A lysimeter experiment to investigate the leaching of veterinary antibiotics through a clay soil and comparison with field data

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This paper describes one of the first studies to investigate the fate of veterinary medicines in cracking clay soils.

Abstract

Pharmaceuticals used in livestock production may be present in manure and slurry as the parent compound and/or metabolites. The environment may therefore be exposed to these substances due to the application of organic fertilisers to agricultural land or deposition by grazing livestock. For other groups of substances that are applied to land (e.g. pesticides), preferential flow in clay soils has been identified as an extremely important mechanism by which surface water pollution can occur. This lysimeter study was therefore performed to investigate the fate of three antibiotics from the sulphonamide, tetracycline and macrolide groups in a clay soil. Only sulphachloropyridazine was detected in leachate and soil analysis at the end of the experiment showed that almost no antibiotic residues remained. These data were analysed alongside field data for the same compounds to show that soil tillage which breaks the connectivity of macropores formed over the summer months, prior to slurry application, significantly reduces chemical mobility.

Keywords: Veterinary medicines; Lysimeters; Clay soil; Leaching; Preferential flow

1. Introduction

Veterinary medicines are used in agriculture to prevent diseases in livestock and treat illness. Subsequently, the potential exists for quantities of these drugs to be excreted as the parent compound and/or metabolites and enter the environment due to the spreading of manure and slurry on agricultural land, or direct deposition by grazing livestock (Halling-Sørensen et al., 1998).

Available data already show that residues may indeed be present in manure and slurry spread to land (Haller et al., 2002) and that this may subsequently lead to acute and sub-lethal effects in the environment (Holten-Lüthhoft et al., 1999) including the development of antimicrobial resistance (Chee-Sanford et al., 2001). Only a limited amount of information is available, however, on concentrations of these compounds in soil (Hamscher et al., 2002), surface water and groundwater (Kolpin et al., 2002; Hirsch et al., 1999). Moreover, very few studies have looked at the processes determining the transport of veterinary medicines in the environment. It is therefore difficult to fully assess their risk to terrestrial and aquatic ecosystems and the extent to which agricultural management protocols need to address these compounds to ensure minimal adverse environmental impact.

A wealth of information exists to indicate that chemical application to under-drained clay soils poses...
a highly significant risk to the environment due to the rapid movement of runoff, solutes and sediment associated contaminants to surface waters via soil macropores and field drains (Kladivko et al., 1991; Brown et al., 1995). These studies have, however, focused on pesticides and nutrients which are somewhat different from veterinary medicines. Veterinary products have different usage patterns, are applied to land in manure and slurry and tend to have high molecular weights, many different functional groups and be polar (Boxall et al., 2002b). It may not therefore be appropriate to apply our understanding of other chemicals to veterinary medicines.

This lysimeter study was performed to complement a field investigation (Kay et al., 2004) which addressed the fate of antibiotics in an under-drained clay soil. Lysimeters have been widely used to investigate the leaching behaviour of plant protection products as they are easier to run than field experiments, less costly (Beck et al., 1995; Vink et al., 1997; Kamra et al., 2001) and are more likely to produce an accurate mass balance of chemical transport (Kamra et al., 2001; Francaviglia and Capri, 2000). In this case, the lysimeter study also made it possible to investigate the effects of incorporating the slurry into the soil immediately after application, which was not done in the field as normal agricultural practise was followed. The results of this study should help to assess the threat posed by veterinary medicines to terrestrial and aquatic organisms as well as provide an indication of potential management options that could be used to alleviate any risks.

2. Materials and methods

2.1. Lysimeters

Twelve undisturbed soil cores measuring 25 cm diameter and 60 cm depth (corresponding to the depth of soil above the tile drains in the field experiment) were extracted for the study. The soil was the same clay loam as in the field experiment (Table 1). The field from which the lysimeters were taken had been in ‘Set-Aside’ during the preceding growing season but was ploughed in the autumn, several months before the lysimeters were taken. The lysimeters were extracted by placing a metal cutting ring on the down turned end of a piece of underground drainage pipe and pushing this perpendicularly into the soil using the back actor of a JCB digger. The soil around the cores was then dug away and the lysimeters removed, with plastic caps protecting the ends of each column. The cores were transported to the laboratory in an upright position before being set up outdoors (Fig. 1). Any smearing of the soil at the base of each lysimeter, caused by contact with the plastic cap, was picked away with a hand-held trowel. Each lysimeter was then supported on a high density polyethylene funnel filled with non-calcareous rinsed pea gravel to support the soil and aid drainage. The junction between the lysimeter sleeve and the funnel was sealed using an underwater cement (Quentsplass Underwater Metal, Boston Chemical Company Ltd, Wetherby, UK). Leachate samples were collected in 1 l amber glass bottles and stored at −24 °C prior to chemical analysis. Precipitation was monitored onsite daily using a Casella raingauge.

2.2. Study compounds

The compounds studied were chosen as they were commonly used in veterinary medicine (Veterinary Medicines Directorate, 2002), had a range of physicochemical properties (e.g. Rabølle and Spliid, 2000; Ingerslev et al., 2001) and were largely excreted as the parent molecule (Parfitt, 1999). These comprised three antibiotics, which are used in greater quantities than other classes of veterinary medicine (Boxall et al., 2002b; Koschorreck et al., 2002). Oxytetracycline (OTC) belongs to the tetracycline group of antibiotics which

Table 1

<table>
<thead>
<tr>
<th>Soil characterisation</th>
<th>Ap horizon 0–37 cm</th>
<th>Btg 1 horizon 37–60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (63 μm–2 mm), %</td>
<td>42.6</td>
<td>34.2</td>
</tr>
<tr>
<td>Silt (2 μm–63 μm), %</td>
<td>32.3</td>
<td>27.7</td>
</tr>
<tr>
<td>Clay (&lt;2 μm), %</td>
<td>25.1</td>
<td>38.2</td>
</tr>
<tr>
<td>pH (in CaCl₂)</td>
<td>6.8</td>
<td>7.3</td>
</tr>
<tr>
<td>CEC, mEq/100 g</td>
<td>22.4</td>
<td>25.2</td>
</tr>
<tr>
<td>OC, %</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Bulk density, g/cm³</td>
<td>1.3</td>
<td>1.56</td>
</tr>
</tbody>
</table>
accounted for 66% of veterinary antibiotic usage in the EU in 1997 (2294 tonnes) (Boatman, 1998). They are also the most used group in the UK, with 228 tonnes being sold in 2000 (Veterinary Medicines Directorate, 2002). In urine and faeces, 40–80% of the quantity excreted is so as the parent compound (Halling-Sørensen, 2000; Parfitt, 1999), which has been measured in pig slurry in combination with tetracycline (TC) at concentrations up to 410 μg/l (Campagnolo et al., 2002). The parent has also been detected in soil up to around 10 μg/kg (Hamscher et al., 2000). OTC has been found to sorb strongly to a range of soils, manure particles and sediment (Rabolle and Spliid, 2000) but has nevertheless been measured in combination with TC in surface water at 1 μg/l (Campagnolo et al., 2002).

Sulphachloropyridazine (SCP), in contrast, is a very mobile antibiotic like the other sulphonamides (Haller et al., 2002), with a measured $K_d$ of between 0.9 and 1.8 (Boxall et al., 2002a), and therefore has significant potential to pollute surface and groundwaters. In the UK, the sulphonamides are the second most widely used group of veterinary antibiotics, accounting for 22% of sales (Veterinary Medicines Directorate, 2002) although this figure is only 2% in the EU as a whole (Boatman, 1998). Following treatment, livestock will excrete between 50 and 100% of the administered dose, usually within several days, the parent making up 30–95%. Acetic acid conjugates will be present between 5 and 60% of the excreted dose although these will revert back to the parent compound during manure storage as the acetyl moiety is cleaved by bacteria (Parfitt, 1999). Although few data are available on their persistence, some works have suggested that the sulphonamides have the ability to resist degradation (Haller et al., 2002; van Dijk and Keukens, 2000). A recent investigation into the degradation of SCP in the same clay loam as used in the current study produced a half-life of only 3.5 days, however (Blackwell, pers. comm.). The sulphonamides have been measured at concentrations of up to 12.4 mg/l in pig slurry (Haller et al., 2002) and 900 mg/kg in cattle manure (Migliore et al., 1995).

The third compound studied was tylosin (TYL) which is a macrolide antibiotic used exclusively in veterinary medicine (Halling-Sørensen, 2000). Radio-tracer studies with rats, cattle, dogs and pigs indicate that tylosin has low oral bioavailability (22.5%) and that between 94 and 100% of an applied dose is excreted (Committee for Veterinary Medicinal Products, 1997) having undergone minimal metabolism (Boxall et al., 2002b). Data are available to show that tylosin degrades rapidly in manure (Loke et al., 2000) and soil (Ingerslev and Halling-Sørensen, 2001) to its metabolites, desmycosin (tylosin B), macrosin (tylosin C) and relomycin (tylosin D) (OSTC, 1998). $K_d$ values between 553 and 7988 have been measured for tylosin in a range of soils (Rabolle and Spliid, 2000), indicating that the compound will be slightly mobile to immobile in the environment (Hollis, 1991).

2.3. Slurry and antibiotic application

The antibiotics were applied to the lysimeters in slurry from a working pig farm. The slurry had been stored for 0–3 months. The pigs were treated continuously with tylosin at 100 g per tonne of feed which was sufficient to feed 67–78 pigs for a one-week period. The pigs were not treated with OTC and SCP as, although it would have been preferable, this was impractical. The pigs could not be administered with all three compounds at the normal dosage as this would have resulted in a total dose of antibiotic three times greater than that recommended. It was also impractical to give each antibiotic to separate groups of pigs and then combine the slurry before application to the field. It would not be possible to measure such large volumes of slurry accurately when being pumped into a tanker. This could have resulted in relatively more of one compound being applied than another. Moreover, differences in the make-up of the slurry may have resulted due to the administration of the compounds to different groups of pigs. OTC and SCP were therefore mixed with the slurry before spreading at concentrations predicted using the model developed by Spaepen et al. (1997), which is commonly used in the environmental risk assessment of veterinary medicines. These were 26 and 19 mg/l for SCP and OTC (nominal concentrations as an analytical method for detecting the antibiotics in slurry was not available at the time of application), respectively. These concentrations are within the same order of magnitude as peak concentrations measured in slurry in recent studies for the sulphonamides (Haller et al., 2002; Campagnolo et al., 2002) and tetracyclines (Hamscher et al., 2002). The slurry was applied at a rate of 45 000 l/ha, the same as in the field experiment where normal agricultural practise was followed.

The lysimeters were left open to natural precipitation to ensure that they were at or close to field capacity prior to slurry application. A leachate sample was collected from each of the cores prior to the application of any slurry or cultivation. A conservative tracer (aqueous solution of KBr (67% Br), volume equivalent to 0.5 mm rainfall per lysimeter) was applied to the surface of half of the cores at a rate of 100 kg/ha. Slurry containing the antibiotics was then applied uniformly across the surface of these lysimeters. The top 25 cm of soil was extracted from each of the cores prior to the application of any antibiotics (Committee for Veterinary Medicinal Products, 1997) having undergone minimal metabolism (Boxall et al., 2002b). Data are available to show that tylosin degrades rapidly in manure (Loke et al., 2000) and soil (Ingerslev and Halling-Sørensen, 2001) to its metabolites, desmycosin (tylosin B), macrosin (tylosin C) and relomycin (tylosin D) (OSTC, 1998). $K_d$ values between 553 and 7988 have been measured for tylosin in a range of soils (Rabolle and Spliid, 2000), indicating that the compound will be slightly mobile to immobile in the environment (Hollis, 1991).
The columns received natural precipitation but were also irrigated with 0.01 M CaCl₂ solution after the 10th day following application in order to initiate the production of leachate from the bottom of the cores, as would have happened under the hydrological conditions experienced around the time of application in the field experiment. This resulted in the first leachate samples being collected three weeks after slurry spreading. The irrigation was applied using a syringe to mimick natural storm events recorded in the field, ranging in intensity from 0.5 to 8 mm/day at a rate of 0.4–2 mm/h. In the spring, each lysimeter was covered with a plastic cap to eliminate water loss through evapotranspiration and maintain leachate production. After this time, the cores only received simulated rainfall. Four months after slurry application, the experiment was concluded and 50 cm soil cores were taken for analysis of drug residues using a Geonor MLC3 mechanical soil corer.

2.4. Chemical analysis

Soil and water samples were analysed using high-performance liquid chromatography (HPLC) with ultraviolet (UV) detection (Blackwell et al., in press a,b). Prior to extraction, soil cores were sectioned whilst they were still frozen using a Draper chop saw fitted with a diamond tipped blade and, when defrosted, the sections were placed in aluminium foil trays and homogenised by hand. Sub-samples (4 g) of the soil were placed in plastic centrifuge tubes and 2.5 ml of buffer (100 ml 0.1 M Na₂EDTA (AnalaR grade, BDH, Poole, Dorset, UK) (to chelate with metals), 60 ml 0.2 M citric acid, 40 ml 0.4 M Na₂HPO₄ and 2 ml H₃PO₄ (to adjust pH to 7)) and methanol (all HiPerSolv grade, BDH, Poole, Dorset, UK) were added. Each sample was then vortex mixed at 2500 rpm for 30 s using a Yellowline vortex mixer and, following sonication in an Ultrawave sonic bath for 10 min, the water samples were then centrifuged for 15 min at 3500 rpm to separate the solid and liquid phases. The liquid phase (5 ml) was poured into a Duran bottle and the extraction procedure repeated a further two times to give a total of 15 ml of extract. The extracts were made up to 400 ml with distilled water to ensure that their methanol content was not so great that the study would pass through the HLB cartridge. H₃PO₄ (200 μl) was then added to adjust the pH to 2.8.

The three antibiotics were extracted from the solution by solid phase extraction (SPE), using an Isolute SAX (strong anion exchange) (International Sorbent Technology, Mid-Glamorgan, UK) cartridge to remove interfering humic materials in tandem with an Oasis HLB (hydrophilic–lipophilic-balanced) cartridge (Waters, Watford, UK) to extract the compounds. The SPE cartridges were preconditioned using MeOH and buffer (comprising 400 ml distilled water, 3.75 ml EDTA, 1.55 ml 0.4 M Na₂HPO₄, 0.3 ml 0.2 M citric acid and 200 μl H₃PO₄) and eluted after washing (5 ml buffer, 5 ml 0.1 M NaOAc (AnalaR grade, BDH, Poole, Dorset, UK), 5 ml distilled water, 2 ml 20% MeOH) with 2 × 1 ml of methanol. A flow rate of 10 ml per min was used for the extractions.

Water samples were stored in amber glass bottles at −24 °C prior to analysis and after defrosting were initially centrifuged at 3500 rpm for 15 min. The water was then filtered through a 0.8 μm membrane filter (Whatman International Ltd, Maidstone, UK).

Concentrations of the antibiotics in the soil and water extracts were determined by HPLC with UV detection using a Dionex (Sunnyvale, CA, USA) Summit system, comprising a GINA 50 autosampler and a P580 quaternary gradient pump with a UVD 170S UV/visible spectrophotometric detector. Separations were performed using a GENESIS 4 μm C₁₈ 150 cm × 4.6 mm internal diameter column with 4 μm packing (Jones Chromatography, Mid-Glamorgan, UK). Analysis was performed using gradient elution over 25 min with a tetrahydrofuran (THF), acetonitrile (ACN) and 0.05% trifluoroacetic acid in water (TFA) mobile phase (all HiPerSolv for HPLC™ grade, BDH, Poole, Dorset, UK). This contained 5% THF throughout the analysis. At the start of the analysis, the mobile phase contained 2.5% ACN and 92.5% TFA which was maintained for 4 min, the composition then changed linearly between 4 and 18 min to give a composition of 75% ACN and 20% TFA. Between 18 and 20 min, the composition changed linearly to 2.5% ACN and 92.5% TFA and these conditions were then maintained for the remainder of the run. Each extract (20 μl) was injected into the HPLC and the compounds were detected at 285 nm (SCP and TYL) and 355 nm (OTC). The method was validated by spiking river water to give a concentration of 1 or 10 μg/l. Recoveries and detection limits are shown in Table 2. The soil concentrations reported are corrected for recoveries. The soil extraction method was validated using the same clay loam soil used in the lysimeter experiment as well as sandy loam soil. For method development, the soils were air dried and sieved to <5.6 mm prior to fortification with a mixed solution of OTC, SCP and TYL such that the concentration of each compound in soil was 1 mg/kg.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Recovery (%)</th>
<th>Limit of detection (μg/kg or μg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Water</td>
<td>Soil</td>
</tr>
<tr>
<td>OTC</td>
<td>38.1 ± 3.9</td>
<td>99.6 ± 4.6</td>
</tr>
<tr>
<td>SCP</td>
<td>68.1 ± 9.9</td>
<td>99.9 ± 2.2</td>
</tr>
<tr>
<td>TYL</td>
<td>47.3 ± 3.9</td>
<td>94.9 ± 2.4</td>
</tr>
</tbody>
</table>
To determine bromide concentrations 30 ml of each water sample was filtered through a 0.45 μm SFCA Nalgene syringe filter and a 25 μl neat sub-sample injected into a Dionex DX-100 ion chromatograph. The mobile phase comprised 108 mM Na₂CO₃ and 1.7 mM NaHCO₃. The limit of detection was 1 mg/l.

3. Results

3.1. Leachate

The total rainfall for the four months following slurry application was 196.7 mm (Fig. 2) which correlates very well with the long-term average of around 200 mm which would usually fall in this period after autumn manure/slurry application in the UK. Rainfall was variable though with monthly totals of 63.8, 92.9, 28 and 12 mm which is indicative of the variation in rainfall totals about the long-term mean during the field experiment also (monthly totals for the same time period in the field ranged between 24 and 130 mm). Mean leachate production from the cores receiving the surface application of slurry and those where the slurry was incorporated was 164 and 148 mm, respectively, equating to an effectiveness of 84 and 75%. This represents a mean of 0.63 of one pore volume for both the surface and incorporated cores, ranging between 0.55 and 0.7 for the surface application and 0.6 and 0.67 for the incorporated cores.

Bromide breakthrough occurred between 21 and 35 days after the slurry had been applied. Concentrations of bromide were detected at every subsequent sampling timepoint although they generally declined over time (Fig. 3).

Breakthrough of SCP occurred at the same time as bromide after 0.13 and 0.12 pore volumes of leachate had been produced by the surface applied and incorporated cores, respectively. SCP was detected at a maximum mean concentration of 0.51 μg/l (the
maximum concentration from an individual lysimeter was 0.77 μg/l) in leachate collected 35 days after application (Fig. 4). OTC and TYL were not detected.

Mass losses of SCP were extremely low whether the slurry was incorporated or remained on the surface, and in both cases were estimated to be no more than 0.00015% of that applied. Incorporation of the slurry had no discernable effect on leaching of SCP or bromide: 26.27% and 30.69% of the bromide leached to the bottom of the surface application and incorporated cores, respectively, with concentrations of up to 60.9 mg/l being detected.

3.2. Soil

At the end of the experiment, only one soil sample (20–30 cm depth) from one of the lysimeters where the slurry had been incorporated was found to contain antibiotic residues (33 μg/kg of SCP). None of the other soil samples contained any detectable residues of SCP, OTC or TYL.

4. Discussion

The results indicate that neither OTC nor TYL will leach to tile drains following slurry application and that only compounds that display an affinity for the water phase, like SCP, will be transported through soils to tile drains and subsequently to surface waters, albeit in very small quantities. This indicates that antibiotic residues in slurry pose very little risk to the aquatic environment, given that only the very mobile compound was detected in leachate and concentrations this low would easily be diluted even further in the environment. The results also infer that the highest concentrations to reach field drainage systems will be found in the first period of drainflow after slurry application, agreeing with the field data and other literature (Kladivko et al., 1991; Kamra et al., 1999).

Whilst the results for TYL correlate with the field data, the behaviour of SCP and OTC was significantly different to that in the field experiment. Concentrations and mass losses in drainflow in the field were up to 2–3 orders of magnitude higher. This difference may be due to a number of factors. The connectivity of macropores with the soil surface had a strong influence on runoff and solute losses to the tile drains in the field experiment. Concentrations of the antibiotics in drainflow were two orders of magnitude lower when the soil was tilled prior to slurry application. The macropores in half of the lysimeters used for the current study would of course have been disturbed by the mimicking of ploughing immediately after slurry application. The macropores in half of the lysimeters used for the current study would of course have been disturbed by the mimicking of ploughing immediately after slurry application. The other lysimeters, in which the slurry was not incorporated, had still been disturbed by ploughing several months before the cores were taken, however. Although macropores had visibly formed in the soil since this cultivation, the desiccation cracks formed over the summer months would not have been present.

The difference in results must also be partially due to the test system. Even though the soil had been tilled in the second year of the field study before slurry application, mass losses of SCP remained two orders of magnitude greater and concentrations were an order of magnitude higher than in the lysimeter experiment. OTC also still reached the drains when the soil was pre-tilled in the field experiment. It is possible that the lysimeters did not replicate the spatial heterogeneity of the field soil in terms of hydrology (Beck et al., 1995). This may be due to them having a diameter of only 25 cm. Another work (Brown et al., 2000) using larger lysimeters (80 cm diameter) found much greater concentrations of the hydrophilic herbicide isoproturon.
leaching from a clay loam soil. The low mass losses of bromide and diminishing concentrations at the end of the experiment do indicate though that preferential flow was occurring and that much of the tracer was present in the soil away from these flow routes (Brown et al., 2000). Hydrological data also indicate that the test system may have resulted in different processes operating to in the field experiment. The amount of effective rainfall was 4–8 times greater in the lysimeters than the field. This has also been found to be the case in another experiment (Brown et al., 2000) where transport through clay loam lysimeters was investigated. It is probable that this is because water can only move vertically in a lysimeter and not laterally (throughflow and overland flow) as may be the case in a natural system. This is somewhat anomalous though as we may expect solute transport to be greater with more effective rainfall.

A further reason for the difference may be the absence of any backfill in the lysimeters. High hydraulic conductivities in this region have been found to be important for solute transport to drains (Øygarden et al., 1997; Kamra et al., 1999). The lysimeters were also maintained above ground so soil temperatures may have been higher than that experienced under natural conditions and thus degradation of the antibiotics could have been more rapid (Jurado-Exposito and Walker, 1998; Taylor-Lovell et al., 2002).

The fact that there were discrepancies between the data produced in the lysimeters and the field is not unusual (Beck et al., 1995). Some of these differences have previously been explained in terms of the nature of the test system (Fogg and Carter, 1994).

Slurry incorporation seemed to have little influence on chemical mobility. No significant difference existed between the amounts of leachate produced and solute concentrations from the surface applied or incorporated lysimeters. This may, however, be because the soil was tilled several months before the lysimeters were taken, again indicating the important influence on chemical fate of desiccation cracks formed over the summer months.

The soil residues data from the end of the experiment indicate that a range of antibiotics which may be present in slurry will be degraded in the soil before reaching any drainage system. This would be expected of TYL given its short half-life in slurry (Loke et al., 2000) and soil (Ingerslev and Halling-Sørensen, 2001) and agrees with the findings of the field experiment. Rapid degradation of SCP, with a small residual concentration persisting, also agrees with the field data. Rapid degradation of OTC, however, disagrees with the field data and most literature which has found the tetracyclines to be persistent (Hamscher et al., 2002; Ingerslev et al., 2001). Nevertheless, one study has reported 96% degradation after nine days in sea water (Lunestad et al., 1995). The only possible reason for this faster degradation seems to be warmer soil temperatures in the lysimeters due to them being maintained above ground.

5. Conclusions

A lysimeter study has been carried out to investigate the leaching of three veterinary antibiotics through a clay soil to the depth of tile drainage systems. The experiment also examined the impact of slurry incorporation on chemical fate. The results produced were compared with field data for the same compounds in the same soil type. Sulphachloropyridazine was detected in leachate from the lysimeters at a peak concentration of 0.77 µg/l whilst oxytetracycline was completely degraded within the soil column over a period of four months. Tylosin was also degraded entirely, during slurry storage and/or in the soil. Mass losses of sulphachloropyridazine were no greater than 0.00015% of that applied.

Incorporation of the slurry had little or no effect on the mobility of the antibiotics. This is likely to be because even where the slurry had not been incorporated the soil cracks formed over the summer months had been disturbed by ploughing several months before the lysimeters were taken. Importantly, this has highlighted that it is the soil macropores formed over the summer months which are largely responsible for the rapid movement of solutes to tile drainage systems and surface waters. Smaller macro pores which can visibly still form throughout the autumn and winter, as was the case in the lysimeters, appear to have a much less significant effect.

The results of the present lysimeter study and an accompanying field investigation (Kay et al., 2004) have, thus, highlighted that soil tillage between crop harvest and slurry application can significantly reduce the risk of surface water pollution by antibiotic residues in slurry. It is also likely to be beneficial to the environment, where possible, to apply organic fertilisers to fields after the onset of winter rainfall when soil macro pores are not as well developed as they are at the end of the summer and into autumn. It is also evident that lysimeters may not be subject to all of the processes occurring in macroporous clay soils in the field. This problem may, however, be addressed by collecting relatively large lysimeters and/or incorporating important hydrological pathways, such as drain backfill and desiccation cracks, into the lysimeters.

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References


