Injecting Bio Solids into Grass and Arable Crops, Part I: Design and Evaluation of a Shallow Injector

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Abstract

Shallow injection of liquid bio solids at depths of 50 to 70 mm into grass and arable crops offers many advantages over existing application methods. However, current shallow injection equipment only places the sludge or slurry into slots leaving it exposed with a high runoff risk. The aim of this study was to determine the benefits and limitations of injecting digested sewage sludge into land growing arable crops using shallow injection techniques. It is documented in two parts. One part describes the agronomic trials undertaken to determine the effect of application technique and timing on combinable crops. This part describes the work undertaken to understand the mechanics of shallow injection and develop an improved injector design. Here, laboratory and field studies were undertaken to compare both existing and new winged shallow injector designs. These showed a winged injector penetrated better with an equal or lower draught than existing designs. The design also incorporated the sludge into the soil with minimal crop damage at rates of at least of 50 m^3/ha when working 50 mm deep.

1. Introduction

The injection of sludge or slurry into grassland at shallow depths, that is 50 to 75 mm, is a relatively new development. It causes less soil disturbance and damage than deep injection techniques, that is 400 to 600 mm deep, offering the possibility of injecting into arable crops throughout the growing season. Shallow injection also meets increased environmental demands to use sludge and slurry at low application rates. However, current equipment only places the sludge or slurry in a slot at the soil surface. This increases the risk of odour and ammonia emissions and of it running along the slot in sloping terrain to lower parts of the field. Current shallow injectors also have difficult in penetrating the soil surface in hard conditions.

The project aim was to develop the equipment and techniques for injecting digested sewage sludge into land growing arable crops using shallow injection techniques at the rate of 50 m^3/ha. The project is documented in two parts. This paper describes the investigation into the design of shallow injection tines. The agronomic studies to determine the effect of different application techniques and systems on crop growth are described by Pullen *et al.* (2004).

To met the project aim it was identified the injection tines should penetrate easily, have low draught, cause little crop damage and incorporate the sludge into the soil below the surface to reduce the risk of runoff, minimise odour and ammonia emissions. This study was conducted in the controlled conditions of the Soil Dynamics Laboratory at Silsoe and in the field.

2. Literature Review

The effect of tine geometry on soil disturbance, draught and vertical forces is well documented. Payne and Tanner (1959) showed the angle of inclination of the tine, the rake angle, had a dramatic effect on implement performance. Forward inclined tines, those with small rake angles, minimise draught forces and create more surface disturbance. Increasing the rake angle causes a rapid rise in the draught force and changes the vertical force direction so it opposes penetration. However, surface disturbance is reduced.

Soil disturbance is influenced by the tine depth to width aspect ratio. For tines with an aspect ratio between one and seven a soil wedge forms in front of the leg and a crescent-shaped soil prism develops sliding up the lower failure surface. This splits into halves as it moves around the soil wedge. The wedge moves up the face and is replenished with soil from the tine base. As the aspect ratio increases the disturbance below a certain depth is replaced by compaction as soil is forced to move around the tine. The depth at which this change occurs is known as the critical depth. This was first described by Zelenin (1950). It depends on the soil and tool characteristics. Critical aspect ratio (McKyes 1985) ranges between one in wet plastic soils to 16 in dry brittle soils. Typically a value of six is common in agricultural soils (Godwin & Spoor, 1977) this, however, being dependent upon the rake angle.

Spoor and Godwin (1978) found soil disturbance patterns could be changed by attaching wings or sweeps to rigid deep loosening tines. This produced soil disturbance increases, with lower specific resistance, i.e. draught divided by the total loosened area. Ahmed and Godwin (1983) considered the effect of the wing position from the tine tip for subsoiler tines. They found wing position had no significant effect on the draught or soil disturbance although the draught did reduce as the wing position was moved further back.

Injecting liquid waste was first studied in the 1970s. Although some variation in injector design existed most of these early units used two or three spring shanks with either 50 to 75 mm wide chisels or sweep-shovels. A discharge pipe was attached to the back of the shank to supply the sludge. The volume of soil disturbed was inadequate for containing the quantity of slurry discharged.

Field evaluation of a winged foot (*Fig. 1*) based upon the work of Spoor and Godwin (1978) was undertaken by Negi *et al.* (1976 & 1978) and showed that under arable conditions, up to 100 m^3/ha of sludge could be incorporated at a working depth of 150 mm, with an injector tine spacing of 750 mm.

In developing a deep injector for grassland Pullen (1976) found that increasing tine width, by adding wings, improved the incorporation rate without substantially increasing the draught or suppressing grass growth. The wings also increased the lateral distribution of slurry. Rolling immediately after injection reduced the quantity that could be applied by 40 per cent. However, it reduced the grass kill and stabilised the slurry in the soil. Based on this study an injector was developed to incorporate between 10 and 100 m^3/ha of slurry. It comprised a straight disc coulter positioned between 350-450 mm in front of the injection tine and working at a depth of 50-75 mm. The injection tine had a wing 200 mm wide working between 100 and 200 mm deep depending on the application rate. This was followed by 225 mm wide roller positioned about 750 mm behind the tip of the main tine (*Fig. 2*). Field evaluation confirmed the ability of the injector to inject slurry into grassland at the design rate without any long term damage to the grass (Bruce *et al.,* 1979).

Warner and Godwin (1988) injecting slurry into dry grassland conditions using the above injector, proved the principles adopted by Negi *et al.* (1976) that for all depths twice the volume of sludge could be incorporated with a winged tine (*Fig. 3*). Warner *et al.* (1991) showed a low-rake angle leading tip dominated surface disturbance, while wing profile was secondary. However, removal of the tip resulted in problems with penetration. Press wheel design had little effect on final surface profiles, but did improve grass response.

3. Materials and methods

3.1. *Shallow injector designs*

From existing designs, it is known that the minimum width of pipe needed to supply sludge without blocking must be between 25 and 30 mm wide. Working at a depth of 50 mm and on spacings of 250 mm, it is possible using a tine of this size to create slots that can hold sludge at the rate of 50 m^3/ha. Thus, the problem with current designs is not their ability to meet the design application rate but the way in which it is achieved. To prevent sludge runoff and it being left exposed to the atmosphere it must be incorporated into the new void space created by the tine.

As shown on deep injectors (Warner & Godwin 1988) the creation of new voids can be improved by adding wings (*Fig. 3*). New void space per unit run (*Fig. 4*) is a function of tine geometry and working depth (Negi *et al.* 1976).

The sectional area loosened behind a tine A_i in m^2 is given by:

$$A_i = d^2 \cot\beta + dW \qquad (1)$$

where: d is the tine working depth (m); β is the angle subtended by the line joining the soil rupture surface and the edge of the tine (deg); W is the tine width (m) and the new voids (v) in m^3/m created per m length are:

$$v = A_i \frac{(\gamma_i - \gamma_f)}{\gamma_f} \qquad (2)$$

where: γ_i is the initial soil density in kg/m^3; and γ_f is the final soil density in kg/m^3. Typically $(\gamma_i - \gamma_f)/\gamma_f$ ranges from 0.1 to 0.5 and cotβ is 0.59. Table 1 gives the predicted void space created by different width tines at two depths assuming a tine spacing of 250 mm.

Two design approaches were adopted one based on a single piece tine with a rearward sloping leg and the other on a multi piece tine with a forward sloping leg, see Table 2. The rearward sloping leg of the single piece tine allows for a light construction and was designed to fit a 12 m wide boom applicator that was able to operate off the crop and from the tramlines, Wheeler *et al.* (2000). To minimise the high draught forces and resistance to penetration caused by rearward sloping tines the leg was only 3.0 mm wide. Five tines of this type were designed (*Fig. 5*). Three had the same leg profile but were fitted with different wing widths (*Fig. 5a*). Their purpose being to determine if increasing wing width would produce similar benefits to those found on deep injectors.

The other two tines were similar to the 40 mm wide tine but used different leg profiles (*Fig. 5b & c*). Both profiles included a crop deflector followed by a horizontal section designed to cut the crop and soil surface. Their purpose was to determine whether integration of a crop cutter effected tine performance.

For the multi piece injector (*Fig. 6*) the roles of injection and crop cutting were separated. This approach was adopted to allow the replacement of wearing parts and it was expected this design might be used on a conventionally tractor mounted implement.

This injection tine (*Fig. 6a*) had three components, the supply pipe providing the leg and support for the other parts. To minimise the draught force and soil mixing, the leading edge was designed to work at 45 degrees to the travel direction. It was also fitted with a metal wedge to prevent a soil wedge forming. A tip 10 mm wide at the base aided penetration and the 40 mm wide wings increased soil loosening. These parts could be unbolted and replaced separately. Two deflectors were attached onto the rear of the wings whose role was to mix the soil and sludge below the surface.

Three types of cutter were used with the injection tine (*Fig. 6b*). Cutter I had a short leading cutting edge followed by a section that ran clear of the ground. The role of the latter was to prevent surcharging on the injection tine. Cutter II had a continuous cutting section sharpened along its length. A standard disc was used as the final cutter type.

3.2. *Experimentation*

3.2.1. *Laboratory tests*

The tines evaluated are listed in Table 2. They fall into three categories, the single piece tines (*Fig. 5*), a multi piece tine with alternative cutters (*Fig. 6*) and commercial tines (*Fig. 7*). The slipperfoot and both shallow injectors represent best current practise. The winged foot, an early commercial design, consisted of a large cast-iron foot with small wings.

Each tine was evaluated at two depths, nominally 50 and 75 mm, ie a total of 24 treatments were conducted. A randomised replicated block design with three replications was adopted for the experiment.

3.2.2. *Field evaluation*

Three different field tests were conducted:

(1) Observation tests in a permanent grass lay.
(2) Agronomic trials described in part II (Pullen *et al.* 2004).
(3) A commercial demonstration trial using the single piece tine, profile III (S5), in winter wheat

to determine whether the injection process would cause any crop damage. The trial area was split into three plots each being 100 m by 20 m wide, see Table 3.

3.3. *Procedure*

3.3.1. *Laboratory tests*

Laboratory tests were all conducted in the Soil Dynamics Laboratory at Silsoe. This facility contains a bin which is 20 m long, 1.7 m wide and 1.0 m deep, filled with a Cottenham series sandy loam soil and provides controlled conditions for evaluating soil engaging implements. A hydraulically controlled processor unit prepares the soil and carries the implement under test. The soil properties used in these tests are shown in Table 4.

Each tine was fitted to a mounting bracket that included a supply pipe for the sludge. This bracket was attached to an extended octagonal ring transducer (Godwin 1975) fitted to the soil processor. The transducer allowed simultaneous and independent recording of the horizontal draught force, the vertical force and the moment on the tine during its passage along the bin. All the tests were conducted at a nominal speed of 0.5 m/s.

After each test the surface disturbance created by the injector was measured by placing a profile meter (*Fig. 8*) across the surface. Each profile was traced on to paper and subsequently digitised.

From the data collected four factors were used to assess tine performance, these being:

(1) the average draught force (kN) over the test run;
(2) the average vertical force (kN) over the run;
(3) the estimated application rate (m^3/ha); and
(4) the specific application resistance (N ha/m^3).

For this study, positive vertical forces are upward and show the magnitude of the force resisting injector tine penetration. The surface disturbance values were used to estimate the new void space created. For this it was assumed the area of soil above the original surface, excluding the area left by the tine leg below the original surface, was the new void space created in the total loosened area. This excludes the existing pore space but provides a method of comparing relative performance of the tines. The application rate was estimated, for a tine spacing of 250 mm, by assuming all the new voids and the total area left by the leg could be filled with sludge.

The fourth factor, termed the 'specific application resistance' is defined as the draught force divided by the estimated application rate, that is the draught force needed to inject a unit application rate (N ha/m^3). A good relative performance indicated by a low value.

A separate analysis of variance was conducted and where appropriate a least significant difference ($lsd_{5\%}$) at the 5 per cent probability level calculated for each data set.

3.3.2. *Field tests*

(1) Observation trial in grass: Simple tests were conducted to find out the performance of the single piece tine with profile III (S5) in grass (*Fig. 5c*). The tines were fitted to a standard shallow injection frame and sludge supplied from a tanker (*Fig. 9)*. This observation study took place in the late Spring into a permanent grass lay under dry sandy soil conditions.

(2) Agronomic trials: Replicated trials were conducted over two years to access the damage and effect on the yields of combinable crops of injecting bio solids into the growing crop (Pullen *et al.*, 2004). As part of these trials the performance of the shallow I (C2), slipperfoot (C1) and the single piece with profile III (S5) was observed under field conditions.

(3) Commercial demonstration trial: For this trial the application rig was fitted with the single piece tine with profile III (*Fig. 5c*) and adapted to allow sludge to be supplied from an umbilical hose (*Fig. 10*). This is similar to the system currently adopted by many contractors.

A 94 kW tractor fitted with flotation tyres pulled the applicator at 1.0 m/s for all treatments. Sludge supplied by road tanker was pumped straight to the applicator through a single 200 m length of 100 mm diameter lay flat hose. A radio link allowed the application tractor to control the pump remotely.

The trials were conducted at the end of February on a sandy loam soil planted with winter wheat, variety Brigadier. The application rate was nominally 50 m^3/ha. All other crop management operations such as spraying, on the whole trial area were identical. At harvest, grain yields across each plot were sampled with a plot combine harvester. Each sample area was nominally 2.2 m wide by 18.0 m long and 12 samples were taken for each plot. A paired t-test was used to determine differences between pairs of plots.

4. Results

4.1. *Laboratory tests*

The results are presented in *Fig. 11*. Four graphs are shown, that is the draught force, the vertical force, the estimated application rate and the specific application resistance. Each graph gives mean values and the least significant difference ($\mathrm{lsd}_{5\%}$) value. All results were significant at the 99.9 per cent level.

Excluding the multi piece tine M1 the draught force (*Fig. 11a*) of all the different tines increased with operating depth. However the differences were only significant on the commercial tines C1, C2, C3 and C4 and the single piece tine with the 10 mm wing, S1. At 50 mm deep there was no significant difference between the draught of any tine except the slipperfoot (C1) and the single piece tine (S5) which were both significantly higher. Draught of the winged foot was also significantly greater than either of the single piece tines S1 & S2 at this depth. The draught of the slipperfoot (C1) and the single piece tine (S5) were both also significantly higher than the other tines at a depth of 75 mm. The winged foot (C4) also had a significantly higher draught than any of the other single and multi piece tines. Both shallow tines, C2 & C3, at 75 mm deep had a draught which was significantly greater than S2, S3, M1 and M3.

The vertical force (*Fig. 11b*), on the slipperfoot, shallow I and II was significantly higher than all the single and multi piece tines except M3. The vertical force of the winged foot (C4) was significantly higher than S1, S2, S3, S4 at both depths and M1 at 50 mm. There was no significant difference between the vertical force of any of the single and multi piece tines except that fitted with a disc. Except for the shallow II injector, changing the working depth had no significant effect on the vertical force.

Estimated application rates (*Fig. 11c*) ranged from 37 m^3/ha for the shallow injector I (C2) at 50 mm deep to 233 m^3/ha for winged foot tine at 75 mm. Application rates significantly increased with working depth on S1, S3, S4, M3, C1, C2 & C4. Other treatments were not significantly effected by the change in working depth. At a depth of 50 mm there was no significant difference between the estimated application rate of the slipperfoot, shallow I, shallow II, 10, 25 & 40 mm all with profile I, profile II with 40 mm wing, or any of the multi piece tines. The potential application rate for the 25 mm single piece tine was significantly lower than S1, S3, S4, S5, M3, C1, C2 & C4 at 75 mm deep.

Comparing the specific application resistance (*Fig. 11d*), for treatments at the same depth, the slipperfoot was significantly higher than all the other tines except for the two shallow injectors, the single piece tine with profile III and the 25 mm winged tine at 75 mm. Also, the specific application resistance of the shallow injector at 50 mm deep was significantly higher than S1, S2, S3, S4, M1, M2 & M3 at 50 mm. But, at 75 mm deep the difference was only significant with M3. At 75 mm the specific application resistance of the shallow II tine was significantly higher than treatments S3, S4, M1, M2, M3 & C4. The winged foot tine was not significantly different from any of the experimental tines except S5. Equally there was no significant difference between any of the single or multi piece tines except for the tine with profile 3, which was higher than the others. Increasing working depth of any tine from 50 to 75 mm had no significant effect on the specific application resistance except for the 25 mm single piece tine, S2.

4.2. *Field tests*

i) Grass tests: The single piece tine with profile III (S5) placed the sludge below the surface and there was no sludge visible after injection. The test area was not rolled because it was found this would force the sludge onto the surface however, the turf quickly recovered (*Fig. 12*). Grass damage was small and with tines at 200 mm spacing there was no noticeable stripping caused by uneven application of the sludge.

ii) Agronomic trials: During these trials it was observed the operation of the slipperfoot (C1) and shallow I (C2) were similar. Both created narrow slots with very little soil loosening along the edges. Also in dry hard conditions it was impossible to get either to penetrate. Whereas, the single piece tine with profile III (S5) penetrated much better and did not leave an open slot.

iii) Commercial demonstration trial: The yield results showed that no significant difference occurred between pairs of plots, even on the trial area where the crop was subjected to the greatest mechanical damage (*Fig. 13*). The crop quickly recovered from any damage caused during the injection process. *Figure 14* shows the condition of the control and both injected plots both six weeks after injection and at harvest.

5. Discussion

Estimates of the application rates suggest most tines could incorporate the design rate of 50 m^3/ha when working at 50 mm deep. The agronomic trials (Pullen *et al.* 2004) with the slipperfoot, shallow injector and the single piece tine with profile III confirm application rates of 50 m^3/ha at 50 mm deep would also be achieved in the field. The laboratory tests suggest all tines would exceed the design rate as depth increased. The estimated rates also fall within the range predicted by the theory, see Table 5, except for the single piece tine with the 10 mm wing. Here, the predicted disturbance under estimates the actual value. This may have been due to the supply pipe, which was 25 mm wide, masking the 10 mm wide wing.

The winged foot produced the largest void space in the laboratory tests however its physical size, being 100 mm wide, and the disturbance created (*Fig. 15l*) would make it unsuitable for applying sludge through arable crops because of the potential crop damage. Performance of the two commercial shallow injectors were similar. This is to be expected as the main difference between them is minor. One is single piece while the other is split into two parts that can be replaced separately. The slipperfoot, shallow I and shallow II all left slots in the soil surface (*Fig. 15i, j & k*). Under field conditions the effect was more marked (*Fig. 16a*). While the slot was less obvious with the single and multi piece tines (*Fig. 15a, b, c, d, e, f, g & h*). A similar performance was obtained in field conditions (*Fig. 16b & c*). This suggests a tine such as the single piece tine with profile III was more likely to place the sludge/slurry into the new void space than the commercial tines. This difference in the placement of the sludge/slurry also probably explains the reduced ammonia releases and odour levels achieved with the single piece tine with profile III, Moseley *et al.* (1998) and Pahl *et al.* (2001).

The draught force on all the commercial tines was more sensitive to changes in working depth than the experimental tines. This is expected as the commercial tines had a wide backward sloping profile. The shape also explains why these tines had increased penetration problems.

Of the single piece tines the three with the same leg profile (S1, S2 & S3) had similar performance. All produced, as expected, the smallest upward force, as the downward force created by the wing compensates for the upward component caused by the leg. The decline in draught force, at 75 mm deep, with increasing wing width can be attributed to the effect of the supply pipe working in less disturbed ground when used with the narrower winged tine. Despite these advantages the tines would only be suitable for working in trash free conditions.

Under laboratory and field conditions both single piece tines with integral cutters, S4 & S5, provided better penetration than the commercial tines although, as would be expected, not as good as S1, S2 & S3. Initially there were problems with the single piece tine with profile III (S5) cutting trash in loose conditions in the field but this was overcome by increasing the radii of the corner at the front of the edge leading to the horizontal section to ensure the trash flowed under the cutting surface. Equally increasing the size of the deflectors that moved the soil around the supply pipe prevented this build up.

The draught force of the tine with profile II (S4) was similar to the other single piece tines. However, the single piece tine with profile III (S5) had a much higher draught force, being similar to that of the slipperfoot. Further investigation suggests this large difference in the draught force between these two tines (S4 & S5) is caused by the differences in the wing design and not a manufacturing fault as suggested by Moseley *et al.* (2000). The wing on the single piece tine with profile II (S4) extends under the cutting edge and this creates, as any positive raked tine, a tension soil failure in front of the cutting edge. While tine S5 had a negative raked leading edge causing a compressive failure similar to the slipperfoot. Although this design produces a higher draught it does not become blocked with trash, preventing penetration, in field conditions.

The multi piece tine with any of the cutters had similar loosening performance to the single piece tines. Performance of cutters I & II were similar. The relieved section on cutter I used to reduce the surcharging on the injector had no measurable effect on the draught and vertical forces. Using the disc makes injector penetration more difficult although it is less likely to block under cropped conditions. Draught force and loosening were similar to the single piece tines (S3 & S4) because the tine creates the same soil failure pattern. Fitting deflectors to the wings to improve incorporation of the sludge had no noticeable effect and has little benefit, probably becoming blocked in some conditions.

6. Conclusions

(1) There is little benefit in fitting narrow wings, ie 10 and 25 mm wide, as their effect would be masked by the sludge supply pipe. A wing of 40 mm provides a void space for an estimated application rate of 60 m^3/ha at 50 mm deep and 110 m^3/ha at 75 mm. This matched the theoretical estimate.

(2) Either a single piece tine with integral cutter or a multi piece tine fitted with a 40 mm wide wing could successfully be used to meet the design specification of injecting sludge at 50 m^3/ha in arable crops. Both penetrated the ground more efficiently than current commercial tines and the wings assisted incorporating the sludge into the soil below the surface reducing odour and ammonia emissions.

(3) The single piece tine with profile III (S5) had a similar draught as the slipperfoot while the multi piece tine had a draught between 17 and 24 per cent of that of the slipperfoot.

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