Draft requirements for contrasting liquid manure injection equipment

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McLaughlin, N.B., Li, Y.X., Bittman, S., Lapen, D.R., Burtt, S.D. and Patterson, B.S. 2006. **Draft requirements for contrasting liquid manure injection equipment.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 2.29 - 2.37. There are many different types of liquid manure injection equipment on the market. Livestock producers need information on draft requirements of the various injector systems to make informed decisions on selection of appropriate systems for their particular farm. The objectives of this study are to compare draft requirements for different types of injection equipment under different soil and crop residue conditions. Representative single injectors from different broad classes including single disk (Yetter), sweep (Husky), and combination of a chisel and sweep (University of Manitoba), and a 4.7-m wide field cultivator (Kongskilde) and a 3.1-m wide soil aerator (AerWay®) configured for manure injection were included in the study. The AerWay® is a unique machine with rollers running at an angle to the direction of travel similar to a disk harrow except that soil engaging tines are used instead of circular disks. The tines open pockets in the soil, and manure is deposited into the pockets via drop tubes located immediately behind the tines. Draft measurements for the different injector types were made with the Agriculture and Agri-Food Canada instrumented tractor and instrumented toolbar at three soil and crop residue conditions, three operating depths, and three forward speeds. Draft data for each injector in each soil type were fitted to a separate model. Both soil and crop condition and operating depth had a significant effect on energy input. Speed had a small effect, but for most cases, it was not statistically significant ($P > 0.05$). A model with a quadratic depth term fitted the data for all injectors better than one with only a linear depth term. Increasing the roller angle from 0 to 10° increased the draft for the AerWay®, but only marginally. At 100-mm operating depth and 6 km/h speed, draft ranged from 2.68 to 4.93 kN per metre width for the AerWay® and from 4.35 to 4.86 kN per metre width for the Kongskilde. The single disk injector, Yetter, had a higher draft than the sweep or combination chisel and sweep injectors. At 100-mm depth and 6 km/h speed, draft ranged from 2.06 to 2.66 kN per injector for the Yetter, from 1.55 to 2.01 kN per injector for the Husky, and 1.5 kN per injector for a combination chisel and sweep injector. **Keywords:** energy input, liquid manure, injection.

Plusieurs types d'équipements d'injection du lisier sont disponibles sur le marché. Les producteurs d'animaux d'élevage ont besoin d'informations sur les demandes en puissance de tirage des différents systèmes d'injecteurs pour prendre une décision informée sur la sélection de systèmes répondant aux besoins de leur propre ferme. Les objectifs de cette étude étaient de comparer la demande en puissance de tirage pour différents types d'équipements d'injection sous différentes conditions de sol et de résidus de culture. Des injecteurs simples représentatifs de différentes catégories incluant un disque simple (Yetter), un soc à ailes ouvertes (Husky) et une combinaison de cultivateur et de soc (University of Manitoba) et un cultivateur de 4,7m de largeur (Kongskilde) et un aérateur de 3,1m de large (AerWay®) configuré pour l'injection de lisier ont été considérés dans cette étude. Le AerWay® est une machine unique munie de rouleaux placés à angle par rapport à la direction d'avancement de manière similaire à une herse à disques, toutefois les dents travaillant le sol sont utilisées au lieu des disques circulaires. Les dents ouvrent des sillons dans le sol et le lisier y est déposé via des tubes installés directement en arrière des dents. La mesure de la puissance de tirage pour les différents types d'injecteurs a été réalisée par le tracteur instrumenté d'Agriculture et Agroalimentaire Canada remorquant une barre outil instrumenté dans trois sols et conditions de résidus de culture, trois profondeurs d'opération et trois vitesses d'avancement. Les données de tirage pour chaque injecteur dans chaque type de sol ont été soumises à un modèle séparé. Le type de sol, les conditions de culture et la profondeur d'opération avaient un effet significatif sur les besoins en énergie. La vitesse avait un effet plus faible, qui dans la plupart des cas n'était pas statistiquement significatif ($P > 0.05$). Un modèle quadratique lié à la profondeur d'injection représentait mieux les résultats expérimentaux pour tous les injecteurs par rapport à un modèle linéaire. Une augmentation de l'angle d'opération des rouleaux de 0 à 10 augmentait la puissance de tirage pour le AerWay® mais seulement de façon négligeable. À 100 mm de profondeur de travail et à une vitesse d'opération de 6 km/h, la puissance de tirage variait de 2,68 à 4,93 kN par mètre de largeur pour le AerWay® et de 4,35 à 4,86 kN par mètre de largeur pour le Kongskilde. L'injecteur simple Yetter requérait une puissance de tirage plus élevée que le soc à ailes ouvertes ou la combinaison chisel et l'injecteur à soc. À une profondeur de 100 mm et une vitesse de 6 km/h, la puissance de tirage variait de 2,06 à 2,66 kN par injecteur pour le Yetter, de 1,55 à 2,01 kN par injecteur pour le Husky et 1,5 kN par injecteur pour une combinaison chisel et injecteur à soc. **Mots clés**: demande énergétique, lisier, injection.

INTRODUCTION

Livestock manure applied to land is the traditional method of both manure disposal and providing nutrients for crop production. Broadcast spreading on the soil surface is a popular method for both solid and liquid manure application. The equipment for broadcasting liquid manure is simple requiring only a pump and splash plate on the manure spreader. The method is fast as a single splash plate can spread a 13 m wide swath, and field application rate is limited mainly by the capacity of the pump on the spreader. Many spreaders use a

PTO driven pump with a capacity of about 6 m^3/min. The splash plate is relatively simple, and consequently the field equipment is low cost. However, surface application deposits manure on soil and plant surfaces and poses a risk for odor and loss of nitrogen via ammonia volatilization. Also, there is potential for nutrients and pathogens from surface-applied manure to contaminate surface water via runoff.

Subsurface injection or incorporation of liquid manure is generally recommended to both control odor and reduce nutrient losses. This method usually employs tillage tools to loosen the soil and places the manure below the soil surface. The loosened soil can cover and absorb the manure which reduces potential for odor, loss of nitrogen, and surface water contamination. Producer acceptance of subsurface injection is often impeded by the perception of excessive tractor power requirements. In a recent review of land application systems, Laguë et al. (2005) identified the need for energy-efficient manure application equipment. Some injector systems cause excessive soil disturbance increasing erosion risk and damaging roots in perennial forage crops, and some are prone to plugging of the tillage tools with plant residue in high residue conditions. Injectors may be unsuitable in stony soils and in sloped fields under high rainfall conditions where the injection furrows may serve as runoff channels (Personal Communication, B. Krahn, Dairy Centre Manager, Oregon State University, Corvallis, OR). A new type of injector, trade-named SSD, was recently developed for the AerWay® soil aerator (Holland Equipment Ltd., Norwich, ON) which creates discrete pockets in the soil avoiding the formation of runoff channels.

The objectives of this study were to compare draft requirements for the AerWay® SSD with several types of injectors available for manure application. This information will help producers make informed decisions on selection of appropriate injection systems for their particular farm and cropping system.

LITERATURE REVIEW

There is a wide variety of liquid manure injectors on the market. Many are built by short-line farm machinery fabricators and are based on modified tillage tools including chisel plow, cultivator sweeps, and disks. Injectors based on cultivator sweeps are often fitted with a cover plate behind the sweep wings to create a cavity under and behind the cultivator sweep. A drop tube (approximately 50-mm diameter), located behind the cultivator shank, deposits manure into the cavity. The manure is covered and absorbed by the loosened soil falling off the rear edge of the cover plate. Sweep injectors are available in widths from about 100 to over 500 mm or even over 1 m (Noble plow), and they can distribute manure in bands equal to the sweep width and effectively mix the injected manure with loosened soil (McKyes et al. 1977; Negi et al. 1978; Laguë 1991; Moseley et al. 1998). The maximum operating depth for sweep injectors is about 150 mm. McKyes et al. (1977) reported that a 300-mm wide sweep injector operating at 150-mm depth and 8 km/h required a draft of 2 to 6 kN for soils varying in texture from loose sand to medium clay loam. Laguë (1991) reported draft of 5.0 to 6.2 kN for a 305-mm wide sweep injector operating at 200-mm depth and 3.2 km/h in a firm clay soil. Other studies report injector draft forces ranging from about 0.25 kN at 15 mm depth in a sandy loam soil (Hansen et al. 2003), to 1.4 kN for a coulter followed by a 220-mm wide sweep at 150-mm depth (Rahman et al. 2001), and 1.6 kN for a 570-mm wide sweep at 150-mm depth (Rahman and Chen 2001). The former was at a depth of only 15 mm while the latter two studies were in loamy sand in an indoor soil bin which might explain why the draft was lower than those reported for field studies with a clay soil.

Injectors based on a modified chisel plow are narrower and can therefore be operated at greater depth and lower draft than sweep injectors. McLaughlin and Campbell (2004) reported injector drafts of 3.3 kN for a 60-mm wide chisel point injector compared to 6.7 kN for a 470-mm wide sweep injector, both operating at 160-mm depth and 8 km/h in a fine sandy loam soil. Since the chisel injector opens a narrower furrow than sweep injectors, the maximum manure application rate must be lower to maintain adequate soil mixing and cover or more injectors must be used per unit width of implement.

Chen (2002) developed a prototype low-draft injector (hereafter referred to as U of MB) which combined a chisel and 200-mm wide sweep to better mix manure with soil and to accommodate a high manure application rate. The injector required 4.7 kN draft in a clay soil when operating at depth of 112 mm and speed of 5 km/h.

The underlying principle in either sweep or chisel designs is to fragment the soil so that it can absorb the manure, but this process undoubtedly causes some damage to roots of perennial forage crops. Disk type injectors which deposit manure into a narrow slot cut in the soil are a popular choice for applying manure to forage crops. Although the disk severs some forage roots, the soil disturbance and adverse effects on crop performance are relatively small. The trailed sliding foot applicator is popular in some European countries for applying manure to forage crops. This implement uses a foot with a flat bottom and curved front surface similar to a cultivator shank, and is suspended by two swinging vertical arms on a parallel arm linkage (Huijsmans et al. 1998). The foot slides along the soil surface and forage and plant residues are lifted by the leading curved surface. Manure is deposited directly on the soil surface behind the sliding foot without damaging the roots (Chen et al. 2001; Rodhe et al. 2004). The parallel arm linkage maintains the foot in a horizontal orientation and allows it to swing back and up out of the way if it hits an obstacle.

Injectors for side dressing row crops are usually attached to a single toolbar mounted behind a spreader, or on a toolbar attached to a tractor three point hitch and supplied with manure from a stationary nurse tank via a drag hose. Several manure application systems have been developed for field cultivators. These usually consist of a manure distributor with hoses approximately 50-mm diameter leading to drop tubes mounted behind each cultivator shank to deposit manure in the furrow. The multiple gangs of cultivator shanks result in better residue clearance and more mixing of manure with the soil than is possible with injectors on a single gang. Similar to the row crop injectors, the cultivator can be either attached behind and supplied with manure from a mobile tank spreader or supplied from a stationary nurse tank via a drag hose. One popular system manufactured by Kongskilde Industries Ltd., Strathroy, Ontario utilizes the Kongskilde Vibro-Flex shanks which are designed to vibrate aiding in clearing residue and increasing soil

Fig. 1. AerWay® soil aerator (3.1 m wide) fitted with SSD manure application kit including distributor and drop tubes. Concrete parking curbs were used as ballast to ensure adequate penetration in hard soil. The machine is operating in soybean residue at site 3.

Fig. 2. Close-up of roller on AerWay® soil aerator showing arrangement of tines bolted to hubs on the roller axle.

shattering and residue incorporation. Manure application with a field cultivator can be combined with a tillage operation in a conventional till cropping system, but the field cultivator concept is not compatible with a no-till cropping system.

A new type of injection system based on a soil aerator trade-named "AerWay®" was recently developed (Anonymous 2001; Bittman et al. 2003, 2005). The AerWay® has horizontal rollers approximately 1.5 m in length and running at an angle to the direction of travel. It is similar to a disk harrow except that soil engaging tines are used in place of the disks. Each roller is fitted with a series of flanges or hubs spaced at 190 mm and four flattened tines are bolted to each hub with 200 mm of the tine protruding beyond the hub and available for soil engagement (Figs. 1 and 2). The tine angular location on the roller is offset slightly on adjacent hubs so that the tines form four helixes on the rollers (Fig. 2).

The tines create discrete pockets in the soil surface. The roller angle can be adjusted from 0 to 10° (from perpendicular to the direction of travel) to create a lateral motion of the tine as it engages the soil and a corresponding change in the size of the pockets. Experiments were conducted at Agassiz, British Columbia to determine the effect of roller angle on pocket volumes in tall fescue stubble (after harvest) in a relatively dry silty loam soil by measuring the amount of liquid manure required to fill the pockets. For 100-mm operating depth, increasing the roller angle from 0 to 7.5° increased pocket volumes from 133 to 208 mL, and at 150-mm operating depth, increasing the roller angle from 0 to 7.5° increased pocket volumes from 245 to 312 mL (unpublished data).

A liquid manure application kit, trade-named "SSD" (an acronym for Sub Surface Deposition) was developed for the AerWay® and is available from the manufacturer. The kit consists of a manure distributor and drop tubes positioned behind the tines to deposit manure in bands over the pockets opened in the soil. Bittman et al. (2005) reported 46 to 48% lower ammonia emissions in the two weeks following application and slightly higher orchard grass yield for manure applied with the SSD compared to broadcast (surface spread). In dry runs (no manure applied), there was little difference in yield with the SSD compared to a control with no tillage, indicating that the AerWay® tines did not cause excessive damage to the plant root system. Lau et al. (2003) reported lower odor emission rate for hog manure applied with the AerWay® SSD compared to conventional splash plate surface applicator. Chen et al. (2001) also found lower odor levels from the aerator system. Shah et al. (2004) reported variable results in runoff water quality for liquid dairy manure applied on grassland with and without mechanical aeration with an AerWay® machine. van Vliet et al. (2005) reported that the aeration system significantly reduced runoff and nutrient loads from a sloped field under high-rainfall conditions. Energy inputs for the AerWay® SSD have not been reported in the literature.

MATERIALS and METHODS

Experimental sites

Field experiments to measure draft requirements for manure injection equipment were conducted at three sites in eastern Ontario in 2001 and 2002. Site 1 (2001) was on loam soil with regrowth of forage at the Central Experimental Farm (CEF) in Ottawa, Ontario (N 45° 22´, W 75° 43´). Site 2 (2002) was on a loam soil with barley stubble at the CEF. Site 3 (2002) was on a clay loam soil with soybean stubble at Winchester, Ontario (N45° 03´, W75° 20´). Soil water content for each site was measured using a TDR probe before testing the injector systems. Details on the soil and residue cover at the three sites are summarized in Table 1.

A split-split plot randomized complete block experimental design with three replicates was employed at all three sites. The main plot treatments were the injector units including two systems based on full width tillage equipment modified for manure application and three single injectors based on sweep,

Table 1. Soil conditions and vegetation at the three experimental sites.

Parameter	Site 1 CEF 2001	Site 2 CEF 2002	Site 3 Winchester 2002
Soil texture	Loam	Loam	Clay-loam
Soil water content (% vol)	25.9 (0-100 mm) 30.8 (100-300 mm)	21.5 (0-150 mm)	22.2 (0-150 mm)
Bulk density (Mg/m^3)*	1.3	1.3	1.3
Vegetation	Forage, 200-300 mm regrowth	Barley stubble	Soybean stubble

*Soil bulk density was not measured at the time of experiment. The values reported are averages for nearby fields with similar soil types and at similar soil condidtions.

disk, and combination chisel and sweep tillage tools. Each main plot was 250 m long and 5 m wide to allow one pass of the widest machine used. Each main plot was divided into three 80-m long sub-plots which were further divided into three 15-m long sub-sub-plots. The three sub-plot treatments were target operating depths of 75 to 150 mm. The sub-sub-plot treatments were forward speeds (4, 6, and 8 km/h). A 5- to 10-m buffer zone was left between each sub-sub-plot to provide space to change depth and/or speed.

Table 2. Dimensions of soil engaging tools for injector systems used in experiment.

Injector/Parameter	Dimension
Kongskilde (field cultivator)	
Rake angle (at tool tip)	16°
Sweep angle	86°
Injector width	108 mm
Injector spacing	275 mm
Total number of injectors	17
Total machine width	4.7 m
AerWay® - SSD (soil aerator)	
Tine length (beyond hub)	200 mm
Tine width	75 mm
Tine thickness	13 mm
Hub diameter	165 mm
Number of tines per hub	4
Hub spacing	192 mm
Number of hubs	16
Total machine width	3.1 m
Husky (medium width sweep)	
Injector rake angle	13°
Injector sweep angle	67°
Injector width	304 mm
U of MB (combination chisel sweep)	
Chisel rake angle (at tip)	31°
Chisel sweep angle	47°
Chisel width	42 mm
Chisel depth below sweep	32 mm
Sweep rake angle	13°
Sweep sweep angle	47°
Sweep width	200 mm
Yetter (single disk)	
Disk diameter	635 mm
Offset angle (from direction of travel)	5°

Full width machines

The two full width injector systems were an AerWay® soil aerator and a Kongskilde field cultivator, both fitted with manure injection hardware. The AerWay® machine (Fig. 1) was 3.1 m wide, and had eight hubs on each of the two rollers for a total of 16 hubs or rows of tines and 64 individual tines. (See Table 2 for dimensions of soil engaging tools for each injector system.) The AerWay® machine was configured for liquid manure application with the SSD kit which includes a 16-outlet rotary manure distributor and a drop tube located immediately behind each hub on the rollers. The five standard roller angles of attack 0, 2.5, 5.0, 7.5, and 10° (measured from perpendicular to direction of travel) were used as separate treatments in this study.

A Kongskilde field cultivator was selected as a representative system combining manure injection with tillage. It had 17 Vibro-Flex shanks spaced at 275 mm and mounted on two gangs (Fig. 3) with a total working width of 4.7 m. The Kongskilde Vibro-Flex shanks had a large flat spring at the point of attachment to the cultivator frame and were designed to "vibrate" when working in the soil to increase soil shattering and residue incorporation. Each shank was fitted with a 108-mm wide reversible sweep (Fig. 4). Furrow levelers were installed behind the rear row of shanks. Modifications for liquid manure injection consisted of a 17-outlet rotary manure distributor, and a 50-mm diameter drop tube behind each shank.

Fig. 3. Kongskilde field cultivator (4.7-m wide) with 17 Vibro-Flex shanks spaced at 275 and 108-mm wide mulch sweeps. The unit was fitted with a distributor and drop tubes for manure application. The machine is operating in barley stubble at site 2.

Fig. 4. Close-up of the 108-mm wide reversible mulch sweep used on the Kongskilde field cultivator.

Single injectors

Three single injector units representative of disk (Yetter), sweep (Husky), and combination chisel and sweep (U of MB) were included in the study. The Yetter (Fig. 5) injector was based on the Yetter Avenger® (Yetter Manufacturing Co., Colchester, IL) side-band fertilizer applicator. It used a single 635-mm diameter flat disk opener running at an angle of 5° from the direction of travel to cut a slot through grass and crop residue. A stationary shoe was located on one side of the disk in an arrangement similar to a single disk seeder opener described in ASAE standard S477 DEC01 (ASAE 2005). Manure was deposited via a drop tube between the disk and a stationary shoe (Fig. 5). The furrow is closed with a pair of rubber packer wheels behind the disk. The Husky injector (Husky Farm Equipment Inc., Alma, ON) was made from a standard 304-mm wide cultivator sweep. A cover plate fitted with a 50-mm diameter drop tube located immediately behind the sweep provided a cavity for manure deposition (Fig. 6). Soil flowing over the sweep and cover plate covered the manure. The U of MB combination chisel and sweep injector (Fig. 7) consisted of a narrow 40-mm wide V-shaped chisel with a 200-mm wide sweep located about 50 mm above the tip of the chisel (Chen 2002). Manure was deposited under the sweep wings via a drop tube located behind the shank.

Fig. 5. Yetter single disk injector. Manure is deposited via the drop tube located between the stationary shoe and the disk. The furrow is closed with the rear press wheels.

Fig. 6. Husky injector fabricated from a 304-mm wide sweep and fitted with a rear cover plate and drop tube.

All the injectors were run dry without manure. Since the manure is deposited behind the injectors, it was reasoned that draft measurements for operating dry would not be appreciably different from operating with manure.

Fig. 7. U of MB combination chisel - sweep injector.

Fig. 8. **Instrumented toolbar for measurement of single injector draft. The toolbar is suspended on a parallel arm linkage to isolate extraneous forces and moments from draft force acting on the injector.**

Draft measurements

Draft measurements were made with the Agriculture and Agri-Food Canada's instrumented research tractor (McLaughlin et al. 1993). This tractor was fitted with a set of sensors and an on-board data logger to measure and record tractor operational parameters such as implement draft, fuel consumption, and engine speed as the tractor is doing normal field work. A special tractor drawbar connected to the hitch points on the three-point hitch lower links was designed to allow three-point hitch instrumentation to be used to measure draft of trailed implements.

The AerWay® SSD machine was fitted with transport wheels and was hitched to the tractor drawbar with a single pin as a trailed implement. The target depth of the AerWay® was controlled with cylinder stops attached on the hydraulic cylinder on the transport wheels. The AerWay® was provided with ballast trays, and depending on soil conditions, some ballast is normally required to ensure penetration of the tines into the soil. The machine was ballasted with approximately 1650 kg of concrete parking curbs to ensure that the tines would achieve the target depth when operating in hard soil (Fig. 1). The Kongskilde was three-point hitch mounted (Fig. 3) and the target depth was controlled by cylinder stops on the tractor three-point hitch booster cylinder. The depth gauge wheels on the Kongskilde had to be removed as there was insufficient clearance between the gauge wheels and the tractor wheels.

A trailed instrumented toolbar was designed to measure draft for single injectors (Fig. 8). The toolbar utilized a parallel arm linkage to isolate draft force from moments and extraneous forces (orthogonal to draft force) acting on the injector. Draft was measured by a strain-gage load cell attached to the parallel arm linkage, and the signal from the load cell was logged on the instrumented tractor data logger along with the other tractor operational parameters. Target depth was controlled with cylinder stops on the hydraulic cylinder controlling the transport wheels on the instrumented toolbar.

The same tractor no-load engine speed (2000 rpm) was used throughout the entire experiment. Different nominal ground speeds of 4, 6, and 8 km/h were achieved by using different tractor transmission gear ratios. The tractor no-load engine speed and gear ratio were selected while the tractor was stopped in the buffer zone between the sub-sub-plots. The tractor was then brought up to speed, and data were logged for the 15-m sub-sub-plot length. Stakes at either end of the sub-sub-plot provided a visual cue to the data logger operator to start and stop the data logger. Engine speed was not adjusted while in the plot. There is some drop in engine speed for varying draft, but this is typically less than about 5% for moderate draft and less than 10% for very high draft. After each main plot was completed, the implement was unhitched from the tractor and a "zero" file was logged with no load on the tractor hitch. These zero files were subsequently used to correct the draft data for minor drift in the strain-gage signal conditioners on the tractor data logger.

The data logger scan rate was set at 100 complete scans per second. This resulted in approximately 700 to 1400 records (depending on forward speed) while the tractor was within the 15-m plot. Low pass analog filters for the strain gage transducers on the tractor were set at 10 Hz cut-off frequency.

Manual depth measurements

Even though the same settings on the machines were used, actual injector depth varied considerably throughout the experiments. Flexibility in the implement frame and variability in soil conditions, both among and within the three sites, contributed to the variability in operating depth. A special tool was constructed to manually measure actual operating depth for each pass. The tool consisted of a 140 x 200 mm wooden foot with a 1.4-m length of 25-mm diameter PVC electrical conduit attached to the foot via a threaded pipe wall flange. A hole was drilled through the foot in line with the PVC conduit. A depth probe made from a 6 x 18-mm aluminum flat with a slightly pointed end was inserted inside the PVC conduit. A steel ruler was attached to the probe such that the zero on the ruler lined up with the top end of the PVC conduit when the tip of the probe was flush with the bottom of the wooden foot which corresponded to zero depth. In operation, the foot was set on the undisturbed surface of the soil and the probe was inserted into the furrow with a slight up and down motion until the bottom of the furrow was felt. Depth was then read off the steel ruler which was near eye level. Ten depth measurements spaced at approximately 1.0-m intervals were made for each sub-sub-plot.

Data analysis

Means for draft were calculated from the 700 to 1400 records logged for each sub-sub-plot, and were then corrected for minor drift (usually less than about 5%) in the instrumentation offset using "zero" files logged under no-load conditions with the implement unhitched from the tractor. The means were then considered as the dependent variable for the individual sub-sub-plots and were fitted to a regression equation using the General Linear Models (GLM) procedure in SAS Ver 8.0.

The working widths of the injection equipment varied from a single injector to 3.1 m for the AerWay® SSD and 4.7 m for the Kongskilde. For an appropriate comparison of draft among the different devices tested, draft for the full width machines

Table 3. Regression coefficients and standard errors (in parenthesis) for draft prediction (Eq. 2) for liquid manure injectors at three sites.

Injector	Site 1	Site 2	Site 3
AerWay® SSD-0°*	0.268 (0.0081)	-	0.404 (0.0123)
AerWay® SSD-2.5°	0.270 (0.0056)	0.416 (0.0118)	0.425 (0.0262)
AerWay® SSD-5.0°	0.288 (0.0082)	0.429 (0.0149)	0.406 (0.0179)
AerWay® SSD-7.5°	0.285 (0.0100)	0.411 (0.0132)	0.443 (0.0251)
AerWay® SSD-10°	0.337 (0.0096)	0.420 (0.0111)	0.493 (0.0406)
Kongskilde	-	0.438 (0.0446)	0.472 (0.0230)
Husky	0.205 (0.0072)	0.173 (0.0113)	0.200 (0.0096)
U of MB	-	0.155 (0.0081)	0.153 (0.0125)
Yetter	0.291 (0.0103)	0.268 (0.0060)	0.211 (0.0064)

*Coefficients for the AerWay® SSD and Kongskilde full width implements are draft per metre basis (N/m) and those for the Husky, U od MB, and Yetter single injectors are draft (N) in a per injector basis.

(AerWay® SSD and Kongskilde) was expressed on a per metre width basis (N/m). Following the convention employed in ASAE Standard D497.4 (ASAE 2003), draft for the single injectors was expressed on a per injector basis. These injectors are often mounted on a single toolbar on the rear of a liquid manure spreader and are typically spaced at 760 mm which matches corn row width for side-dressing. Therefore, draft of the single injectors could alternatively be expressed on a per metre width basis by simply dividing injector draft by the row spacing of 0.76 m.

Draft data for each injector at each site were fitted to a separate model. Models with both linear and quadratic depth terms based on ASAE standard D497.4 FEB03 (ASAE 2003) and D497.2 MAR94 (ASAE 1994), respectively, were used. The results indicated that the model with a quadratic depth term fitted the data for all injectors better than that with only a linear depth term. Preliminary analysis showed that speed had a greater influence on draft at higher speeds which suggests a non-linear speed coefficient may be appropriate. Following the general philosophy of simplicity adopted in the recent ASAE standard (ASAE 2003), only a linear speed coefficient was used in the models.

The form of the quadratic model is:

$$D = aT^2 + bT^2 S \qquad (1)$$

where:

Table 4. Regression coefficients and standard errors (in parenthesis) for Eq. 1 for injector-site combinations where the speed effect was significant (P<0.05).

Injector	Site	Regression coefficient	
		a	b
Husky	1	0.142 (0.0234)	0.001 (0.0035)
Husky	2	0.089 (0.0373)	0.015 (0.0064)
U of MB	2	0.093 (0.0285)	0.011 (0.0049)
Yetter	2	0.216 (0.0209)	0.009 (0.0035)

D = draft per meter width (N/m) or draft per tool for single injectors (N/tool),
T = depth (mm),
S = speed (km/h), and
a,b = regression coefficients.

For cases where speed did not have a significant effect on draft, the speed term was omitted from Eq. 1 and the draft data fitted to a reduced model:

$$D = cT^2 \qquad (2)$$

where: c = regeression coefficient.

RESULTS and DISCUSSION

The models in Eqs. 1 and 2 force the regression curve through the origin. This is physically meaningful as zero draft is expected for zero depth when the machine rolling resistance is subtracted.

Speed had a small effect on draft which was significant ($P < 0.05$) only for the Husky at site 1 and for the Husky, Yetter, and U of MB injectors at site 2. The speed effect was not significant for either the AerWay® SSD or the Kongskilde at any of the three sites or for any of the injectors at site 3. As the main purpose of the project was to compare draft requirements among the widely different injector types, and as the speed had a only a small effect and was significant for only some of the injectors at some of the sites, draft data for all of the injectors at all of the sites were fitted to Eq. 2 for the reduced model. The regression coefficients for the three sites are given in Table 3. Draft data for those cases where speed had a significant effect were fitted to Eq. 1 for the full model, and corresponding regression coefficients are given in Table 4. The models explained from 85 to 98% of the observed variance in draft.

Increasing the roller angle of the AerWay® SSD from 0 to 10° had a small and inconsistent effect on draft. In site 2, the draft coefficient for the AerWay® SSD with a roller angle of 0° was approximately 10% higher than any of the other roller angles. This is counter intuitive as the tillage is more aggressive with more soil disturbance at larger roller angles. Site 2 was known to have compacted areas, and even though the treatments were randomized, the variability associated with these areas may have given rise to the abnormally high draft coefficient for a roller angle of 0°. The standard error of the draft coefficient for the AerWay® SSD at site 2 was the highest at a roller angle of 0° indicating more variability in the input data. The draft coefficient for the 0° roller angle at site 2 was considered an outlier and was omitted from Table 3. Draft for the AerWay® SSD followed the expected trends in sites 1 and 3 with higher draft associated with larger roller angles (Table 3). Draft coefficients for the AerWay® SSD at sites 2 and 3 were similar, but draft at site 1 was about 33% less than the other two sites. The different performance of the AerWay® SSD at the different sites may be attributed to the difference in crop residue, soil texture, and soil water content at the three sites. Site 1 was in forage while sites 2 and 3 were in barley and soybean stubble, respectively, left after harvesting the crops earlier in the season. Also, the volumetric soil water content in site 1 (25.9%, 0-100 mm) was greater than site 2 (21.5%, 0-150 mm) and site

3 (22.2%, 0-150 mm). Draft for most tillage equipment is lower at higher soil water contents (ASAE 2003).

The concrete parking curbs (Fig. 1) with a total mass of about 1650 kg were required to ensure adequate tine penetration for the AerWay® SSD in all soil conditions, but this ballast mass was excessive for shallow target depths. Rolling resistance of the wheels supporting the excess ballast would create additional draft. The ballast was located approximately one third of the way between the AerWay® transport wheels and the hitch point, and consequently approximately 33% of the excess ballast is carried by the tractor and 67% is carried by the AerWay SSD transport wheels. Draft due to the excess ballast can be estimated from the additional rolling resistance of the AerWay® SSD transport wheels which must support the 67% ballast not required to ensure tine penetration. Using a rolling resistance of 4% of axle weight (ASAE 2003), the transport wheel rolling resistance resulting from carrying 67% of the 1650 kg ballast would be 0.43 kN or 0.14 kN/metre width. This is an upper limit of the error due to excess ballast as some of the ballast is supported by the AerWay® SSD rollers to create tine penetration into the soil, and this portion must be considered as part of the AerWay® SSD draft.

Draft per meter of implement width was similar for both the Kongskilde and AerWay® SSD in both sites 2 and 3 (the Kongskilde was not tested at site 1). The speed effect was not significant (P>0.05) at any of the sites for either the AerWay® SSD or the Kongskilde. Considerable difficulty with depth control was experienced for the Kongskilde in site 2. The soil surface was quite hard in some areas of site 2, and the machine had difficulty penetrating the soil. Without the depth wheels for stability, the machine sometimes tilted so that it was running deeper on one side than the other. These difficulties resulted in a large scatter in the data as indicated by the relatively high standard error of the regression coefficient for the Kongskilde in site 2, nearly twice that for site 3 (Table 3). As noted previously, the draft coefficients for the AerWay® SSD in site 2 did not follow the expected trends of higher draft associated with higher roller angles.

The draft predicted by the regression equations for AerWay® SSD ranged from 2.68 to 4.93 kN/m for all three sites at a depth of 100 mm. Draft for the Kongskilde at the same depth ranged from 4.38 to 4.72 kN/m. The draft coefficients for the AerWay® SSD at mid to high roller angles are comparable with those for the Kongskilde (Table 3) indicating similar draft for the two implements when expressed on a per meter width basis, and when operating at the same depth.

The draft for each of the Yetter, Husky, and U of MB (U of MB was not tested at site 1) was similar at all sites. For a given depth, the Yetter disk injector required higher draft, particularly in sites 1 and 2, than the other two sweep-type injectors. This was initially surprising as a straight rolling disk coulter cuts the soil with a relatively sharp edge and creates little soil disturbance. However, the disk on the Yetter Avenger® runs at a non-zero (5°) angle of attack relative to the direction of travel, and the disk and shoe must both push the soil sideways to create the open furrow. As there is very little lifting action with a flat disk, the soil must be compressed laterally, and this would account for the high draft. Huijsmans et al. (1998) reported draft of 0.71 kN per injector for a double disk injector at 50-mm depth in a dry clay soil. Draft calculated from the Yetter prediction models at 4 km/h and 50-mm depth ranged from 0.53 to 0.62 kN per injector in a clay loam soil. The speed effect for the Yetter was not significant (P > 0.05) at sites 1 and 3 which is consistent with findings of Huijsmans et al. (1998). Speed had a small effect on the Yetter disk opener at site 2 (Table 4).

The U of MB injector, designed specifically for low draft (Chen 2002), proved to have the lowest draft of all injectors in sites 2 and 3. The draft for the U of MB in our study was lower than the 4.7 kN/injector at 112 mm reported by Chen (2002) likely because our trials were carried out in loam to clay loam soil whereas Chen (2002) conducted the study in clay soil.

The Husky injector had a higher draft than the U of MB in site 3, but only slightly higher in site 2. Higher draft was expected for the Husky injector as it was based on a 304-mm wide sweep compared to 200-mm wide wings for the U of MB. Also, as the wings were located 32 mm above the chisel tip in the U of MB (Table 2), they were operating at a shallower depth than the measured depth which was to the bottom of the furrow formed by the chisel.

Draft coefficients for the single tool injectors (Husky, U of MB, and Yetter) were much lower than those for the full width machines (AerWay® SSD and Kongskilde). This was expected since the draft coefficients for the single tool injectors are on a per injector basis, and draft for the full width machines are on a per meter width basis. The AerWay® SSD has 5.2 rows of tines per meter of machine width, and the Kongskilde has 3.6 rows of injectors per meter width. Normally, single injectors are spaced at 0.76 m on a toolbar at the rear of a liquid manure spreader to match corn row widths for side dressing with liquid manure. Draft for all of the injectors tested fell within the broad range of draft for sweep type injectors reported by McKyes et al. (1977) and Negi et al. (1978). They also used a quadratic depth term for draft prediction equations and reported draft ranging from 2 to 6 kN per injector for a 300-mm wide sweep injector operating at 150-mm depth and 8 km/h in a clay soil.

CONCLUSIONS

Both soil condition and operating depth had a significant effect on draft. Speed had a small, but not always significant effect. Draft for the AerWay® SSD was lower in the forage field than either the soybean or barley stubble fields, both of which had lower soil water content than the forage field. Increasing the roller angle from 0 to 10° increased the draft for the AerWay® SSD, but only marginally. At 100-mm operating depth and 6 km/h speed, draft for the AerWay® SSD ranged from 2.68 to 4.93 kN/m width. Draft for Kongskilde at the same depth and speed ranged from 4.35 to 4.86 kN/m. Draft for the AerWay® SSD with tine spacing of 192 mm at medium to high roller angles was comparable to the Kongskilde with injector spacing of 275 mm.

The Yetter single disk injector had a higher draft than either the sweep or combination chisel-sweep injectors at all three sites. At 100-mm depth, draft for the Yetter single disk injector ranged from 2.11 to 2.91 kN per injector while the Husky sweep and U of MB combination chisel and sweep injector ranged from 1.73 to 2.05 and 1.53 to 1.55 kN per injector, respectively.

Speed had only a small effect on injector draft, and was significant ($P < 0.05$) for only four of the injector site combinations. The speed effect was not significant ($P > 0.05$) for either the AerWay® SSD or Kongskilde full with implements at any of the three sites.

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