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Injecting Bio Solids into Grass and Arable Crops, Part II: Development of a Shallow Application Technique for Injecting into Combinable Arable Crops

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Abstract

Digested sludge contains valuable crop nutrients but these are largely lost because current application techniques limit where and when it can be applied. Soil injection to depths in excess of 150 mm to reduce odour problems can only be used on fallow land or grass because of the damage it can cause. This leads to applications at high rates being applied with increased environmental 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, less than 100 mm deep, injection techniques. Agronomic trials conducted over two years with winter wheat and rape showed the crops were surprisingly resistant to mechanical damage during the growing season. Crop yields were not effected by injecting sludge into the crop up to March, equivalent to growth stage 30 in winter wheat, using a conventional tractor based system working. Injection is possible later in the growing season based on systems with the tractor operating along "tramlines" for field traffic control.

1. Introduction

The nutrient value as a crop fertiliser of bio-solids such as digested sludge and slurry is well known (Bowden, 1997). However, this fertilising value is rarely fully utilised because current application methods are inefficient and/or can have a high environmental impact. Deep injection techniques, ie injecting 150 to 450 mm below the soil surface, are not used in the spring in arable crops because of the damage caused by the injection tine (Hann *et al.,* 1992). This restricts the area and time where it can be used and as such, applications rates tend to be high with consequent pollution risks. Also it has a relatively high draught force requirement, whereas surface application techniques have virtually no draught force requirements, cause little crop damage but do not contain the odour problem, Moseley *et al.* (1998) and Pahl *et al.* (2001).

Shallow injection 50 to 70 mm below the soil surface in grass is a recent development. Here, application rates are much lower 50 m^3/ha. Using this technique for injecting sludge into the soil in arable crops at rates and times when its nutrient value could be used by the crop would have many advantages, namely it would:

(1) reduce the environmental impact;
(2) replace some of the inorganic fertiliser needs;
(3) improve the opportunity for injection and reduce haulage distances as more land would become available; and
(4) extend the time during which sludge could be applied.

For successful injection into growing crops it is important the application vehicle causes no long-term damage and the sludge can be supplied at high rates. Currently, sludge is often supplied to injection equipment by trailing an umbilical hose behind the tractor. This has the advantage of continuous supply without the concentrated wheel loadings caused when using the alternative tanker supply system. The umbilical hose causes little damage on grass (Godwin *et al.,* 1990) but its effect in combinable crops is unknown.

The aim of this project was to develop a system to incorporate digested sludge into the soil at 50 m^3/ha through combinable arable crops during the growing season and to determine the best application times. The project is documented in two parts. The first describes an investigation into the design of shallow injection tines (Pullen *et al.*, 2004) and the second, this paper, describes the agronomic trials undertaken as part of this study. These trials were designed to determine the long term physical damage to the crop at different times during the growing season times caused by:

(1) the injector;
(2) the umbilical hose; and
(3) the tractor wheels.

2. Materials & Methods

2.1. *Experimentation*

All work took place on Cranfield University Farm, Silsoe, Bedford over a two year period. In the first year commercially available equipment was used to apply the sludge (*Fig. 1*). For the second, a single piece tine with profile III and 40 mm wing (S5), hence forth known in this paper as the single piece tine *(Fig. 2),* that had been developed in a parallel study (Pullen *et al.,* 2004) evaluated alongside existing commercial designs. All agronomic management decisions not described in the following sections were similar across each trial and undertaken as part of the normal commercial farm operations.

2.1.1. *Year one trials*

Two trial sites were used, one on a clay soil sown with winter wheat and the other on a sandy loam soil planted with winter rape. Two identical experiments were set up on each site. One was designed to find out the physical damage caused to the crop by different application techniques carried out at different times over the growing season. The other experiment was designed to determine if supplying sludge by dragging a hose across the ground behind the injector would cause any lasting crop damage.

A replicated block design with split plots was used for the main experiments. Each had three replications with 20 treatments each at two sludge application levels. The treatments included three application techniques, one dribbling the sludge on to the soil surface below the crop canopy and the other two applying the sludge below the ground surface at a depth of about 50 mm. For the subsurface techniques two different machines were used (*Fig. 1*). The three different application techniques were used at six different times during the crop growing season. These were spread over the period from just after crop emergence to mid or late flowering (*i.e.* May - early July).

Each plot was split into two equal parts. On one-half digested sludge was applied at the rate of 50 m^3/ha. In the other half the applicator was used but no sludge was applied. The purpose of which was to determine the effect of the physical disturbance caused by the tines alone. On all plots the quantity of granular nitrogen fertiliser was reduced by 35 kg/ha. This being equivalent to the estimated fertiliser value of the digested sludge (Bowden, 1997).

Two control treatments were included. One control in the winter wheat was given no nitrogen. In the rape the equivalent control was given a small quantity of nitrogen at the rate of 26 kg/ha as part of an application of ammonia sulphate. The second control as with the sludge application treatments was split into halves. One-half received the same quantity of granular fertiliser as the other plots, that is 35 kg/ha less than the recommended rate. On the other half of this control granular fertiliser was applied at the recommended rate for the crop, *i.e.* winter wheat 190 kg/ha and rape 155 kg/ha.

The nominal gross plot length and width were 45 m and 4.0 m respectively and the net split plot size was 18 m by 2.2 m, see *Fig. 3*.

For the umbilical hose trial a separate replicated experiment was set up using the same application treatments as the crop damage experiment. Each replicate was positioned at the end of each plot on the main experiment, see *Fig 3*. This permitted the applicator to be drawn straight out from the crop damage plots and across the area used for the hose tests. On the area used for the hose trails the sludge supply to the applicator was switched off. Granular nitrogen was applied at 35 kg/ha less than the recommended rate. The nominal gross plot size was 4.0 m wide by 20 m long. Net plot size was 2.2 m by 2.0 m.

2.1.2. *Year two trials*

In the second year two identical replicated experiments were set up, one on clay and the other on sandy loam soils. Both were planted with winter wheat. The purpose of these experiments was to gain further evidence of the effect of injecting sludge into growing crops and to compare the single piece tine (S5) (Pullen *et al.,* 2004) with the existing commercial slipperfoot (C1).

The design used for both experiments was the same. Each was a randomised block design with three replications. The gross plot size was 20 m long by 4.0 m wide. The net size was 18 m long by 1.6 m wide. The net width kept the wheels of the tractor pulling the injector outside the harvested area (*Fig. 4*).

Ten treatments were undertaken. Seven treatments received a single application of sludge during the growing season but at different times. This included three with the slipperfoot (C1), that is December, March and May, and four with the single piece tine (S5) , that is December, February, March and May. The eighth treatment received two sludge applications, one in February and the second in March, applied with the single piece tine (S5) . The granular fertiliser rate was reduced by 35 kg/ha on all the plots where sludge was applied. Two controls were used, one where the recommended granular fertiliser rate was applied and the other received no fertiliser.

2.2. *Equipment & procedures*

2.2.1. *Year one trials*

Two machines were used to inject the sludge. These were the shallow I (C2) and the slipperfoot (C1). Both machines were designed to inject animal slurry into grassland, neither being specifically designed to work in arable crops. The shallow I was also used to provide a surface application by simulating the dribble bar application technique (C2D). For this the individual arms were locked parallel to the travel direction and pulled across the plot with the tines just clear of the ground surface but below the crop cover.

The general layout of the implement onto which the shallow tines (C2) were attached is shown in *Fig. 5*. It consists of a rotary distribution valve and twelve injection units. The injection units are grouped in pairs. Each pair being attached to the mainframe on a pivot that allows it to swing sideways. They were also spring-loaded. In work the height of the main toolbar was approximately 450 mm from the ground, whilst, the clearance under the frame connecting two injectors was only 120 mm. Each injector consisted of an opening disc and a blade to form a slot into which the sludge was placed. The shape of the foot (*Fig. 1 a*) is similar in design to a Suffolk Coulter and had a negative rake angle, that is trailing backwards and downwards from the front. Spacing between individual injectors was 250 mm and the overall machine working width was 3.0 m.

The overall design of the distribution system, frame and weight transfer system used on the implement which the slipperfoot were fitted was similar to that used for the shallow tines. The main difference being each injection blade was independently mounted on the frame allowing each to freely swing sideways. Soil engaging parts were also mounted on a spring-loaded parallel linkage. These consisted of a small opening disc followed by the opening tine, the slipperfoot (*Fig. 1 b*). The machine used in the trials had an overall working width of 3.6 m with tines spaced at 200 mm.

For all the tests the application equipment was mounted on a 93 kW 4WD tractor. Flotation tyres were fitted for applications early in the growing season. Later, as soil conditions improved these were replaced with standard tyres. The rear wheel centres used with the different tyre arrangements were 2.0 and 1.8 m respectively. All applications were undertaken at a forward speed of 0.56 m/s (2.0 km/hr) and parallel with crop rows.

Sludge was delivered to site on the day of application and loaded in small quantities to a tanker drawn by a tractor. This was used to transfer sludge to the applicator working in the field. To minimise crop damage the tractor and tanker ran down existing tramlines alongside the applicator. The sludge was transferred between the two vehicles through a flexible pipe. The tractor working the supply tanker was driven at a set engine speed to provide a given discharge rate to the applicator. Two engine speeds were used to cater for the different working widths of the applicators. For the shallow injector the calibrated flow rate was 500 l/min and for the slipperfoot 600 l/min.

For the umbilical hose trials a 10.5 m long and 100 mm diameter piece of semi-rigid plastic pipe filled with water was utilised. This was pulled with either one or two vehicles (*Fig. 6*) immediately after injection to simulate field operations. Hose tests were conducted perpendicular to the applicator path and crop rows.

2.2.2. *Year two trials*

A standard slipperfoot distribution valve and frame were used as the application platform for the trials. As a result of observations from the first year trials, spacing brackets were made to fit between the mainframe and individual parallel linkages. These were fitted to alternate linkages to stagger the tines by 200 mm reducing the interaction between adjacent tines. Also, to allow the mainframe to work at 700 mm above the ground, extension brackets were fitted between the tines and the bottom of each parallel linkage.

Both the slipperfoot (C1) and the single piece tine (S5) (*Fig. 1*) Pullen *et al.* 2004, were attached to the frame. A 93 kW tractor was used for all the tests with the wheel centres, set at 2.2 m, leaving 1.6 m clear between the tyres. Standard tyres were used throughout as the application tractor did not run on the crop (*Fig. 4*). Sludge was again supplied to the applicator from a tanker towed along the normal tramlines with a 'flying' umbilical hose to the injectors.

2.3. *Data collection and analysis*

During both trial years the rainfall and evaporation were recorded daily. In addition a chemical analysis of the digested sludge was undertaken immediately after each application.

2.3.1. *Year one trials*

The soil conditions and damage caused by the tractor tyres was recorded at each application. Measurements taken included resistance to a drop cone test (Godwin *et al.,* 1991), soil strength using a shear vane, the depth of the impression caused by the tractor tyre lugs and the soil moisture content.

At harvest two data sets were collected for both main experiments. Firstly quadrat samples were taken to assess the relative damage caused by the injector only and the injector and tractor tyre. All samples were taken on the non-sludge area of the plots treated with the slipperfoot (C1). For the rape trial the total biomass yield was recorded while, on the wheat trials the clean grain yield was recorded. For both data sets an analysis of variance was undertaken and where appropriate a least significant difference ($lsd_{(5\%)}$) calculated at the 5 per cent level to show real differences between treatment means.

Secondly, for the main yield data, each plot was harvested with a plot combine driven along the plot centre. All grain/seed yields were standardised at 15 per cent moisture content. For the analysis the results of individual treatments were grouped to identify any overall trends. For example, the effect of application technique was examined by conducting an analysis on the combined yields of all the plots treated with the shallow I (C2), the slipperfoot (C1) and dribble techniques (C2D). In total nine such comparisons were examined. For those results that were significant an $lsd_{(5\%)}$ was calculated.

For both umbilical hose trials a photographic record was made for each treatment. The condition of the crop immediately after the passage of the applicator and then a second taken immediately after the hose had been dragged across the plot. At harvest a quadrat sample was taken to indicate the possible effect on the final crop yield of both the applicator and the hose damage. In the rape crop the total biomass on each plot was recorded because of the difficulties collecting the seed when the crop was ripe. On the wheat trial the clean grain yield was recorded. For both data sets a simple analysis of variance was undertaken and where appropriate an $lsd_{(5\%)}$ calculated at the 5 per cent level to show real differences between treatment means.

2.3.2. *Year two trials*

On these experiments the plots were harvested with a plot combine and grain yield standardised at 15 per cent moisture content. An analysis of variance was undertaken and where appropriate, an $lsd_{(5\%)}$ at the 5 per cent level calculated.

3. Results

General information about the experimental conditions existing during both trial years are given in Table 1. The rainfall and evaporation pattern (*Fig. 7*) shows over the trial period conditions were relatively drier than average. Only on six occasions did the monthly rainfall exceed the 25 year monthly average. Evaporation was also higher than the average.

3.1. *Year one results*

3.1.1. *General data*

Soil physical conditions occurring at each application rate are shown in *Fig. 8*. As expected using flotation tyres early in the season when the soil strength was low reduced soil damage. Later in the season at lower soil moisture contents the strength increased and the soil damage was reduced.

3.1.2. *Relative damage behind applicator only and wheel & applicator*

Results of the quadrat data presented in *Fig. 9*, show that the relative wheat yield between those parts of the slipperfoot plots treated with the injector only and the untreated control were not significantly different. For treatments conducted up to late February, there was also no significant difference between the yield behind the injector only and the area where the tractor wheels had passed. However, on applications conducted from April onwards the yield was significantly lower than the part of the plot treated with the injector only and the control. The wheels had no significant effect upon the yield for applications in the early part of the season but significantly reduced the yield in April, June and July.

There was no significant difference between the yields of rape biomass on those parts of the plot treated only with the injector and the equivalent untreated control as shown in *Fig. 9 (b)*. However, the tractor wheels did cause damage and this was significantly different from that only effected by the injector for those applications conducted during November, December, April and May. On applications in February and March the difference between the growth behind the injector only and behind the wheel and injector was lower but not significantly different. The damage caused by the wheels was only significantly different from the control for the applications in December and May.

3.1.3. *Final plot yield*

A summary of the analysis of results of the combine yield data are given in *Figs. 10 & 11* and in Table 2. These show in the winter wheat only a very highly significant effect was caused by application technique and time. Whereas in the rape only application time had any significant effect. Each graph presents the results of one analysis giving the mean yield values, level of significance and appropriate $lsd_{(5\%)}$.

Figure 10 gives the interaction between application technique and time on the winter wheat. This shows there was no significant difference between the yield of any treatments conducted in November, December and February. These were also not significantly different from the fertilised control. However, they were significantly higher, except the surface treatment (C2D) in February and the shallow I (C2) treatment in March, than the unfertilised control. All treatments conducted in April, June and July produced yields that were significantly lower than the treatments conducted before April. Those treatments conducted in June and July were also significantly lower than the two controls.

At the final application there was a significant difference caused by the application technique. The yield due to the shallow I injector (C2) was significantly lower than both the slipperfoot (C1) and dribble technique (C2D). In June there was no significant difference between the shallow and slipperfoot but both were significantly lower than the surface application. There were no significant differences between the application techniques conducted at the same time for applications up to and including those conducted in March.

Figure 11 (a) shows while rape yields at the application in May were much lower than those at other times they were not significantly different. Pooling the techniques in *Fig. 11 (b)* shows that the time effect was very highly significant. Overall, the last application significantly suppressed the yield in comparison with both the control and applications conducted at other times during the growing season.

3.1.4. *Umbilical hose tests*

The mean yield results and analysis are summarised in *Fig. 12 (a)* for the winter wheat. These show that there is no significant difference between the winter wheat yields of any of the application techniques conducted at any application time except that conducted in July. Here, the yield following the shallow I (C2) was significantly lower than on the plot treated with the dribble technique. The yield on all the plots treated in April & June, and the dribble technique applied in February, were all significantly better than the yield from the control treatment which was not treated with the umbilical hose. All treatments conducted in July produced yields that were significantly lower than the control.

Although the May treatment in the rape (*Fig. 12 b*) had a lower yield, the difference was not significantly different from any other application technique treated at any application time. All treatments were similar to the control.

3.2. *Year two results*

The soil moisture content at the different application times is given in Table 3. It is as would be expected.

The yield results for both experiments are summarised in *Fig. 13*. These show there were no significant differences between any treatments on the sandy loam soil, Showground. However, on the clay soil, Home Close, the highest yield occurred on the granular fertilised control. This was significantly better than the unfertilised control and all treatments where the experimental tine (S5) was used except the plot that received two applications of sludge. There were no significant differences between any of the slipperfoot treatments and the fertilised control. All injection treatments were significantly better than the unfertilised control. Yields on plots treated in December and May with the single piece tine (S5) were significantly lower than the slipperfoot application in December. There were no significant differences between the yields on any plots treated with the single piece tine (S5). Equally, plots treated at different times with the slipperfoot were not significantly different.

4. Discussion

4.1. *Year one trials*

The control for the main experiment was treated at the recommended granular nitrogen rate and achieved a yield of 9476 kg/ha. The unfertilised control produced an equally good average yield, this being 9247 kg/ha. This is unexpected and could be attributed to the dry cold spring delayed mineralisation of soil nitrogen. The previous rape crop, a known source of nitrogen may also have contributed to the response.

The oil-seed rape yields obtained in the experiment were as expected for this soil type. The control treatment with the recommended application of granular fertiliser achieved a mean yield of 3031 kg/ha. The unfertilised control performed equally well with a mean yield of 3068 kg/ha. This is similar to that found in the wheat trial but here the cold dry spring cannot fully explain this result and a combination of other reasons may have been the cause. First, the low rainfall may have resulted in the rape grown in 1993/94 contributing to the fertiliser reserve. Secondly, this control received nitrogen at the rate of 26 kg/ha as part of an application of ammonia sulphate. Finally, the yield of the untreated control on one block was exceptional high and this increased the overall mean. The plot was in the lowest part of the field and yielded 4545 kg/ha. Excluding these values the mean for the unfertilised control would have been 2675 kg/ha. The high coefficient of variation in this experiment was probably caused by unexpected variation in yields in this block.

The time of application of sludge did not effect the wheat yield on any treatments conducted up to the end of February. A small suppression of yield followed the application in April and this became progressively worse on following applications. Wheel damage appears to have been a major cause in the suppression of final yields. At harvest the tractor wheel marks were not visible on any plots treated before the end of February. From April onwards damage caused by the wheels was increased. For plots treated in June the crop began to regrow and noticeable quantities of unripened green grain appeared in the samples. Those treated in July did not recover. The wheel damage was not visually different on those plots treated with different application techniques. The results from the study of the crop damage on the slipperfoot plots would suggest that if the vehicle wheels had been kept off the crop later in the season then the yield would have been similar at all application times.

The wheel damage in the rape occurred both at the start and at the end of the growing season. For applications in November and December where the flotation tyres were used, the crop was very delicate and the passage of the wheels had a long-term effect on the crop biomass yield. Though this was visible at harvest (*Fig. 14*) the crop did compensate and the final seed yield was not affected. For those applications conducted in April and May using the standard tyres, this was not the case. Here, the crop did not recover once it had been run over by the wheels. This contributed to the reduction in yields on the plots treated in May during flowering. The results from biomass measurements would suggest this was the reason.

Damage caused to the soil as shown by the tyre sinkage was small with the configurations examined. By the last application soil strength had become high and the wheels left no mark on the surface. There is evidence to suggest it would have been possible to replace the standard tyres with row crop wheels hence reducing the width of crop damage. This would have reduced the potential crop damage although the wheel marks would still have been visible.

The soil engaging parts on the application equipment did not appear to cause any damage to the crop. However, their lack of ground clearance was a problem at the later growth stages. At most growth stages the crop recovered but at the last application on both crops the plots were flattened and did not recover (*Figs. 14 & 15*). This is not surprising as the clearance under parts of the implement used with the shallow I tines was only 120 mm.

There was little difference in the way either commercial injector placed sludge into the soil. Both formed a trench or slot that was large enough to hold sludge at the rate of 50 m^3/ha. However, it is unlikely that higher application rates could be applied unless the soil was dry. The sludge laid in the slot and it was clear there was a risk of run off. Penetration of both machines proved difficult in hard ground and applying weight through the transfer system did not always overcome this problem. However, neither caused any serious physical damage to the crop.

There were no problems using the simulated dribble bar (C2D). However, later in the season at high air temperatures a strong smell was noticeable on these plots, while the odour from the injected plots was undetectable even though the sludge was not fully incorporated below the soil surface.

The results for the hose tests showed that dragging an umbilical hose across the crop during treatment did not increase yield loss. It was surprising throughout the range of soil moisture conditions how resilient the crop was to this treatment. Although there was some visual damage, at the beginning of the season where the hose smeared the plants with soil, the yield was not affected. At other times when the crop was taller it recovered almost immediately and the damage appeared to be little greater more than caused by the applicator. On a field scale, as reported by Pullen *et al.* (2004), the effect of dragging the hose across the crop had no effect on the yield.

4.2. *Year two trials*

Yields for both experiments were comparable with those on other farm fields. Coefficient of variations were both low, 5.1 and 6.0%, showing the uniformity of individual treatment yields on each experiment.

On the sandy loam soil site, the yield on the unfertilised control was lower than the fertilised control, but not significant. This possibly was due to the dry growing season and a carry over of residual nitrogen from the previous rape crop. As expected significant yield differences occurred between the two controls on the clay site. Here, the crop followed winter wheat. On both sites the total nitrogen content was lower in the grain on the unfertilised plots.

The autumn rainfall was small and this did lttle to compact the seedbed and this made injection more difficult than in the previous year for the first and second applications. On the sandy loam soil in Showground field the surface layers also included large quantities of hard rape trash. The clay soil, Home Close field, had been re-sown and this had produced a soft loose layer sitting on the plough tilth. The crop and sludge were placed in this zone. In these conditions both injectors pushed and sometimes dragged trash, rather than cutting it. On Home Close it was necessary to remove the opening discs from the slipperfoot on the first application to reduce soil movement. On both sites this left an uneven surface and parts of the crop covered with soil. The visual damage remained on both sites throughout the early part of the growing season. Some of the visual impact might have been reduced by rolling the site. This would also reduce the risk of any possible damage caused by frost or drying out of the soil. Although the finish after the two early applications had a poor appearance it did not effect yields, on any plots treated with the slipperfoot injector or plots treated on sandy loam soil, Showground, with the single piece tine (S5).

On the clay soil, Home Close, the yield on all the plots treated with the single piece tine (S5) were slightly suppressed because an interaction between adjacent tines probably disturbed some of the crop roots. The effect occurred at all application times. The single piece tine (S5) was designed to cause more loosening than the slipperfoot (C1) and moving them further apart would have prevented any interaction in these conditions. Increasing the spacing to 250 mm would be sufficient in all but extreme conditions. The tines performed better in the firm soil behind the tractor wheels. On the sandy loam soil the effect was less and did not affect final yields.

Injecting the crop twice in the same season did not cause any more damage than a single injection on either site.

5. Conclusions

The following conclusions are made:

(1) It is possible by using the correct techniques, to inject sludge into winter wheat and rape over a wide time period (ie Nov to Mid July) without causing any loss in crop yield.

(2) Operating the application vehicle, fitted with low ground pressure tyres, on the crop up to March would be possible, this matches growth stage 30 in winter wheat. Later applications should be conducted from tractors operating in tramlines for traffic control.

(3) There was no long term residual yield damage caused by dragging an umbilical hose over the crop.

(4) For combinable arable crops the tines should be placed at a spacing of 250 mm and the implement frame should be at least 500 mm above the ground to avoid damaging the crop later in the season.

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