Liquid Manure Application Techniques to Minimize Odours

Ying Chen, Department of Biosystems Engineering, University of Manitoba

Abstract

This paper focused on evaluation of existing liquid manure application methods and equipment from an odour-related perspective. Requirements for liquid manure injection and how to select injectors and the operation parameters were also addressed.

Odour levels associated with land application of liquid manure are not directly related to the application method. That manure injection provides lower odour level than surface application is not necessarily true in some injection cases where excessive manure is exposed to the air as a result of poor injection operation or the use of an inappropriate injector. Odour levels are directly determined by the amount of manure exposed to the air and the surface area covered with exposed manure, if other conditions are the same. Injection may not reduce odour to a background level (equivalent to odour over an unmanured soil surface), even it is properly done. Odour concentration at the ground level following manure injection varies from approximately double 18 times higher than the background value, depending on the extent of manure exposure.

The primary criterion for selecting an injector should be based on the tool capacity that must be sufficient in order to minimize exposed manure, and consequently odours. Other criteria should be also considered, such as the hose power requirement and manure distribution in soil. In grassland application, minimum soil disturbance is also an important criterion. The performance of an injector on these perspectives is not only affected by tool type, but also by injection depth and other factors.

Generally, manure application to grassland was feasible using low-disturbance injection, infiltration enhancement, surface banding and sub-canopy application methods, in terms of grass production. However, there is the potential for odour if excessive overflow-manure occurs.

Introduction

Land application of liquid manure has been recognized as recognise a cost-effective and sustainable practice for manure utilization. Comparable crop yields can be achieved when using liquid manure to replace chemical fertilizers (Chen et al., 1995). However, all stakeholders recognize that some adverse environmental impacts are associated with manure application, such as nutrient losses through volatilization, nuisance odour emissions, runoff of phosphorus to surface water and nitrate leaching to groundwater. Among these, odour has become a major concern in some cases.

Surface applications, especially broadcasting, have been associated with odour problems. Over the past years, more environmentally friendly methods of manure application have been developed, such as surface banding, infiltration enhancement, surface incorporation and injection of manure into soil. As compared with broadcasting, these methods can reduce odour emissions to a certain extent, with injection methods generally being the most effective. Manure injection or incorporation also provides more available nutrients to the plant (Schmitt et al., 1995). Although manure injection is considered as an effective mitigation approach to odours (Pain et al., 1991; Misselbrook et al., 1996), significant odour emissions (Chen et al., 2000) can still occur following liquid manure injection operations. The effectiveness of an injector in controlling odour depends on the design of the injection tool and other factors, such as injection depth, target manure application rate and field conditions.

In the past, liquid manure has been applied frequently to annual crops as a source of nutrients. Due to the high cost of chemical fertilizer, no or little fertilizers are applied to grassland. The lack of nutrients in grassland, pastureland or hay land, limits the production potential of these soils. Grasses use large quantities of nitrogen, and grassland poses less risk of leaching or runoff losses (Bittman et al., 1999). Diverting some of the manure applied to grassland would no doubt be a viable alternative. Furthermore, hogs in Western Canada are often raised within close proximity to grassland. Application of manure to nearby grassland would be less expensive due to the lower transportation costs.

Objectives

The objectives of this paper were (1) to review existing methods and equipment for liquid manure applications, and (2) to propose the requirement for liquid manure injection and criteria on how to select injector and operation parameters, to minimize odour emissions.

Odour sources and the contributing factors

Odours are emitted not only from the soil surface following a manure application (referred as to manured surface), but also from the point where manure is released from an applicator during an application operation (referred as to manure-delivery-point).

Odour concentration at manure-delivery-points is affected by the height at which manure is released and the pressure of discharge of sprays, which affects the manure-air contact time. For example, the fan spreading pattern of a broadcast application increases odour emission during manure spreading, since manure is sprayed at high pressure into the air and travels a long distance before reaching the ground. Surface banding, such as by using a dribble bar, causes fewer odour problems by releasing manure near the ground at low pressure, and by reducing the air contact time.

Odour concentration above a manured surface following manure applications is directly related to the area covered with manure and amount of manure that is exposed to the air (hereafter referred to as manure exposure) (Jokela and Côté, 1994). Reducing manure exposure can significantly reduce odour concentration over a manured surface (Chen et al., 2000).

Application methods with respect to odour

Broadcasting. Broadcasting with a tank wagon, sprayer boom or irrigation gun is the common application method among surface application methods. A tank wagon discharges manure through a single or multiple large deflector or splash plate to create a fan spreading pattern. In most cases of broadcasting, manure is projected with high pressure into the air and travels a notable distance, especially in high-trajectory systems. In this method, 100% of the ground surface is covered with manure, representing maximum manure exposure. In grassland application, “painting” of existing crops provides additional area with exposed manure. The broadcast method has high potential for causing odour both at manure-delivery-point during manure spreading and from the manured surface following manure spreading. Using low-trajectory systems can reduce the problem in the former situation.

Surface banding. As a result of the problems associated with broadcasting, surface banding has also been tried on grassland and annual cropland to reduce the odour problem. Surface banding methods, such as using a dribble bar, deliver manure near the ground at low pressure, while reducing the manure-air contact time. Negligible ammonia volatilization was detected at the manure-delivery-point during manure application with a dribble bar (Chen et al., 2000). On this basis, an insignificant odour level would be the case for low-pressure surface banding.

Since manure is spread in bands, the area covered with exposed manure is smaller when compared with broadcasting. Consequently, odour concentration in the former case will be lower than in the latter, when other conditions are the same. An application of surface banding to grassland is discussed later.

Surface incorporation. In the method of surface incorporation, manure can be spread on the surface by broadcasting or surface banding, followed by an incorporation of manure by a tillage operation to cover or mix the manure with soil. Incorporation can be combined with spreading as one operation or can be a separate operation. Most tillage tools, such as discs, tines, sweeps and harrows could potentially be used for manure incorporation. Surface incorporation is not usually an option for grassland where excessive soil disturbance would damage the crop stands.

Since manure is mixed and covered with soil through incorporating, less manure is exposed when compared with only broadcasting. The extent to which the manure is being mixed with soil depends on the tillage tools used for incorporation and tillage depth. For example, discs will provide better manure-mixing than harrows. However, manure is only partially covered with soil in such cases. This implies that odour can only be reduced to certain extent. Hanna et al. (1998) reported that incorporation typically reduced odour level by a factor of three to ten as compared to a broadcast application. Other advantages of incorporation include enhancing aerobic stabilization of manure (Negi et al., 1978), nutrient uptake by the plant (McKyes et al., 1977), and reducing surface runoff of manure nutrients.

Infiltration enhancement. Infiltration enhancement can be achieved by using an aerator to create perforations on the top 50- to 150-mm of soil layer, while maintaining most of the residue cover on the soil surface. Within either the same or a separate operation, manure is broadcast on the perforated ground and a portion of the manure infiltrates into the ground perforations. The surface area covered with manure is quite large since manure is spread by broadcasting methods. Therefore, significant odour reduction may not be expected when using this method.

This method can be used as pre-plant manure application in annual crop systems, especially in the cases where producers use aeration tillage for their no-tilled fields or grassland. The aeration tillage used for manure incorporation had a beneficial effect on yields (Chen and Samson, 2001). The advantage of the method is that manure can reach the plant’s root zone. However, this method seems to present potential for greater nitrate leaching to groundwater (Chen and Samson, 2001) due to manure being placed to a greater depth and the aeration favouring a rapid infiltration of manure under a silt loam soil, compared with surface incorporation method. Note that the greater values in the groundwater nitrate concentration associated with the aerator incorporation of manure were detected only once over two years due to the high variation of data.

Manure injection. In this method manure is placed below the soil surface and covered with a layer of soil. Manure injection can be performed with most tillage tools, such as discs, knifes, openers, chisels, shovels or sweeps. Since manure-delivery-points of an injector are normally below the soil surface, the odour level at those points is expected to be minimal. Therefore the following discussion focuses on the odour concentration from manured surfaces following manure injection operations.

Major requirement for liquid manure injection to meet odour objectives

If the main goal of manure injection is to minimize odour, avoiding manure exposure becomes the most important requirement. Exposed manure on a manured ground may come from two sources: “overflow-manure” and “in-furrow-manure” (fig. 1). Overflow-manure occurs when manure is injected into soil at a rate which is too high such that it overflows to the soil surface, while in-furrow-manure occurs when the injection tool leaves a soil opening (such as a furrow or slot) through which manure appears (fig. 1). Both contribute to the overall manure exposure, and consequently to the odour concentration.

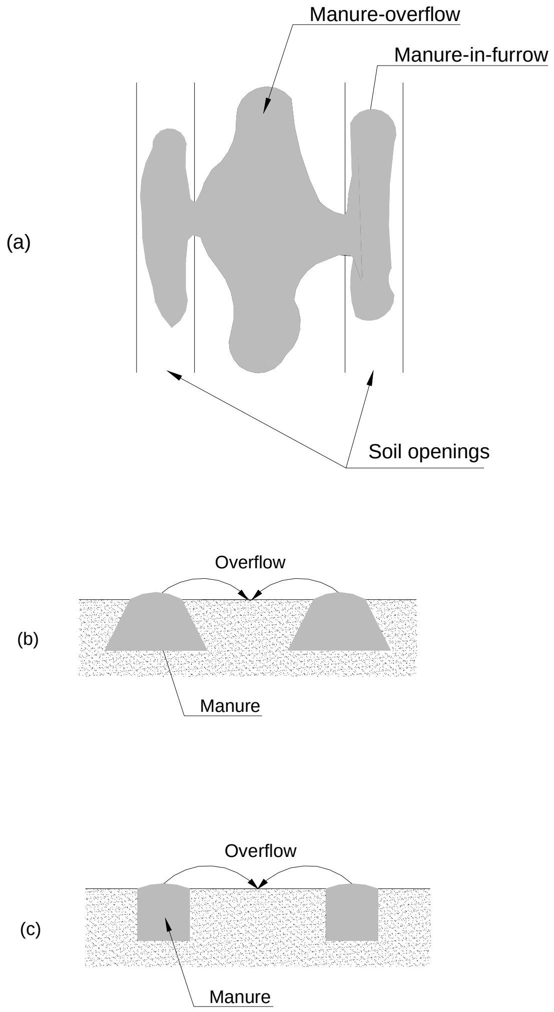

Figure 1. Diagram showing overflows of manure: (a) top view of soil openings and overflow-manure and in-furrow-manure; (b) cross-section of soil-openings; (c) cross-section of furrows.

In practice, injection tools, such as knives and discs, will unavoidably result in in-furrow-manure situations (Chen et al., 2000; Rahman and Chen, 2001) unless furrow closing devices are used. Although this occurrence may be minimized with other types of tools, such as winged tools, complete closure of soil openings seems difficult (Rahman et al., 2000). Therefore, only “no overflow-manure” remains as a practical and rational requirement that can be addressed in the selection of a tool for liquid manure injection.

The occurrence of overflow-manure is considered as the result of manure application rates exceeding a tool’s capacity for injection. Tool capacity is an important performance indicator of an injection tool, and is defined as the maximum amount of manure that can be injected into the soil by the tool without overflow-manure occurrences. Quantitative assessment on the tool capacity is described in the study of Chen and Tessier (2001).

Comparison of injection tools

Tool capacity for injection. Winged injection tools, such as sweeps and shovels, provide higher capacities in terms of application rates, when compared with discs or knives. The higher capacity of the former is mainly due to the larger volume of soil cavity created in soil to contain the manure injected. A disc or knife creates an open furrow into soil, and the volume of the soil cavity, in this case, is that of the opened furrow. Furrows are generally not large in size due to the limited cutting depth and the narrow cutting edges of these tools. A chisel can go fairly deep and create a deep soil cavity that may contain more manure than a furrow. However, since the slot is narrower, a chisel generally has lower capacity than a sweep that creates a larger soil cavity for the same injection depth.

Manure distribution in soil. Liquid manure that is deposited in a deep and concentrated manure band, without much mixing with soil may promote odour emission and denitrification, causing nutrient losses and greenhouse gases emissions. The ideal situation is manure being distributed uniformly at shallower depths. Sweep-type tools show a better performance from these perspectives, when compared to other tools for a given application rate (Warner and Godwin, 1988).

Power requirement and soil disturbance. The injection method bears a potential drawback of high power requirement that decreases the field operation efficiency and increases the cost of operation. As compared with broadcasting and surface banding, the extra power requirement is associated with the soil-cutting in this operation. More power is normally required with injection than with surface incorporations, as the former tillage operation is carried out at greater depths.

The tool type affects the power requirement of a tool. Sweeps require much more power than discs (Rahman and Chen, 2001) and knives, while the power requirement of a chisel is expected to be intermediate. Within a same type of tool, power requirements vary with the tool cutting width (Chen, 2001). The power requirement is also increased with a higher injector travel speed and greater injection depth. A rougher soil surface and/or a larger surface area will be disturbed with wider tool cutting widths, higher injection travel speeds and greater injection depths.

In summary, winged tools can distribute manure in wide bands and have high tool capacities (Chen and Tessier, 2001), when compared with non-winged tools, such as chisels discs or knives (Godwin et al., 1976). Winged injection tools also have the best performance for manure injection in terms of manure mixing with soil. Furthermore, winged injection tools save significant draft force over chisels that have to work at a greater depth in order to inject the same amount of manure (Warner and Godwin, 1988).

Selection of injection tools to minimize odour

Manure application rate. Since a principal requirement for liquid manure injection is to avoid overflow-manure, injection capacity becomes an important selection criterion. This criterion is directly related to the geometric parameters of the tool, which dictates the volume of the soil cavity created by the tool. For example, in the case of high target manure application rates (greater than 5000 gal/ac), a sweep-type injector may be selected. Note that under heavy soil conditions, such an injector requires higher horse power. Therefore, a chisel-type injector may be an alternative when tractor power is limited. Tool spacing, a factor affecting the application rate, should also be considered in selecting an injector (Chen and Tessier, 2001). If the target manure application rate is low (for example, below 5000 gal/ac), especially for sandy soils, a disc- or a knife-type injector may be used to reduce the power requirement and soil disturbance.

Manure distribution and coverage. For a sweep-, chisel-, or shovel-type injector, two types of soil surface profiles can be formed. One type has the characteristics of a depression in the centre of tool path and two mounds on the side (fig. 2a). This characteristic is not ideal for manure injection, as less soil in the centre implies that the manure band is covered with less soil. Another type of soil surface profile created by these tools features a slightly mounded zone (fig. 2b) in the centre of the tool path (i.e. the centre of the manure band). Such a mound provides an additional soil cover for the manure injected, reducing odour potential.

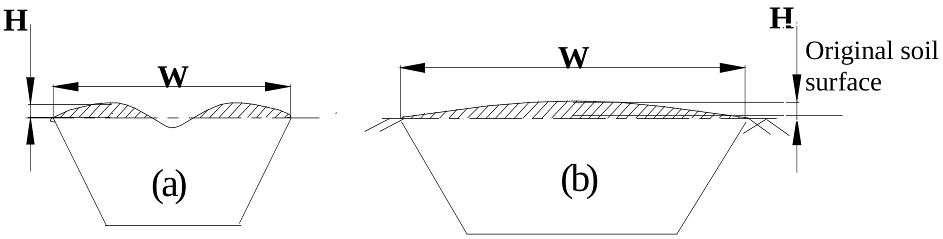

Figure 2. Typical soil disturbance profiles of a sweep-type injection tool; H = height of soil mound; W = width of soil surface disturbance.

An injector is also required to meet the criterion of uniform distribution of manure in soil to minimize uneven crop response to manure nutrients. It is normally expected that the width of manure band in soil is proportional to the tool cutting width within a certain range of width. However, a better performance in manure distribution can be achieved without increasing the tool cutting width, (thus, without increasing the power requirement) with a specially designed manure distributing mechanism (Chen, 2001).

Selection of injection depth

Field tests with sweep-type tools (Chen, 2001) showed that with deeper injection, slightly more soil is mixed with manure, as more loose soil falls back into the manure band. A chisel-type injector creates more or less well-defined slot-openings on the soil surface, especially in wet clay soil and cereal stubble, which results in the injected manure being exposed to the air through the openings. This situation can be significantly improved when increasing injection depth (Chen, 2001). However, deep injection with chisels requires significantly more draft force. Chen (2001) reported that for every two-inch increase in injection depth with chisels, the draft force was approximately doubled.

Shallow injection can not only reduce power requirement and soil disturbance (Huijsmans et al., 1998; Chen, 1999), but also minimize the risk of nitrate leaching to groundwater. In addition, shallow injection favours aerobic stabilization of manure, which would tend to increase mineralization while decreasing denitrification risks (Jokela and Côté, 1994). Considering all the facts, injection depth should be as shallow as practical to minimize the power requirement associated with soil cutting, but deep enough to ensure that manure is properly covered with soil (Chen et al., 1999). Experience showed that injection depths ranging from three to five inches are adequate for most soil conditions.

Grassland applications

Grassland application of liquid manure has been a challenging issue. Injection could not be considered as an option in the past because the cropping cycle does not include annual tillage operation or ground disturbance. Traditionally, the only option available for applying liquid manure on grassland was surface application (broadcast and surface banding). Besides odour problems associated with surface applications, some other unique problems exist for grassland. These include surface application that makes the grass less palatable for grazing, and fouling or burning of grass.

Recently, infiltration enhancement and injection methods have been adopted for applying manure to grassland. Pain et al. (1991) showed that efficient injection of manure can reduce odour emission up to 80% compared to surface application. It also prevents risk of crop contamination and pathogenic activities (Warner and Godwin, 1988). However, tools used for stubble or tilled soil conditions may cause grass damage resulting from the soil disturbance action (Hann et al., 1987; Warner and Godwin, 1988). The crop yield may be increased (Hultgreen and Stock, 1999) or decreased (Misselbrook et al., 1996), depending on the extent of crop damage associated with the use of an injector.

A technique that avoids soil disturbance and crop damage, while still reducing grass contamination, is placing manure near the soil surface under the crop canopy. This is done through a sliding shoe riding along the soil surface, giving the applicator its name, *sliding-shoe, trailing foot* or *sleigh-foot*. This technique was called *sub-canopy banding* by Jokela and Côté (1994). Using this method, the crop canopy provides less surface exposure of manure and some wind protection (Meisinger and Jokela, 2000), which potentially reduces odour emissions. Thyselius (1988) and Bittman et al. (1999) reported a better grass yield response and nitrogen recovery from a sliding shoe system when compared with broadcast applications, due possibly to its smaller losses in ammonia during and after application.

Comparison of different application methods

Different methods for applying liquid manure to grassland have been compared in a joint study (Chen et al., 2000) between the Department of Biosystems Engineering, University of Manitoba and Prairie Agricultural Machinery Institute (PAMI), at two sites in Manitoba, Libau and Stuarburn. The treatments comprised four application methods: (IJ) injection with a Greentrac knife injector (fig 3a), (SF) sub-canopy application with Greentrac sleighfoot (fig. 3b), (AR) infiltration enhancement with an aerator (fig 3c) and (DB) surface banding with a dribble bar. Assessments were made on both the environmental impact (including ammonia volatilization and odour concentration) and agronomic response (grass damage and grass yield). Only the odour data are presented in this report. Odor concentrations were measured by odor units (OU) which were the average number of dilutions of fresh air required to obtain an undetectable odor (below threshold) for a trained panel of six assessors.

Figure 3a. Greentrac injector (knife-type) used for injection treatment in forage fields.

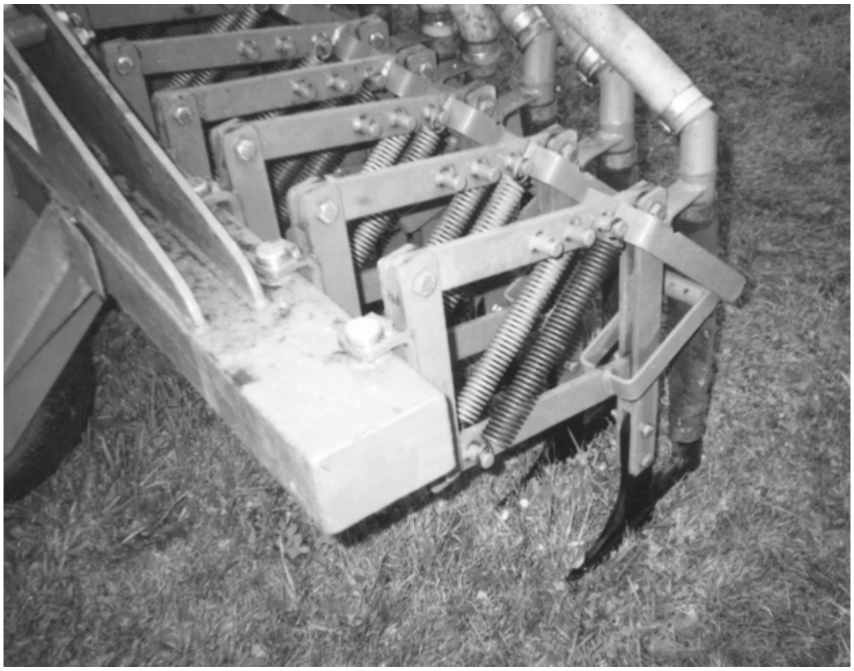

Figure 3b. Greentrac Sleighfoot used for sub-canopy application treatment in forage fields.

Figure 3c. Aerator used for infiltration enhancement treatment in forage fields.

The odour data (Table 1) were highly variable. Many other researchers (for example, Moseley et al., 1998) reported the same findings. Background odor concentrations (38 to 59 OU) generally agreed with those reported by (Moseley et al., 1998). Due to the high coefficient of variability of the data for the Stuartburn site, no significant differences in odour concentration between any of the treatments and the background were detected. Data from the Libau site had a smaller coefficient of variation, and significantly higher odour concentrations were detected in the manured plots than the background, regardless of treatment (Table 1). The same trend was apparent for the Stuartburn site, although it was not significant.

Table 1. Odour concentrations expressed in odour unit (OU)** measured from the background soil and the treatment plots, July 1999

Treatment*	Stuartburn	Libau
IJ	248a[†]	688b
SF	667a	636b
AR	234a	894a
DB	383a	1094a
Background	58a	38c

*IJ = Injection with the runner-opener-type injector, SF = Sub-canopy banding with the sleighfoot, AR = Incorporation with the aerator and DB = Surface banding with a dribble bar.
**Odour unit which was the average number of dilutions of fresh air required to obtain an undetectable odor (below threshold) for a trained panel of six assessors.
[†] Means followed by the same letter in each column are not significantly different at the 0.1 significance level.

Among the treatments at the Libau site, the AR and DB resulted in the higher odor concentration than the IJ and SF. Similar findings were reported by Moseley et al. (1998) in a study on odour emission as effected by injection and surface spreading techniques. The large area of manure exposed of the AR and DB treatments could enhance the gas exchange and contribute to the volatilization (Meisinger and Jokela, 2000). The lower odour concentration of the IJ was as a result of manure being placed into the soil and the grass being cleaner. The odour concentrations from the injection in this experiment may have been greater than those reported elsewhere (Rahman et al., 2000), as overflow-manure was observed on the soil surface (fig. 4). Lower odour concentration of the SF treatment could be possibly attributed to the resultant cleaner grass and/or an internal layer of calm air formatted in the grass canopy, which reduce gas exchange, as indicated by Harper et al. (1983) and Moseley et al. (1998).

Downwind odour concentration

At the two sites aforementioned, the odour concentrations (data not shown) at three different downwind locations were similar and close to the background value. These imply that odour at either site was not carried or dispersed as far as 25 m (82 ft) from the plots where manure was applied. For details on this study, readers are referred to Chen et al. (2001).

Figure 4. Land surface of the manure injection showing the overflow-manure on the soil surface.

TR6000 injector for grassland application.

Field tests. Field tests on the TR6000 injector (Ag Waste Management Corp, Box 179, Oak Bluff, MB R0G 1N0) have been carried out in three forage fields, including two sandy and one clay soil conditions. The injector (fig. 5) featured a six-wheel drive articulated truck with a vacuum manure tank capacity of 5,000 gallons. Manure was delivered to eight injection tools. Each tool consisted of a sweep and a coulter, mounted behind the tank, through flexible hoses. The tools were spaced 22 inches apart forming a total working width of 15 feet.

Odour concentration. For odour measurements, background air samples were collected before manure was applied, and after manure was applied in two treatments: injection with a manure application rate of 5000 gal/ac at a depth from 4.5 to 6.0 inches and with 10000 gal/ac at shallower depths (Table 2), representing intermediate and extreme cases of odour potentials, respectively. The odour concentrations at the soil surface for selected treatments were twice as high as the background concentration (Table 2). Significant differences in odour concentrations were observed between the manured plots and the background in two fields out of three. However, no significant differences in odour concentrations were observed within manure treatments. Odour concentrations from the manure injection using TR6000 were comparatively low, regardless of the injection depths and manure application rates.

For further details on odour, and on other aspects of the injector performance, readers are referred to the report (Chen et al., 2000)

Figure 5. TR6000 injector used for the field study in forage fields

Table 2. Odour concentrations in odour unite (OU)** at the manured surface following the application of manure for two selected treatments and background at three forage fields, Manitoba, 1999.

Injection depth	Manure application rate	Odour concentration (OU)		
(inch)	(gal/ac)	Clay soil	Sandy loam	Fine sand
4.5 - 6.0	5,000	120a*	263a	102a
3.0 – 4.0	1,0000	119a	291a	106a
Background	No manure applied	65a	135b	52b

*Means followed by the same letter in each column are not significantly different (P=0.05) according to Duncan's Multiple Range test.
**Odour unit which was the average number of dilutions of fresh air required to obtain an undetectable odor (below threshold) for a trained panel of six assessors.

Conclusions

Odour emissions at the manure-delivery-points during liquid manure application may increase with the pressure at which manure is discharged and the distance the manure travelled before hitting the ground. It is expected that broadcasting provides the highest potential for odour emissions at the manure-delivery-points.

Following manure application, odour concentrations on the manured surface vary with application methods. For example, injection of manure into soil normally results in least odour occurrence; broadcasting the most, and surface incorporation an intermediate value. However, direct comparison in odour level between application methods may be meaningless in some cases, since the odour concentration is mainly determined by the extent of manure being exposed to the air. A poor injection operation (with exposed overflow-manure) may result in as much exposed manure as broadcasting. In such a case, the same levels of odour are expected from both methods. This concept has particular importance in evaluating an operation of manure application. One should not simply speculate an odour level to a particular operation, but examine how the operation is done and how much manure is exposed.

As compared with injection, broadcasting and surface banding do not require draft force or disturb the soil, and surface incorporation and infiltration enhancement requires less draft force. These aspects affect the field efficiency and energy requirement, which should be considered when selecting manure application method.

Tests indicated that applying liquid manure by injection was more effective in reducing odour emission from the surface than the other three methods. The sub-canopy banding with the sleighfoot was more effective in this regard than the infiltration enhancement by the soil aerator or surface banding.

A knife-type injector may not always able to inject the prescribed volume of manure into the soil without causing the occurrence of overflow-manure, which favours odour emissions. The cutting action associated with an injector may cause some grass damage. However, the effectiveness of an injector in placing the manure near the root zone, making it accessible to plants, can compensate the effects of the damage in terms of grass yields.

References

Bittman, S., C.G. Kowalenko, D.E. Hunt and O. Schmidt. 1999. Surface-banded and broadcast dairy manure effects on tall fescue yield and nitrogen uptake. *Journal of Agronomy* 91(5):826-833.

Chen, Y. 1999. Criteria for selecting liquid manure injector. In *Proc. of the Manitoba Hog Manure Management Workshop*. 18-20. 2nd Annual Workshop, Carman, Manitoba, Oct. 27, 1999. Ed. K. Buchey, AAFC, Brandon Research Center.

Chen, Y. 2001. Development of high efficiency liquid manure injector. Final project report submitted to ARDI.

Chen, Y. and R. Samson. 2001. Soil nutrients and corn grain yields in liquid manure applications into conservation tillage systems. Submitted to Trans. of the ASAE. March, 2001.

Chen, Y., Q. Zhang and S. Baidoo. 2000. Performance evaluation of AgWaste's (TR6000) liquid manure injection system. Final research report submitted to Triple S Hog Manure Management Initiative.

Chen, Y and S. Tessier. 2001. Criterion for the design and selection of tools for injection of liquid manure. Submitted to Trans. of the ASAE. January, 2001.

Chen, Y., R. Samson and G. Schell. 1995. Method of integrating liquid manure into no-till corn production and the effect on soil and water quality. CSAE Paper No. 95-503. Saskatoon, SK:CSAE.

Chen, Y., S. Rahman and X. Ren. 1999. Criteria for selecting injection depth and evaluations on existing liquid manure injection tools. ASAE Paper No. 99-1112. St. Joseph, MI:ASAE.

Chen, Y., Q. Zhang and D. Petkau. 2001. Evaluation of different techniques for liquid manure application on grassland. Applied Engineering in Agriculture. (in press)

Godwin, R.J., E. McKyes, S. Negi, G.V. Eades and J.R. Ogilvie. 1976. Engineering design criteria for slurry injectors. In *Land as a Waste Management Alternative, Proc. Of the 1976 Cornell Agriculture Waste Management Conference*, ed. R.C. Loehr, 657-671. MI:Ann Arbor Science Publishers Inc..

Hanna, H.M., D.S. Bundy, J.C. Lorimor, S.K. Michelson and S.W. Melvin. 1998. Evaluation land waste application machinery to meet odour and environmental objectives. NPPC Project #1851. Final project report. Contact: Mark Hanna, Iowa State University, Erg & Biosystems Engineering, 515-294-0468.

Hann, M.J., N.L. Warner and R.J. Godwin. 1987. Slurry injector design and operational practices for minimising the soil surface disturbance and crop root damage. ASAE paper 87-1610. St. Joseph, Mich.:ASAE.

Harper, L.A., V.R. Catchpoole, R. Davis and K.L. Weir. 1983. Ammonia volatilization: soil, plant, and microclimate effects on diurnal and seasonal fluctuations. *Agronomy Journal* 75(2):212-218.

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

Huijsmans, J.F.M., J.G.L. Hendriks and G.D. Vermeulen. 1998. Draught requirement of trailing-foot and shallow injection equipment for applying slurry to grassland. *J. Agri. Eng. Res.* 71(5):347-356.

Jokela, W., and D. Côté. 1994. Options for direct incorporation of liquid manure. In *Proc. from the Liquid Manure Application System Conference.* 201-215. Northeast Regional Agricultural Engineering Service, Co-operate extension, 152 Riley-Robb Hall, Ithaca, NY 14853-5701.

Jokela, W. E., S.C. Bosworth, P.D. Pfluke, J.J. Rankin and J.E. Carter. 1996. Ammonia volatilization from broadcast and band-applied liquid dairy manure on grass hay. *Agronomy abstracts. p*.315. American Society Agronomy, Madison, WI.

Meisinger, J.J. and W.E. Jokela. 2000. Ammonia volatilization from dairy and poultry manure. pp 334-354. In *Proc. from "Managing, Nutrients and Pathogens from Animal Agriculture"*. 334-354. A Conference for Nutrient Management Consultants, Extension Educators, and Producer Advisors. Natural Resource, Agriculture, and Engineering Service, NRAES – 130.

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

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

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

Negi, S.C., E. McKeys, 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., 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(2):101-110.

Rahman, S. and Y. Chen. 2000. Laboratory investigation on soil cutting forces and soil disturbances resulting from different manure incorporation tools. Soil & Tillage Research. 58 (1): 19-29.

Rahman, S., Y. Chen, Q. Zhang and S. Baidoo. 2000. Evaluation of a liquid manure injector in the soil bin and grassland condition. CSAE Paper AFL100. Saskatoon, SK:CSAE.

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.

Thyselius, L. 1988. Spreading of slurry on ley. In *Volatile emissions from livestock farming and sewage operation.* ed. V.C. Nielsen, J.H. Voorburg and P.H. L'Hermite,117-123. London:Elsevier Applied Science.

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