Slurry Application Techniques to reduce Ammonia Emissions: Results of some UK Field-scale Experiments

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(Received 11 November 2000; accepted in revised form 7 December 2001)

Shallow injection, trailing shoe and band spreading machines were evaluated, in terms of their potential for reducing ammonia (NH₃) emission, by making measurements after application and in direct comparison with surface broadcast applied cattle slurry (pig slurry on one occasion). Several sets of comparative measurements were made with each type of machine on both grassland and arable land (mostly cereal stubbles), covering a range of soil, crop and weather conditions. Measurements of NH₃ emissions were made for 5–7 days following application using a micrometeorological mass balance technique. Mean reductions in NH₃ emission achieved from grassland, in comparison with surface broadcast application, were 73, 57 and 26% for shallow injection, trailing shoe and band spreading, respectively, the latter not being significant (probability P > 0.05). Mean cumulative emissions, expressed as % total ammoniacal N applied in the slurry, were 13, 12 and 35% for shallow injection, trailing shoe and band spreading, respectively. There was a trend (probability P = 0.029) for decreasing emissions with increasing sward height (between 10 and 20 cm) following trailing shoe applications. Abatement was generally less effective when these techniques were used on arable land, with mean reductions of 23, 38 and 27% achieved for shallow injection, trailing shoe and band spreading, respectively, with none achieving statistical significance (probability P > 0.05). There was considerable variation in the efficiency of shallow injection, with reductions achieved in individual experiments ranging from 0 to 90%. The considerable variability in efficiency of the techniques for NH₃ emission abatement warrants further investigation.

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1. Introduction

Increasingly, there are pressures on agriculture to reduce emissions of ammonia (NH₃) to the atmosphere, because of concerns about environmental impact. The land spreading of animal manures accounts for approximately one-third of the total NH₃ emissions from agriculture (Misselbrook et al., 2000) so there has been much interest in the development of abatement measures in this area. There are four main types of slurry application system in use on farms in NW Europe and which are represented in the present study (Fig. 1). Each of the following four techniques can be fitted onto a vacuum or pumped tanker or used with an umbilical supply system: (1) broadcast spreading—slurry forced under pressure through a nozzle, usually onto an inclined plate designed to increase lateral spread; (2) band spreading—a boom with a number of hoses distributing slurry close to the ground in narrow bands, slurry being fed to the hoses in advanced systems via a rotary distribution manifold which controls the flow of slurry evenly to each hose outlet; (3) trailing shoe applicator—similar in configuration to the band spreader, with the hoses discharging via a ‘shoe’ device which parts the crop canopy allowing the slurry to be deposited onto the soil surface; (4) injection—slurry injected beneath the soil surface either via open slot, shallow injection (to 50 mm) or via deep tines (to

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An additional technique is direct ground injection, where jets of slurry are forced into the soil under pressure, mixing with the soil in discrete pockets (Morken & Sakshaug, 1998). This technique has not yet been widely taken up and, due to problems in importing the appropriate machinery, was not used in this study.

Research elsewhere in Europe (particularly in the Netherlands and Germany) has indicated that the recently developed surface placement application techniques for slurry (shallow injection, band spreading and trailing shoe), have resulted in reductions in NH₃ emission of between 70 and 95% compared with surface broadcast application (Huijsmans et al., 1997; Lorenz & Steffens, 1997). However, early experiences with shallow injection using field-scale equipment (Misselbrook et al., 1996; Pain & Misselbrook, 1997) and more recent trials with a small-plot applicator (Smith et al., 2000) suggested that abatement efficiencies under UK conditions may not be so high. The aim of this study was to evaluate the efficiency of these slurry application techniques (excluding the direct ground injection technique) at the field-scale for reducing NH₃ loss on representative grassland and arable soils in the UK.

2. Materials and methods

2.1. Site details

Experiments were conducted on seven sites across England in order to achieve a range of soil types (Table 1) between 1997 and 2000.

2.2. Application techniques

Three application techniques (viz. shallow injection, trailing shoe application and band spreading) were assessed for reductions in NH₃ emission in comparison with conventional surface spreading via a vacuum tanker fitted with a splashplate. For grassland, shallow injection applications were made using either a Green-trac (Greentrac Ltd, Antrim, Northern Ireland) or Duport (Duport BV, Dedemsvaart, Netherlands) machine. The Greentrac had a solid tine to cut the injection slot, a 2.5 m working width and 0.2 m tine spacing. The Duport was of newer design, with angled double discs to cut the injection slot, a working width of 4.4 m and 0.2 m disc spacing. For the arable experiments, a Greentrac arable injector was used, with tines preceded by a curved slot cutter, a working width of 4.5 m and tine spacing of 0.25 m. A trailing shoe machine was provided by Buts Meulepas BV, Oss, Netherlands. This machine had a 6 m boom width with slurry applied in narrow bands at 0.2 m intervals. As a dedicated band spreader could not be secured for use in this project, band spreading to grassland was simulated by adapting the use of the trailing shoe machine and, similarly, to arable land using the Greentrac arable injector. A single measurement using an SAK band spreader (S.A.K. Pumpen A/S, Løgstor, Denmark), with a 21 m boom width and hose spacing of 0.33 m, was made towards the end of the project. Slurry application rates were targeted by previous calibration runs using the equipment and confirmed by weighing the slurry applicator before and after application and measuring the treated area.
### 2.3. Ammonia volatilization

Comparisons were usually made between conventional surface broadcast application and one of the new application techniques, although on some occasions three-way comparisons were also made. Measurements of NH₃ emission were made using a micrometeorological mass balance technique (Denmead, 1983), employing passive flux samplers (Leuning et al., 1985). A mast supporting five passive flux samplers at approximate heights of 0.25, 0.65, 1.20, 2.00 and 3.30 m was placed either at the centre of a slurry-treated square plot (approximately 40 m by 40 m) or downwind of a slurry-treated strip of 20 m by 50 m, such that fetch length (i.e. the distance between the upwind edge of the plot and the downwind sampling position in a windward direction) was always at least 20 m. A background mast, supporting three samplers at approximately 0.25, 1.25 and 3.00 m was positioned at the upwind edge of the treated area. The NH₃ flux, \( F \) in g [NH₃-N] \( m^{-2} s^{-1} \), from the treated area was calculated for each sampling period as the difference between the vertically integrated horizontal flux at the downwind mast (subscript \( dw \)) and that at the upwind mast (subscript \( uw \)), divided by the fetch length, \( x \) in m. Thus:

\[
F = \frac{1}{x} \left[ \int_0^z (\bar{\omega})_{dw} \, dz - \int_0^z (\bar{\omega})_{uw} \, dz \right]
\]

where: \( u \) is the wind speed in m s\(^{-1} \); \( c \) is the NH₃ concentration in g m\(^{-3} \); and \( z \) the vertical height in m. The passive flux samplers measure directly the mean horizontal flux, \( \bar{\omega} \), calculated from:

\[
\bar{\omega} = \frac{M}{At}
\]

where: \( M \) is the mass of NH₃ collected in g in the sampler during sampling period \( t \) in s; and \( A \) in m\(^2 \) is the effective cross-sectional area of the sampler (determined in wind-tunnel calibrations).

All experiments [excepting one, which used pig slurry at the site in Yorkshire (Table 1)] were conducted using cattle slurry. Measurements of NH₃ emission were conducted for 5–7 days after slurry application. Additionally, measurements were made of slurry composition [dry matter, pH, total N, total ammoniacal-N (TAN)], soil type and moisture content at application, crop height or growth stage and meteorological conditions (temperature, relative humidity, rainfall, incident solar radiation). Target application rates were 25–35 m\(^3\)ha\(^{-1} \), according to manufacturer’s recommendations. Details of experiments conducted on grassland are given in Table 2 and those on arable land in Table 3.

### 3. Results

The main effect of the new slurry application techniques was to reduce the peak emission rate observed in the first few hours after application [e.g. Fig. 2(a) — data from Experiment 1], with differences in emission rates on subsequent days being of less significance. As upward of 50% of total emission can occur within the first few hours following application, the difference in emission rates during this period can lead to appreciable differences in total cumulative emission [Fig. 2(b)]. Cumulative emissions reported here are those measured over the measurement period, with no extrapolation for periods beyond 5–7 days.

Target application rates were not always achieved (Tables 2 and 3) and were considerably exceeded in some of the experiments. However, visual observations at the time of application confirmed that the machines performed satisfactorily even at high application rates; slurry did not overspill the injection slots for shallow injection application and remained in narrow bands beneath the herbage with the trailing shoe application. Composition of slurry between treatments, within each experiment, was generally consistent.

As the reduction achieved by an alternative application technique may be biased within individual comparisons, e.g. in some instances when there were exceptionally low losses from surface broadcast application, the data from each set of comparisons were pooled to derive a mean emission for each of the alternative application techniques which could be compared with that for surface broadcast application.

### Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Soil type</th>
<th>Soil series</th>
<th>Soil pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Devon</td>
<td>Coarse sandy loam</td>
<td>Crediton</td>
<td>5.7–5.8</td>
</tr>
<tr>
<td>2</td>
<td>Devon</td>
<td>Heavy clay</td>
<td>Hallsworth</td>
<td>5.1–6.0</td>
</tr>
<tr>
<td>3</td>
<td>Hampshire</td>
<td>Calcareous silty clay loam</td>
<td>Andover</td>
<td>8.0–8.2</td>
</tr>
<tr>
<td>4</td>
<td>Worcestershire</td>
<td>Clay/clay loam</td>
<td>Denchworth</td>
<td>6.8</td>
</tr>
<tr>
<td>5</td>
<td>Cheshire</td>
<td>Loamy sand</td>
<td>Newport</td>
<td>7.2</td>
</tr>
<tr>
<td>6</td>
<td>Herefordshire</td>
<td>Silty clay loam</td>
<td>Bromyard</td>
<td>6.1–6.6</td>
</tr>
<tr>
<td>7</td>
<td>Yorkshire</td>
<td>Silty clay loam over weathered chalk</td>
<td>Panholes</td>
<td>8.0–8.2</td>
</tr>
</tbody>
</table>
under the same conditions. Paired t-test analysis was used to compare the mean emission (% TAN applied) for each application technique with that for surface broadcast application for grassland and arable applications.

3.1. Applications to grassland

Significant reductions in NH3 emission were achieved with shallow injection or trailing shoe application compared with surface broadcast application.
There were only a few observations for band spreading and the mean reduction of 26% achieved was not significant (probability \( P > 0.05 \)), although this was based on only a few observations. Coefficients of variation for emission were large, reflecting the influence of a wide range of factors (which varied with application date) on both emission and efficiency of abatement by each technique. Mean emissions from surface broadcast

Table 3
Experimental details for arable land applications

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Site</th>
<th>Appn. type*</th>
<th>Month of appn.</th>
<th>Slurry</th>
<th>Soil moisture status</th>
<th>Crop type and height, cm</th>
<th>Mean value for first 6h after appn.</th>
<th>Temp., °C</th>
<th>Rainfall, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>SB</td>
<td>May</td>
<td>4.8</td>
<td>1.3</td>
<td>7.4</td>
<td>32</td>
<td>Moist Barley (11-7)</td>
<td>13.1</td>
<td>0.2</td>
</tr>
<tr>
<td>23</td>
<td>SB</td>
<td>Sep</td>
<td>3.2</td>
<td>1.1</td>
<td>ND</td>
<td>25</td>
<td>Moist Cereal stubble (8-4)</td>
<td>15.5</td>
<td>8.8</td>
</tr>
<tr>
<td>24</td>
<td>SB</td>
<td>Sep</td>
<td>7.5</td>
<td>1.2</td>
<td>7.1</td>
<td>28</td>
<td>Dry Cereal stubble (15-4)</td>
<td>9.0</td>
<td>0.8</td>
</tr>
<tr>
<td>25</td>
<td>SB</td>
<td>Oct</td>
<td>ND</td>
<td>0.9</td>
<td>ND</td>
<td>33</td>
<td>Moist Cereal stubble</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>26</td>
<td>SB</td>
<td>Dec</td>
<td>1.8</td>
<td>0.9</td>
<td>7.3</td>
<td>41</td>
<td>Moist Cereal stubble (9-9)</td>
<td>13.6</td>
<td>7.8</td>
</tr>
<tr>
<td>27</td>
<td>SB</td>
<td>Dec</td>
<td>2.9</td>
<td>0.7</td>
<td>7.1</td>
<td>45</td>
<td>Moist Cereal stubble (15-4)</td>
<td>8.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*SB, surface broadcast; SI, shallow injection (subscripts refer to depth of injection in cm); TS, trailing shoe; BS, band spread.
1 DM, dry matter content.
2 TAN, total ammoniacal-N content; ND, no data.

Fig. 2. Typical curves for ammonia emission rate (a) and cumulative emission (b) following slurry application by surface broadcast (x) and shallow injection (+) (data from Experiment 1)
application were lower for the trailing shoe comparison experiments, possibly due to the length of the sward used in these experiments (10–31 cm); surface broadcast slurry may have infiltrated through the longer canopy where restricted air movements and lower temperatures are likely to have reduced volatilization.

Seven experiments were conducted in which comparisons were made between surface broadcast application and shallow injection on grassland. In all but two of the comparisons, reduction in emission with shallow injection was >70%. In Experiment 4, emission from surface broadcast application was low (19% applied TAN) so the relative reduction in emission achieved using shallow injection was less. Experiment 6 was conducted under dry soil conditions, which may have impeded soil penetration by the shallow injector, leading to a lower abatement efficiency. However, Experiment 7 was also conducted under dry soil conditions and on that occasion shallow injection was a very effective abatement technique, although the greater sward height may have further reduced emission following injection. Only two of the experiments were on clay soil but there was no suggestion that injection performance was affected by soil type.

Thirteen experiments were conducted in which comparisons were made between surface broadcast and trailing shoe application to grassland. Results were more variable than for shallow injection, with reductions in emission achieved within the comparisons ranging from 0 to 100%. In Experiment 8, where there was no apparent reduction in NH₃ emission with the trailing shoe, slurry was applied to grass which had previously been grazed very short by sheep and the slurry placed in bands by the trailing shoe flowed across the soil surface, with bands merging and providing a much larger surface area from which volatilization could occur. The application rate, in this case at 40 m³/ha⁻¹, was significantly above the normally recommended operational range for this machine. Losses with trailing shoe application were very low in Experiments 16–20, the placement of slurry beneath a longer sward restricted flux to the atmosphere. In Experiments 17 and 19, emissions after trailing shoe application were below the limit of detection of the measurement technique being employed. In Experiment 18, emissions following both surface broadcast and trailing shoe application were low (7 and 6% of applied TAN, respectively), therefore giving an apparently poor abatement efficiency. An emission of 57% applied TAN after trailing shoe application in Experiment 14 was much greater than for the other experiments. This experiment was conducted on the regrowth following silage harvest of a newly sown ley and, although mean sward height was 17 cm, sward density (which was not measured) was low, therefore offering less protection from volatilization than a denser sward of the same height. Excluding this result from the dataset, there was a trend for decreasing emission with increasing sward height (probability \( P = 0.029 \)) with trailing shoe applications (Fig. 3).

Four experiments were conducted in which comparisons were made between surface broadcast application and band spreading, using the trailing shoe applicator to simulate band spreading by applying slurry with the tines lifted just above the top of the sward. Although the effect of slurry being delivered to the sward via trailing hoses may not have been exactly replicated, this method gave a comparison between the delivery of slurry beneath the canopy and that when there was coating of the herbage with narrow bands of slurry. Reductions in emission achieved in the individual comparisons were generally much lower than for shallow injection or trailing shoe application, ranging between 7 and 52%.

### 3.2. Applications to arable land

Fewer experiments were conducted on arable land. Mean reduction in emission achieved on arable land using shallow injection was much smaller and not significant \( P > 0.05 \); the mean reduction with band spreading was of a similar order to that for grassland applications, but not significantly different from the

### Table 4

Mean NH₃ emission (% TAN applied) and reduction in emission, compared with surface broadcast, achieved by alternative application techniques on grassland

<table>
<thead>
<tr>
<th>Technique</th>
<th>No. of observations</th>
<th>Mean NH₃ emission, % [TAN]</th>
<th>Reduction, %</th>
<th>Significance (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface broadcast</td>
<td>Reduced emission technique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow injection</td>
<td>7</td>
<td>48 (41)</td>
<td>13 (96)</td>
<td>73</td>
</tr>
<tr>
<td>Trailing shoe</td>
<td>13</td>
<td>28 (68)</td>
<td>12 (121)</td>
<td>57</td>
</tr>
<tr>
<td>Band spreading</td>
<td>4</td>
<td>47 (64)</td>
<td>35 (85)</td>
<td>26</td>
</tr>
</tbody>
</table>

Note: (·) coefficient of variation %.
broadcast slurry (P > 0.05), again, there were few observations (Table 5).

Shallow injection to cereal stubble was evaluated in five comparisons, two of these involving injection to different depths. In three of the experiments, no effective reduction in emission was achieved with shallow injection. In Experiment 25, there was very heavy rainfall following application and NH₃ emissions were low from both surface broadcast and shallow injected slurry (to either 4 or 8 cm). However, in Experiments 24 and 26 there was appreciable emission from both surface broadcast and shallow injection but the reason for this was not clear. In only one experiment (Experiment 22) was the reduction in emission comparable to that achieved on grassland. The trailing shoe was used on one occasion to apply slurry to a growing spring cereal crop and a reasonable reduction in emission (38%) was achieved despite the relatively low ground cover provided by the crop. However, the 6 m application width of the trailing shoe machine meant that passes had to be made between the established tramlines, resulting in crop damage. This machine was therefore deemed unsuitable for application to growing cereals and no further comparisons were made. Band spreaders (trailing hose machines) have been specifically developed for applications to growing cereal crops, with boom widths compatible with tramline spacings, but no such machine was available to allow comparisons within this project. Two experiments were conducted with the trailing shoe to simulate band spreading applications to cereal stubble and these gave reductions in emission similar to those achieved on grassland.

4. Discussion

Results from this study have shown reductions in NH₃ emission following slurry applications to land using surface placement and injection techniques in comparison with surface broadcasting of 73, 57 and 26% for shallow injection, trailing shoe and band spreading, respectively, to grassland and 23, 38 and 27%, respectively, to arable land. Cumulative emissions were reported for a 5–7-days period. In practice, additional emission beyond this period would be minimal for slurries, although for solid manures (broiler litter in particular) emissions may continue for a significantly longer period (Chambers et al., 1997). Results from recent, related research (Smith et al., 2000), involving the same application techniques on a small-plot scale, suggested that there was little difference in the abatement efficiency of the three techniques, with reductions in emission of 39, 43 and 57% for band spreading, trailing shoe and

![Fig. 3. Relationship between sward height and ammonia loss following trailing shoe application of cattle slurry to grassland; r², coefficient of determination](image)

<table>
<thead>
<tr>
<th>Technique</th>
<th>No. of observations</th>
<th>Mean NH₃ emission, % [TAN]</th>
<th>Reduction, %</th>
<th>Significance (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow injection</td>
<td>5</td>
<td>47 (66)</td>
<td>36 (94)</td>
<td>23</td>
</tr>
<tr>
<td>Trailing shoe</td>
<td>1</td>
<td>32 (−)</td>
<td>20 (−)</td>
<td>38</td>
</tr>
<tr>
<td>Band spreading</td>
<td>3</td>
<td>83 (9)</td>
<td>61 (21)</td>
<td>27</td>
</tr>
</tbody>
</table>

Note: (−) coefficient of variation %.
shallow injection, respectively, as compared with surface broadcast application. The improved abatement efficiencies reported in the present paper for shallow injection and trailing shoe applications to grassland are probably due to the application techniques being used under more appropriate conditions than in the earlier studies (i.e. shallow injection used on moist soils and trailing shoe used when sward height > 10 cm) and using application rates which were closer to the design specifications of the machines.

The abatement efficiencies reported here are comparable with those reported in the Netherlands by Huijsmans et al. (1997) (i.e. reductions of 80% for open slot shallow injection and 69% for trailing shoe) and those reported in Germany by Lorenz and Steffens (1997) (i.e. reductions of 90, 70 and 30% for shallow injection, trailing shoe and band spreading, respectively). Lorenz and Steffens (1997) also reported a negative relationship between sward height and NH3 emission for trailing shoe applications to grassland. Application rates used in both the Dutch and German studies were generally lower than those used in the present study, ranging between 7–50 m³/ha. Previous work by Misselbrook et al. (1996) recorded reductions in emission of 40 and 79% following applications to grassland in March and June, respectively, by shallow injection compared with surface broadcast application. The range of abatement efficiencies quoted by various researchers suggests that performance of the reduced emission application techniques may be influenced by a number of factors, including machine configuration (there are various types of shallow injector or trailing shoe machine commercially available), slurry analysis, soil, weather and crop conditions, as well as by operational conditions such as application rate, machine set-up (e.g. angle of tines for trailing shoe machine) and operator skill. These areas warrant further investigation to enable optimal performance of reduced emission slurry application machinery.

Band spreading to growing cereal crops has been evaluated elsewhere in Europe as a means of reducing NH3 emission with mixed results. Ferm et al. (1999) reported little difference in emission from pig slurry applied by band spreading or surface broadcast, whereas Dosch and Gutser (1996) reported a 40% reduction. Sommer et al. (1997) reported reductions of up to 80%, with greatest reductions achieved when applications were to a tall, dense crop. They measured no reduction when slurry was applied to 10 cm high crop with a leaf area index of only 0.3. Direct uptake of NH3 by the plant leaves was estimated to account for up to 25% of the observed reduction in emission.

It is unclear why shallow injection appeared to be so ineffective as an abatement measure for applications to cereal stubbles, although the build-up, under some soil conditions, of stubble trash in front of the injection tines may have been a contributory factor. Little information exists on the use of shallow injection on arable land; Weslien et al. (1998) reported large reductions in emission with shallow injection to soil prior to cereal planting, with a mean emission of just 1.2% applied TAN. In the earlier, small-plot studies of Smith et al. (2000), a reduction in emission of almost 80% was achieved by shallow injection compared with surface broadcast on arable soils (assessments were generally on moist soils), which makes the disappointing results for the shallow injection on the arable soils in this project of greater concern.

Reducing NH3 emission from slurry application to land may have the adverse effect of increasing subsequent denitrification and nitrous oxide (N2O) emissions (Thompson et al., 1987; Ellis et al., 1998), although N2O emissions have not always been increased (Sommer & Sherlock, 1996; Dendooven et al., 1998; Weslien et al., 1998). Measurements of N2O emission and denitrification were made in some of the present experiments, and the interactions between these and NH3 emissions will form the subject of a separate paper.

In addition to the efficiency of NH3 emission abatement, the cost of the machines and the agronomic benefits need consideration, particularly as the evidence of the latter is both limited and unconvincing (Smith et al., 2000).

5. Conclusions

1. Mean reductions in NH3 emission achieved by applying cattle slurry by shallow injection, trailing shoe or band spreading on grassland, as compared with surface broadcast, were 73, 57 and 26%, respectively, of which the first two were statistically significant (probability P > 0.05). Abatement efficiencies were less on arable land at 23, 38 and 27%, respectively, none of which were statistically significant (probability P > 0.05).

2. Efficiencies of the application techniques for reducing emissions were variable, particularly for shallow injection on cereal stubble. Taken together with the results of other research, it is apparent that a range of ambient, soil and crop conditions, as well as operational factors, will influence the effectiveness of the emission abatement achieved using these techniques and would justify further research.

3. An economic evaluation of using the new application techniques, together with a detailed assessment of factors influencing any agronomic benefits, are areas which would benefit from further study.
Acknowledgements

The authors would like to thank A. Guy for technical assistance, Buts Meulpas BV (Netherlands) for loan of the trailing shoe machine, G. Reed (Greentrac) for assistance with arable injection and C. Ellis (Reed Horsch Ltd., Wiltshire) for loan of the Duport shallow injector. The work was funded by the UK Ministry of Agriculture Fisheries and Food. BBSRC is sponsored by the Biological and Biotechnological Research Council.

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