposed to the air. Occasionally, manure was also visually observed from some slot openings at the shallower depth (D1) combined with either of two higher application rates (R2 or R3).

4.2.2. Odour concentration following liquid manure application to land The background odour concentration measured at the sites ranged from 52 to 135 odour units

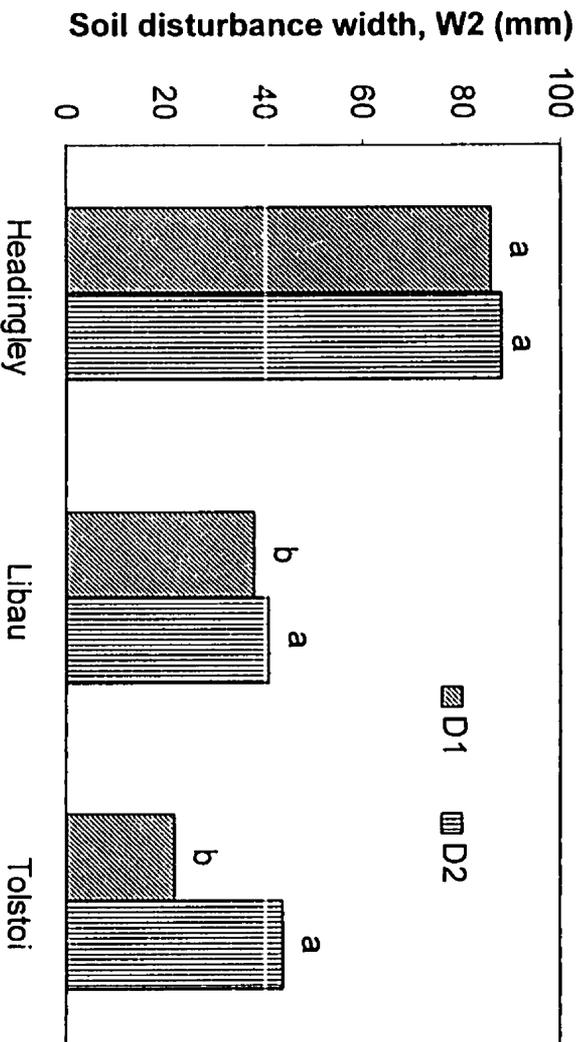


Fig. 27a. Comparison of field soil disturbance width averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level.

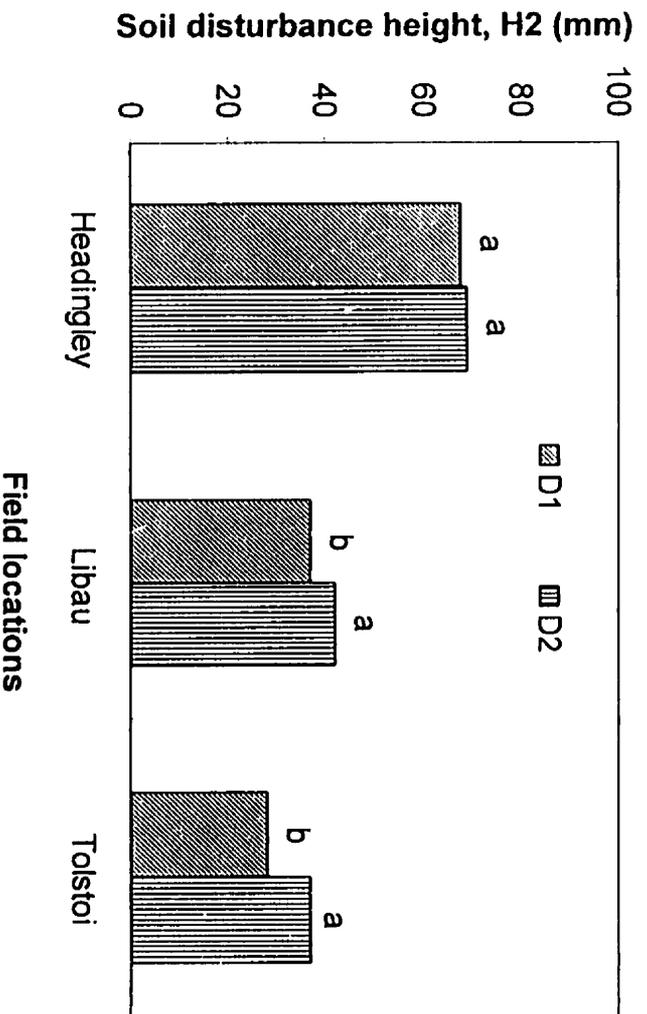


Fig. 27b. Comparison of field soil disturbance height averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level.

(OU) (Table VII), which is consistent with the value of 50 to 150 OU reported by Moseley et al. (1998). The odour concentration for the selected two treatments, following the manure application, was approximately twice as high as the background levels at all sites (Table VII). However, the differences of odour concentration between two treatments were not significant for all sites. Odour concentrations from the Libau site seemed higher than those measured at other two sites. Odour concentration is influenced by manure properties (TS, pH), soil type, moisture content, and infiltration rate (Svensson 1994; Moseley et al. 1998). However, higher odour concentrations at the Libau site could not be explained by those factors.

Table VII. Odour concentration following the application of manure at two different treatments

Application rate	Treatments	Odour units (OU)		
		Headingley	Libau	Tolstoi
5000 gal/acre (56 m ³ /ha)	R2D2	120a*	263b	102a
10000 gal/acre (112 m ³ /ha)	R3D1	119a	291a	106a
	Background	65a	135b	52b

* Means followed by the same letter in each column are not significantly different at the 0.1 probability level (DUNCAN).

4.2.3. Ammonia volatilization Ammonia volatilization from soil was measured immediately after the injector's passes. Except for one treatment (R3D1, in Headingley), where on the average 7.8 ppm ammonia concentration from the soil surface was detected, no ammonia was found in all other treatments. This was attributed to the successful placement of manure under the soil surface, which minimized the manure exposure, and

consequently volatilization. Thompson et al. (1987) also reported that efficient injection of slurry could be reduced ammonia loss to a negligible level.

4.2.4. Yields response To see the effects of injection depths and application rates on grass damage and yields, the control plot yield was compared with the treated plots. The yield was measured at the Headingley site on 7th October 1999 and at Libau on 22nd 1999. Harvesting was done earlier due to an early frost season. As mentioned before, the yield at Tolstoi site was not measured due to the manure application in late season. Therefore, the discussion in this section is focused on the results from the other two sites.

4.2.4.1. Crop damage Compared to the control plot C, CD1 and CD2 plots showed slightly lower crop yield (Fig. 28), likely attributable to crop root damage from the action of injectors as also reported by Thompson et al. (1987) and Misselbrook et al. (1996). However, these differences were not statistically significant at both sites owing to high variation of the data. The CD2 resulted in lower crop yield than the CD1 at Headingley due to the slot openings not being closed properly. In contrast, at the Libau site, the CD2 produced higher yield compared with the CD1. This may be explained by the fact that deeper operation depth cuts less grass roots since grass roots are concentrated within the upper soil layer.

Significant increases in soil bulk density were observed on the wheel tracks compared with the background value at all sampled locations (at Headingley). The soil compaction was attributable to several factors including heavy injection truck, soil texture and high soil moisture content (Bédard et al. 1997). To further describe the effects of change in load on the extent of soil compaction, values of density are plotted (Fig. 29) in a chronological order in soil sampling following the manure injecting. The trend was

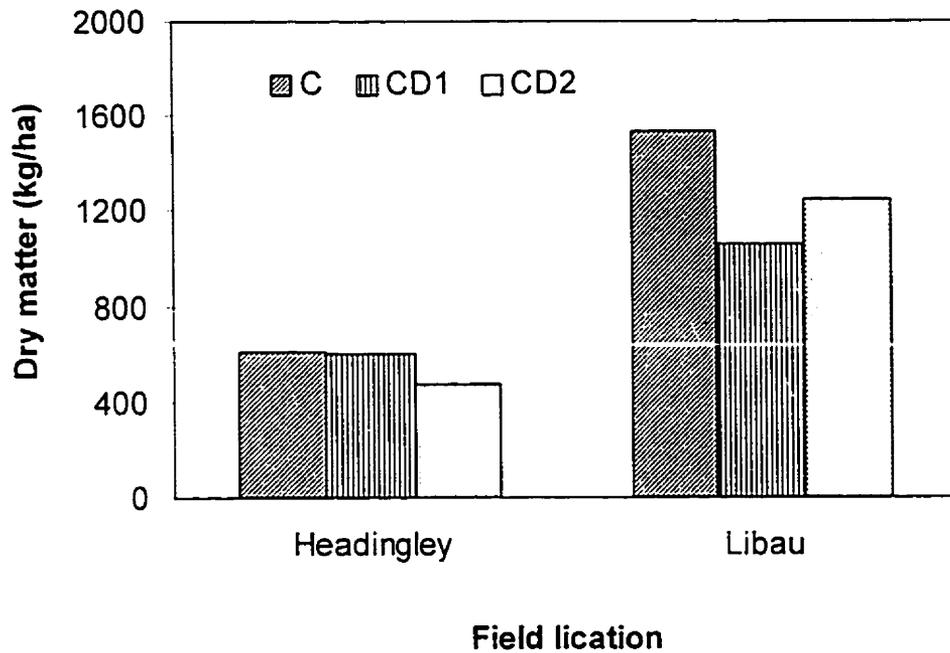


Fig. 28. Comparison of field soil disturbance width averaged over application rate; values with the same letter within each site are not significantly different at 0.1 level

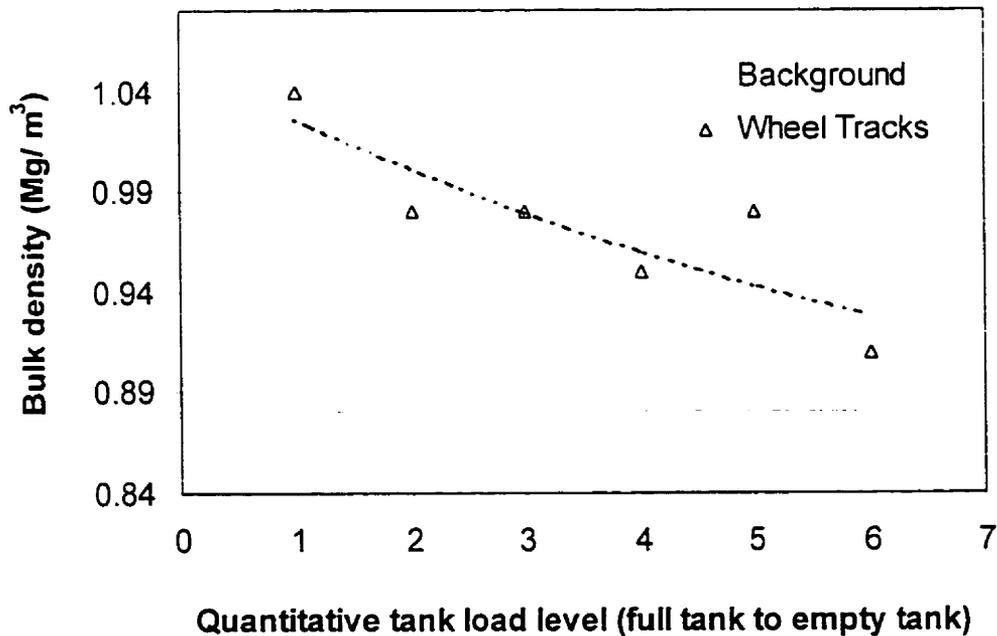


Fig. 29. Dry soil bulk density versus soil sampling order, showing the effect of changes in load on the extent of soil compaction at the Headingley site.

that the bulk density decreased along the course of sampling depending on tank load capacity while injecting manure. Therefore, avoiding injecting manure using this injector under a wet clay soil condition would be suggested.

4.2.4.2. Crop yield The two higher application rates (R2 or R3) trend to favor higher yields for both sites, but these trends were not significant. At Headingley, for the same application rate, injection at greater depth (D2) resulted in a significantly increased yield than at the shallow depth (D1) (Fig. 30). The same trend was observed for the Libau site, although it was not significant. Similarly, no significant differences were observed with their interaction for both sites. On the average, the yield of the Headingley site was 475 kg/ha and that of the Libau was 1350 kg/ha. The yields for both sites are seemed very low due to early harvesting of crop.

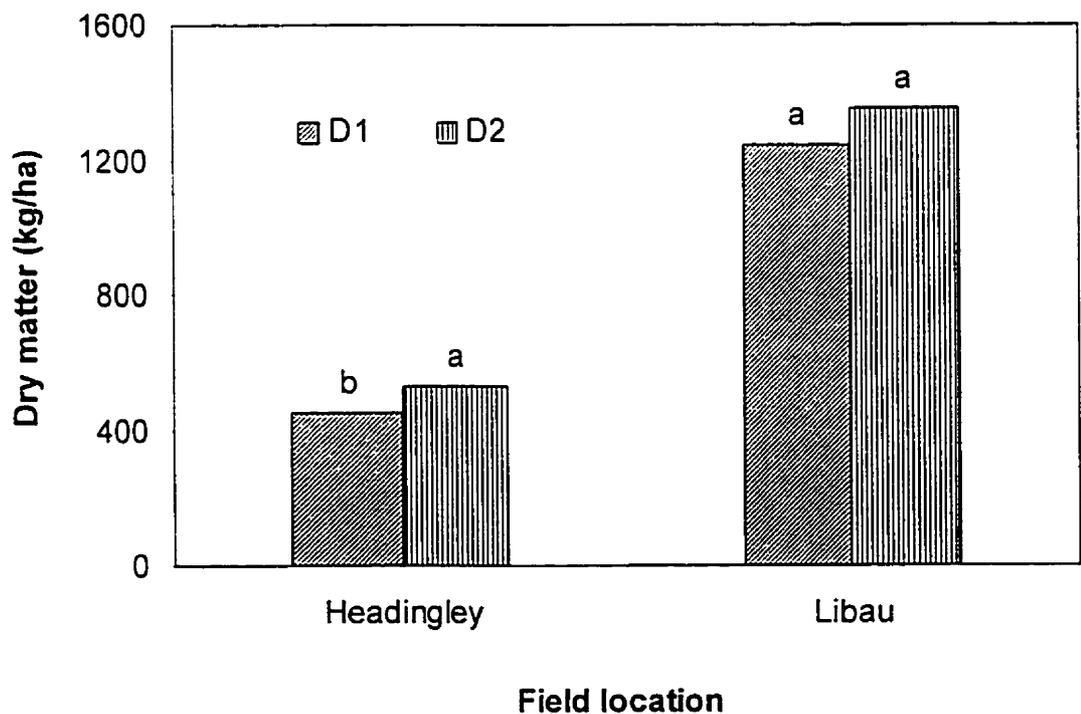


Fig. 30. Injection depth effects on crop yields; values with the same letter within each site are not significantly different at 0.1 level

5. CONCLUSIONS

1. Injection depth is more critical than tool forward speed, in terms of their effects on draft forces and soil disturbances. The draft force significantly increases with injection depth for both sweep and disc-type injection tools but not with speed except for the sweep A. Compared to sweep A, sweep B and sweep C required 12 and 97% more draft force due to their wider cutting width. For the sweep A, on the average, at 100 and 150 mm depths using a flanged coulter with sweep requires up to 57% more draft force than with out. Similarly, the disc B required more draft force than the disc A due to presence of two penetrating discs with large disc and tilt angle.
2. Soil disturbances (in terms of W and H) increases with injection depth but not with speed. Among the sweeps, the highest soil surface disturbance was observed for the sweep C due to its wider cutting width. On the average, sweep C disturbed 44% and twice as much soil than the sweep B and sweep A, respectively. For the sweep A, using a flanged coulter with the sweep increases soil disturbances by approximately 10%. Sweep injection tools could effectively reduced bulk density from 50 to 100 mm depth and can create up to 29% new soil pores. These new pores would be potentially available for absorbing injected manure according to Negi et al. (1978). Disc A creates a clear furrow at the shallow depth (<100 mm), which would not favor manure-soil mixing. While, for the disc B working at shallow depth (< 80 mm) a section between the two discs was uncovered, which may not be desirable for manure coverage. Therefore, disc B should be used for manure incorporation at a depth greater than 80 mm, while disc A should work at

a depth greater than 100 mm where the furrow was refilled with the loose soil.

3. In field conditions, rougher soil surface was observed in the clay compared to sandy loam and fine sand due to wet soil and crop conditions. The larger slot opening at the higher application rates combined with the shallow injection depth (D1) may cause adverse environmental impact, in terms of odor and ammonia emissions.
4. The odor concentrations at soil surface following the manure application were minimal for all treatments at all sites. No ammonia concentrations were detected following manure application except for one instance where high application rate at shallow injection depth was used.
5. The soil cutting associated with the injection action was obvious but did not significantly reduce forage yields. Compare to control plot C, CD1 or CD2 plot had an equal or slightly less crop yields, likely attributable to crop damage from the action of injectors. The heavy injection unit can cause enough soil compaction on a moist heavy clay soil that no forage yields could be expected over the wheel tracks. Deeper injection depth favored higher crop yield, as highlighted on a heavy clay soil.

6. RECOMMENDATIONS AND FUTURE WORK

1. Considering the draft force requirement and soil surface disturbances, in soil bin conditions, an injection depth less than 100 mm could be used to reduce the power requirement for both sweep and disc injection tools.
2. For sweep A, addition of a flanged coulter in the front of sweep required 27% more draft force. Therefore, a coulter may not be necessary for injecting manure into a tilled soil in order to reduce the draft force.
3. For the disc B, it was difficult to achieve desired injection depth due to flexible spring shank. Therefore, in actual field condition, additional weight might be needed to keep the downward pressure.
4. Use of a heavy injection unit caused significant soil compaction in heavy clay soil on the wheel tracks, which impede crop root development and crop growth. Therefore, it is suggested to avoid injecting manure using this unit under a wet clay soil.
5. Studies on draft force requirements on other soil types and crop conditions are needed.
6. Studies on sub-surface soil disturbances and manure distribution pattern are needed and modeling work can be done on soil disturbances.

7. REFERENCES

- ASAE. 1993. ASAE S358.2, Moisture measurement - forages. In *ASAE Standards 40th Edition*, 451. St. Joseph, MI: ASAE.
- Bayne, G. 1999. Nutrient values of manure. In: *Proceedings of Tri-provincial Conference on Manure Management*. June 22-25, 1999, Saskatoon, SK. p. 580-584.
- Beauchamp, E.G. 1983. Response of corn to nitrogen in preplant and sidedress applications of liquid cattle manure. *Canadian Journal of Soil Science* 63: 377-386.
- Bédard, Y., S. Tessier, C. Lague, Y. Chen and L. Chi. 1997. Soil compaction by manure spreaders equipped with standard and oversized tires and multiple axles. *Transactions of the ASAE* 40(1): 37-43.
- Carter, M. R. 1990. Relative measures of soil bulk density to characterize compaction in tillage studies on fine sandy loams. *Canadian Journal of Soil Science* 70: 425-433.
- Chen, Y. and S. Rahman. 1999. Design criteria and performance evaluation of a liquid manure injection tool for grassland. ASAE/CSAE Paper No MBSK99-122, Saskatoon, SK: CSAE.
- Chen, Y. and S. Tessier. 1996. Soil compaction induced by agricultural practices. 12th International Conference of International Society for Terrain Vehicle Systems, October 7-11, 1996.
- Chen, Y., Q. Zhang and D. Petkau. 2000. Evaluation of different techniques for liquid manure application on grassland. CSAE Paper No AFL099. Saskatoon, SK: CSAE.

- Chen, Y., S. Rahman and X. Ren. 1999. Criteria for selecting injection depth and evaluation on existing liquid manure injection tools. ASAE Paper No 991112. St Joseph, MI: ASAE.
- Chen, Y., S. Tessier and J. Rouffignat. 1998. Soil bulk density estimation for tillage systems and soil textures. *Transactions of the ASAE* 41(6): 1601-1610.
- Chescheir III, G.M., P.W. Westerman and L.M. Safely, Jr. 1985. Rapid methods for determining nutrient in livestock manures. *Transactions of the ASAE* 28(6): 1817-1824.
- Collins, B.A. and D.B. Fowler. 1996. Effect of soil characteristics, seeding depth, operating speed, and opener design on draft force during direct seeding. *Soil and Tillage Research* 39: 199-211.
- Danesh, S., D.G. Hodgkinson and D. Small. 1999. Hog production: Environmental problems and waste management strategies. In: *Proceedings of Tri-provincial Conference on Manure Management*, 117-132. Saskatoon, SK. June 22-25.
- Frost, J. P. 1988. Effect on crop yields of machinery traffic and soil loosening. *Journal of Agricultural Engineering Research* 40:57-69.
- Gameda, S., G.S.V. Raghavan, E. McKyes and R. Theriault. 1985. High axle load compaction and corn yield. *Transactions of the ASAE* 28(6): 1759-1765.
- Génermont, S. and P. Cellier. 1998. An operational model for estimating ammonia fluxes after slurry spreading. *Agricultural and Forest Meteorology* 88: 145-167.
- Geohring, L.D. and H.M. VanEs. 1994. Soil hydrology and liquid manure application. In: *Proceedings from the Liquid Manure Application Systems Conference*. Rochester, New York. December 1-2, 1994.

- Godwin, R.J., E. McKyes, S.C. Negi, G.V. Eades, J.R. Ogilvie and C. Lovegrove. 1976. Engineering design criteria for slurry injectors. In *Proceedings 8th Annual Waste Management Conference*, 657-671. Rochester, NY.
- Godwin, R. J., G. Spoor and M.S. Soompro (1984). The effect of tine arrangement on soil forces and disturbance. *Journal of Agricultural Engineering Research* 30: 47-56.
- Godwin, R.J., N.L. Warner and J.E. Hall. 1986. Soil Injection of liquid wastes. *Soil and Water* 14(2): 10-12.
- Godwin, R.J., G. Spoor and M.S. Soompro. 1984. The effect of tine arrangement on soil forces and disturbance. *Journal of Agricultural Engineering Research* 30(1): 47-56.
- Goodrich, P.R. 1994. Manure application using a towed hose injector. In *Proceedings from the Liquid Manure Application Systems Conference*, Rochester, New York. December 1-2, 1994.
- Goodrich, P.R. and J.L. Petering. 1999. Controlling swine manure odour using the TOASTTM aerobic system. In *Proceedings of Tri-provincial Conference on Manure Management*, 470-477. Saskatoon, SK. June 22-25.
- Hall, J.E. 1986. Soil injection research in the UK. *Efficient land use of sludge and manure*. eds. Kofoed, A.D., J.H. Williams and P. L'Hermite, 78-89. Elsevier Applied Science Publishers, London: Elsevier.
- Hanna, H.M., D.C. Erbach, S.J. Marley and S.W. Melnin. 1993. Changes in soil microtopography by tillage with a sweep. *Transactions of the ASAE* 36(2): 301-307.
- Harrison, H. P. and T. Thivavarnvongs. 1976. Soil reacting forces from laboratory

- measurements with disks. *Canadian Agricultural Engineering* 18(1).
- Hilborn, D. 2000. Choosing a liquid manure application method. In *Proceedings from Managing, Nutrients and Pathogens from Animal Agriculture*, 380-394. Camp Hill, Pennsylvania, March 28-30.
- Hobbs, P.J., T.H. Misselbrook. and B.F. Pain. 1995. Assessment of odorous from livestock wastes by a photoionization detector, an electronic nose, olfactometry and gas chromatography-mass spectrometry. *Journal of Agricultural Engineering Research* 60: 137-144.
- Huijsmans, J. F. M., J.G.L. Hendricks and G.D. Vermeulen. 1998. Draught requirement of trailing-foot and shallow injection equipment for applying slurry to grassland. *Journal of Agricultural Engineering Research* 71: 347-356.
- Hultgreen, G. and W. Stock. 1999. Injecting swine manure with minimum disturbance. In *Proceedings of Tri-provincial Conference on Manure Management*, Saskatoon, SK, Canada, June 22-25, 1999, p. 52-65.
- IGER. 1995. Research to Prevent Pollution. *Institute of Grassland and Environmental Research*, North Wyke, Okehampton, Devon EX20 2SB.
- Janni, K.A. 1982. Modeling dispersion of odourous gases from agricultural sources. *Transactions of the ASAE* 25: 1721-1723.
- Jokela, W. and D. Côté. 1994. Options for direct incorporation of liquid manure. In *Proceedings from the Liquid Manure Application Systems Conference*, 201-215. Rochester, New York. December 1-2.

- Kempainen, E. 1986. Effect of cattle slurry on quantity and quality of barley and grass yield. In *Efficient Land Use of Sludge and Manure*. eds. Kofoed, A.D., J.H. Williams, and P. L'Hermite, 64-72. Elsevier Applied Science Publishers, London.
- Kepner, R.A., R. Bainer and E.L. Barger. 1987. *Principle of Farm Machinery*. CBS Publishers and Distributors, Delhi 110032, India.
- Kitson. I.V. 1987. Development of a three-dimensional tillage force and moment dynamometer. Unpublished M. Sc. Thesis, The University of Manitoba, Winnipeg, MB. R3T5V6.
- Kushwaha, R.L. and C. Linke. 1996. Draft-speed relationship of simple tillage tools at high operating speeds. *Soil and Tillage Research* 39: 61-73.
- Kushwaha, R.L., A.S. Vaishnav and G.C. Zoerb. 1986. Performance of powered-disc coulters under no-till crop residue in the soil bin. *Canadian Agricultural Engineering* 28(2): 85-90.
- Laguë, C. 1991. Design of a semi-liquid dairy cattle manure spreader/injector. *Applied Engineering in Agriculture*. 7(6): 655-660.
- Larsen. K.E. 1986. Injection of cattle slurry to barley, beets, grass and maize. *Efficient Land Use of Sludge and Manure*, eds. Kofoed, A.D., J.H. Williams and P. L'Hermite, 73-77. Elsevier Applied Science Publishers, London.
- Lindvall, T., O. Noren and L. Thyselius. 1974. Odour reduction for liquid manure systems. *Transactions of the ASAE* 17(3): 508-512.
- Lockyer, D.R. 1984. A system for the measurement in the field of losses of ammonia through volatilization. *Journal of the Science of Food and Agriculture* 35: 837-848.

- MacLean, A.J., M.H. Miller and J.B. Robinson. 1983. The fertilizer potential of animal manures and environmental constraints on their use. *Farm Animal Manures in the Canadian Environment*, National Research Council Canada. 21-51.
- McKyes, E. 1985. Soil Cutting and Tillage. *Developments in Agricultural Engineering*, Vol. 7, Amsterdam, The Netherlands: Elsevier Science Publishers B. V.
- McKyes, E. and F.L. Desir. 1984. Prediction and field measurements of tillage tool draft forces and efficiency in cohesive soils. *Soil and Tillage Research* 4: 459-470.
- McKyes, E. and O.S. Ali. 1977. The cutting of soil by narrow blades. *Journal of Terramechanics* 14(2): 43-58.
- McKyes, E., S.C. Negi, R.J. Godwin and J.R. Ogilvie. 1977. Design of a tool for injecting waste slurries in soil. *Journal of Terramechanics* 14(3): 127-136.
- McQuitty, J.B. and A.J. MacLean. 1983. Manure gases and odours. *Farm Animal Manures in the Canadian Environment*, National Research Council Canada 53-58.
- Meisinger, J.J. and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. In *Proceedings from Managing, Nutrients and Pathogens from Animal Agriculture*, 334-354. Camp Hill, Pennsylvania, March 28-30.
- Misselbrook, T., J. Laws and B. Pain. 1996. Surface application and shallow injection of cattle slurry on grassland: nitrogen losses, herbage yields and nitrogen recoveries. *Grass and Forage Science* 51(1): 270-277.
- Morrison Jr., J.E., J.G. Hendrick III and R.L. Schafer. 1996. Soil forces on coulter and disc-opener combination. *Transactions of the ASAE* 39(2): 369-376.

- Moseley, P.J., T.H. Misselbrook, B.F. Pain, R. Earl and R.J. Godwin. 1998. The effect of injector tine design on odour and ammonia emissions following injection of bio-solids into arable cropping. *Journal of Agricultural Engineering Research* 71(1): 385-394.
- Negi, S.C., E. McKyes, R.J. Godwin and J.R. Ogilvie. 1978. Design and performance of a liquid manure injector. *Transactions of the ASAE* 21(5): 963-966.
- Pain, B.F. and T.H. Misselbrook. 1997. Sources of variation in ammonia emission factors for manure applications to grassland. *Gaseous nitrogen Emissions from Grasslands*, eds. S.C. Jarvis and B.F. Pain. pp. 293-301. CAB International. Oxon, UK (cited by Meisinger and Jokela, 2000).
- Pain, B.F., V.R. Phillips, C.R. Clarkson., T.H. Misselbrook., Y.J. Rees and J.W. Farrent. 1990. Odour and ammonia emission following the spreading of aerobically treated pig slurry on grassland. *Biological Wastes* 34: 149-160.
- Pain, B.F., C.R. Clarkson, V.R. Phillips, J.V. Klarenbeek, T.H. Misselbrook. and M. Bruins. 1991. Odour emission arising from application of livestock slurries on land: Measurements following spreading using a micrometeorological technique and olfactometry. *Journal of Agricultural Engineering Research* 48(1): 101-110.
- Parkinson, R., R. Brown, S. Jury, P. O'Neil and R. Heath. 1994. Soil injection of organic waste- the effect of tine design on the fate of injected sludge. *Agricultural Engineering* Spring: 16-19.
- Phillips, V.R. and B.F. Pain, 1998. Gaseous emissions from the different stages of European livestock farming. *Environmentally friendly management of farm*

- animal waste*, ed. T. Matsunaka, 67-72. Kikanshi Insatsu Co. Ltd., Sapporo, Japan (cited by Meisinger and Jokela 2000).
- Phillips, V.R., B.F. Pain, N.L. Warner and C.R. Clarkson. 1988. Preliminary experiments to compare the odour and ammonia emission after spreading pig slurry on land using three different methods. *Engineering Advances for Agriculture and Food*, London, Cox S. W. R, ed., Butterworths: 161-162.
- Prins, W.H. and P.J.M. Snijders. 1987. Negative effects of animal manure on grassland due to surface spreading and injection. In van der Meer, H.G., R.J. Unwin, T.A. van Dijk and G.C. Ennil (eds.), *Animal Manure on Grassland and Fodder Crops*. pp. 119-135. Dordrecht: Martinus Nijhoff (cited by Misselbrook et al. 1996).
- Qu, G., J.J.R. Feddes, R.N. Coleman and J.J. Leonard³². 1999. Background and some developments in measuring the concentration and character of animal production site odours. In *Proceedings of tri-provincial conference on manure management*, June 22-25, 1999, Saskatoon, SK. p. 238-258.
- Rahman, S. and Y. Chen. 1999. Laboratory investigation on soil injection forces and soil disturbances resulting from different manure incorporation tools. ASAE/CSAE Paper No MBSK 99-123. St. Joseph, MI: ASAE.
- Reaves, C.A., W.R. Gill and A.C. Bailey. 1981. Influence of width and depth of cut on disk forces. *Transactions of the ASAE* 24(3): 572-578.
- Rees, Y.J., B.F. Pain, V.R. Phillips and T.H. Misselbrook. 1993. The influence of surface and sub-surface application methods for pig slurry on herbage yields and nitrogen recovery. *Grass and Forage Science* 48: 38-44.
- Ren, X. and Y. Chen. 1999. Optimizing design and working parameters for liquid manure

- injection. ASAE Paper No 993014, St. Joseph, MI: ASAE.
- Riskowski, G.L., A.C. Chang, M.P. Steinberg and D.L. Day. 1991. Methods for evaluating odour from swine manure. *Applied Engineering in Agriculture* 7(2): 248-253.
- Schaaf, D.E., S. Hann and C.W. Lindwall. 1980. Development of performance data on seed drill coulters. CSAE Paper No. 80-303 Saskatoon, SK: CSAE.
- Schmidt, D. and L.D. Jacobson. 1995. Odour and odour policy criteria. Minnesota Extension Service, Department of Biosystems and Agricultural Engineering, University of Minnesota, St. Paul, MN.
- Schmitt, M.A., S.D. Evans and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. *Journal of Production Agriculture* 8(2): 186-189.
- Scotford, I.M., T.R. Cumby, R.P. White, O.T. Carton, F. Lorenz, U. Hatterman and G. Provolò. 1998. Estimation of the nutrient value of agricultural slurries by measurement of physical and chemical properties. *Journal of Agricultural Engineering Research* 71:291-305.
- Smith, R.J. 1993. Dispersion of odours from ground level agricultural sources. *Journal of Agricultural Engineering Research* 54: 187-200.
- Sommer, S.G. and N. Hutchings. 1995. Techniques and strategies for the reduction of ammonia emission from agriculture. *Water, Air and Soil Pollution* 85: 237-248.
- Sommer, S.G. and R.R. Sherlock. 1995. pH and buffer component dynamics in the surface layer of animal slurries. *Journal of Agricultural Science (Camb.)* 127: 109-116.

- Sommer, S.G., H. Mikkelsen and J. Mellqvist. 1995. Evaluation of meteorological techniques for measurements of ammonia loss from pig slurry. *Agricultural and Forest Meteorology* 74: 169-179.
- Sommer, S. G., J. E. Olesen and B. T. Christensen. 1991. Effects of temperature, wind speed and air humidity of ammonia volatilization from surface applied cattle slurry. *Journal of Agricultural Science (Camb.)* 117: 91-100.
- Sommer, S.G., J.E. Olesen. 1991. Effects of dry matter content and temperature on ammonia loss from surface applied cattle slurry. *Journal of Environmental Quality* 20: 679-683.
- Spoelstra, S.F. 1980. Origin of objectionable odourous components in piggery wastes and the possibility of applying indicator components for studying odour development. *Agriculture and Environment* 5: 241-260.
- Spoor, G. and R.J. Godwin. 1978. An experimental investigation into the deep loosening of soil by rigid tines. *Journal of Agricultural Engineering Research* 23(3): 243-258.
- Stafford, J.V. 1979. The performance of a rigid tine in relation to soil properties and speed. *Journal of Agricultural Engineering Research* 24: 41-56.
- Steel, R.G.D. and J.A. Torrie. 1980. Principles and Procedures of Statistics, A Biometrical Approach. 2nd edn., McGraw-Hill, Inc., Montréal, Canada.
- Stevens, R.J., R.J. Laughlin and J.P. Frost. 1992. Effects of separation, dilution, washing and acidification on ammonia volatilization from surface-applied cattle slurry. *Journal of Agricultural Science (Camb.)* 113: 383-389.
- Svensson, L. 1994. Ammonia volatilization following application of livestock manure to

- arable land. *Journal of Agricultural Engineering Research* 58:241-260.
- Tessier, S., C. Laguë, R. Lambert, P. Tremblay and Y. Brochu. 1991. Soil compaction by liquid manure spreaders. CSAE Paper No. 91-411. Saskatoon, Canada: CSAE.
- Tessier, S., L. Chi, S. Richard, C. Laguë and S. Pigeon. 1995. Traffic induced soil compaction and solutions: Farmer's perspectives. Presented at 5th North American Regional Meeting, Saskatoon, May 10-12, 1995.
- Thompson, R.B., B.F. Pain and Y.J. Rees. 1990. Ammonia volatilization from cattle slurry following surface application to grassland. *Plant and Soil* 125(1): 119-128.
- Thompson, R.B., J.C. Ryden and D.R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. *Journal of Soil Science* 38(1): 689-700.
- Threadgill, E.D. 1982. Residual tillage effects as determined by cone index. *Transactions of the ASAE* 25(4): 859-863.
- Tice, E.M. and J.G. Hendrick. 1992. Disc coulter operating characteristics. *Transactions of the ASAE* 35(1): 03-10.
- Tunney, H. and S.P. Molley. 1986. Comparison of grass production with soil injected and surface spread cattle slurry. *Efficient Land Use of Sludge and Manure*, eds. Kofoed, A.D., J.H. Williams and P. L'Hermite, 90-98. Elsevier Applied Science, London.
- Warner, N.L. and R.J. Godwin. 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. *Journal of Agricultural Engineering Research* 39: 287-300.
- Warner, N.L., R.J. Godwin and M.J. Hann. 1990. An economic analysis of slurry

treatment and spreading systems for odour control. *Agricultural Engineering* Winter: 100-105.

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

Wouters, A.P. and M.C. Verboon. 1993. Handling of slurry in relation to the environment on dairy farms in the Netherlands. *Annual Report*, Research Station, Lelystad, Netherlands (cited by Jokela and Côté 1994).