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Research article

Influence of manure application method on veterinary medicine losses to water

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ABSTRACT

Veterinary medicines are routinely used within modern animal husbandry, which results in frequent detections within animal manures and slurries. The application of manures to land as a form of organic fertiliser presents a pathway by which these bioactive chemicals can enter the environment. However, to date, there is limited understanding regarding the influence of commonly used manure application methods on veterinary medicine fate in soil systems. To bridge this knowledge gap, a semi-field study was conducted to assess the influence of commonly used application methods such as, broadcast, chisel sweep, and incorporation on veterinary medicine losses to waters. A range of veterinary medicines were selected and applied as a mixture; these were enrofloxacin, florfenicol, lincomycin, meloxicam, oxytetracycline, sulfadiazine, trimethoprim and tylosin. All the assessed veterinary medicines were detected within surface runoff and leachates, and the concentrations generally decreased throughout the irrigation period. The surface runoff concentrations ranged from 0.49 to 183.47 μg/L and 2.26–236.83 μg/L for the bare soil and grass assessments respectively. The leachate concentrations ranged from 0.04 to 309.66 μg/L and 0.33–37.79 μg/L for the bare soil and grass assessments respectively. More advanced application methods (chisel sweep) were found to significantly reduce the mass loads of veterinary medicines transported to surface runoff and leachate by 13–56% and 49–88% over that of broadcast. Incorporating pig slurries reduced the losses further with surface runoff and leachate losses being 13–56% and 49–88% lower than broadcast. Our results show that manure application techniques have a significant effect on veterinary medicine fate in the environment and as such these effects should be considered in the decision-making processes for the management of manures as well as from a risk mitigation perspective for aquatic compartments.

Introduction

As a result of the intensification of animal husbandry veterinary medicines are routinely administered to improve and protect animal health, however, in some regions sub-therapeutic concentrations of antibiotics are used for growth promotion (Gaskins et al., 2002; Dibner and Richards. 2005; Sarmah et al., 2006; and Subbiah et al., 2011). Administered veterinary medicines are typically excreted in high concentrations which can result in their direct application to land; or following the use of animal manures as organic fertilizers, veterinary medicines can also become incorporated within the soil matrix (Thiele-Bruhn, 2003; Carvalho and Santos, 2016; and Xu et al., 2020). These processes directly result in the exposure of veterinary medicines to the terrestrial environment (Kim et al., 2011). Moreover, there is the potential for veterinary medicines to be present in runoff, which has likely resulted in the contamination of surrounding surface waters (Kay et al., 2005a; Kreuzig et al., 2005; Pinheiro et al., 2013; and Milić et al., 2013). Concentrations of veterinary medicines in the ranges of ng/L to μg/L have previously been reported in surface waters surrounding agricultural fields following rainfall events (Boxall, 2004; and Kasprzyk-Hordern et al., 2008). The biological potency of veterinary medicines and their transformation products presents several risks including contributing to the development of antimicrobial resistance and endocrine disruption, as well as effects on non-target terrestrial and aquatic

Abbreviations: LC-MS, Liquid Chromatography Mass Spectrometry; FLO, florfenicol; TYL, tylosin; SDZ, sulfadiazine; OTC, oxytetracycline; ENR, enrofloxacin; LNC, lincomycin; MLX, meloxicam; TMP, trimethoprim.

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organisms (Ingerslev et al., 2003; Kemper, 2008; Heuer et al., 2011; and Shao et al., 2018). Joy et al. (2014) demonstrated the capability of antimicrobial resistant genes to form and persist during the storage of manures. Specifically, 10 mg/kg of tylosin was detected within pig slurries which was found to degrade rapidly (DT_{50}/half-life 9.7 d), but even when the concentration of tylosin dropped to 0.1 mg/kg the relative abundance of the antimicrobial resistance gene erm(B) remained at 50–60%.

The ability for veterinary medicines to be mobilised within runoff following manure applications has been demonstrated, for example early research conducted by Kay et al. (2005a) established that sulphachloropyridazine and oxytetracycline can be transported via runoff following the application of pig slurry, with concentrations detected in overland flow at 703.2 μg/L and 71.7 μg/L respectively. Similar findings have been reported for a wide range of antibiotics from differing classes with varying physical-chemical properties (Dolliver and Gupta, 2008; and Barrios et al., 2020). For example, field studies and semi-field trials have reported tylosin, chlortetracycline, oxytetracycline, sulphadiazine, sulphathiazole and sulphadimidine concentrations within runoff following the application of manure to land (soils and grasses) (Burkhardt et al., 2005; Blackwell et al., 2007; and Dolliver and Gupta, 2008). Moreover, a comprehensive runoff assessment conducted by Kreuzig et al. (2005) revealed 13–28% of the applied sulphonamides were present within runoff following 2 h of simulated rainfall at 50 mm/h.

Various processes govern the formation and rate of runoff generated following manure applications; some examples include tractor tramlines, manure properties/type, soil type, compaction, timing, and application method (Kay et al., 2005a; Smith et al., 2007; Rotz et al., 2011; and Le et al., 2018). The ability for advanced applicators to reduce nutrient loses via runoff or volatilization has been known for some time (Maguire et al., 2011). For example, Rotz et al. (2011) demonstrated a reduction of 48% and 70% for nitrogen and phosphorus respectively when shallow injection technologies were utilized over that of broadcast. Advanced manure application technologies are now being utilized to improve the retention of nutrients and crop yields (Webb et al., 2010). Based on these findings, it is likely that differences in manure application methods such as these will also influence veterinary medicine fate, and ultimately run-off (Bittman et al., 2005).

To date, the ability for advanced manure application methods to alter veterinary medicine exposure in surface waters has been demonstrated in a limited number of publications. For example, Joy et al. (2013), and Le et al. (2018) observed greater chlortetracycline runoff concentrations under broadcast application over that of injection/incorporation. Subsurface injections and the incorporation of manures to soils were reported to reduce runoff concentrations by 55–93%. Joy et al. (2013), also demonstrated that antimicrobial resistant genes present in manures can also be mobilised via runoff following rainfall, this phenomenon presents a wider risk given the known societal risk of antimicrobial resistance (Zainab et al., 2020).

Previous publications such as Blackwell et al. (2009), have demonstrated that soil cultivation practices such as tilling can reduce sulphachloropyridazine leachate concentrations by 16.6%, with similar findings reported in a field study conducted by Dolliver and Gupta (2008). The authors accredited this to an increase in soil surface area, which in return increased adsorption complexes between veterinary medicines and organic components. Despite current understanding of how soil cultivation can affect veterinary medicine concentrations in receiving waters, there is, to the best of our knowledge, no research that has considered the influence of injection technologies on the leaching of veterinary medicines. It is important this knowledge gap is addressed given previous concerns that injections can potentially promote the leaching of contaminants (Rotz et al., 2011; and Fangueiro et al., 2015). Moreover, tillage usage is declining in modern agriculture and shallow injection methods are becoming increasingly popular; their popularity stems from a reduction in farmers' time and money as no incorporation (ploughing) is required (CTIC, 2004; Maguire et al., 2011; and Busari et al., 2015; and Niles et al., 2019). Manure application method has been shown to influence the concentration of veterinary medicines in run off, however we currently lack the comprehensive understanding of surface runoff and leaching behaviours within soil and grass settings which is required in order to accurately and representatively understand risks associated with these exposure methods (Powell et al., 2011).

The aim of this study was to therefore assess the influence of a suite of manure application methods on the environmental exposure of veterinary medicines to receiving waters. Assessments were conducted on both bare soils and grasses to present a comprehensive evaluation of real-life exposures. A semi-field experiment with simulated irrigation was constructed, and the study encompassed a wide range of veterinary medicines, commonly reported in the environment, with a broad range of physical-chemical properties.

2. Methodology

2.1. Chemicals and dosage concentration

A wide-range of veterinary medicines from differing pharmaceutical classes with a broad array of physiochemical properties were selected for this study, selection was based on Log K_{ow}, K_{OC}, solubility, and environmental persistence. The veterinary medicines purchased were of the highest possible purity (94–99%). Florfenicol (FLO), and meloxicam (MLX) were purchased from Fischer Scientific (UK). Sulfadiazine (SDZ), tylosin (TYL) enrofloxacin (ENR), oxytetracycline (OTC), lincomycin (LNC), acetyl-salicylic acid (AS) and trimethoprim (TMP) were purchased from SLS (UK).

Pig slurry was dosed at the respective Predictive Environmental Concentration (PEC), this was calculated using the Spaepen et al. (1997) model and utilized the highest available administration dose within the Summary of Product Characteristics. Veterinary medicines were dosed into pig slurries using methanol as a carrier solvent, and concentrations were as follows: FLO 5.53 mg/kg, MLX 11.02 mg/kg, ENR 2.76 mg/kg, OTC 4.97 mg/kg, LNC 3.65 mg/kg, SDZ 6.9 mg/kg, TMP 1.38 mg/kg, SA 6.65 mg/kg and TYL 16.5 mg/kg (see SI Table 1 for physical-chemical properties of the selected veterinary medicines).

2.2. Box plots and irrigation rates

Box plots were constructed using plastic Eurostack containers (600 × 400 × 220 mm) which were amended to facilitate the collection of runoff and leachate (Fig. 1), with PVC guttering attached at the top and bottom to enable sample collection. In order to achieve this, a 20 mm lip was removed from the front of the box and guttering was attached, for leachate 10 mm holes were drilled into the base. Pea shingle gravel (20 mm) was installed into each box to a depth of 5 cm and weed mesh used to promote leachate flow for collection. Dry soil (sieved to <4 mm) was uniformly packed into the box using a taper so that the bulk density of the soil was 1.3 g/cm^3. The soils were then wetted to saturation and left for 12 h after which additional soil was compacted into the box resulting in a total of 42 kg of soil being used in each box. For the grass treatments turf (*Lolium Perenne*) which was purchased from Inturf (UK) was laid onto the soil surface and irrigated for one month prior to the experiment to allow the grass' roots to establish. The grass was uniformly cut to 7 cm using shears prior to the experiment. A corrugated plastic cover was installed (Fig. 1 B) to prevent irrigation directly entering the runoff collector.

2.3. Manure sampling, properties and application rates

Pig manure was sampled from a farm in Welburn, York, UK (54°05′31.2″N, 0°53′03.0″W) and the manure was then stored at 3 °C for 1 week prior to the experiment. Storing slurry for one week prior to the study provided adequate time for the farmyard manure to be

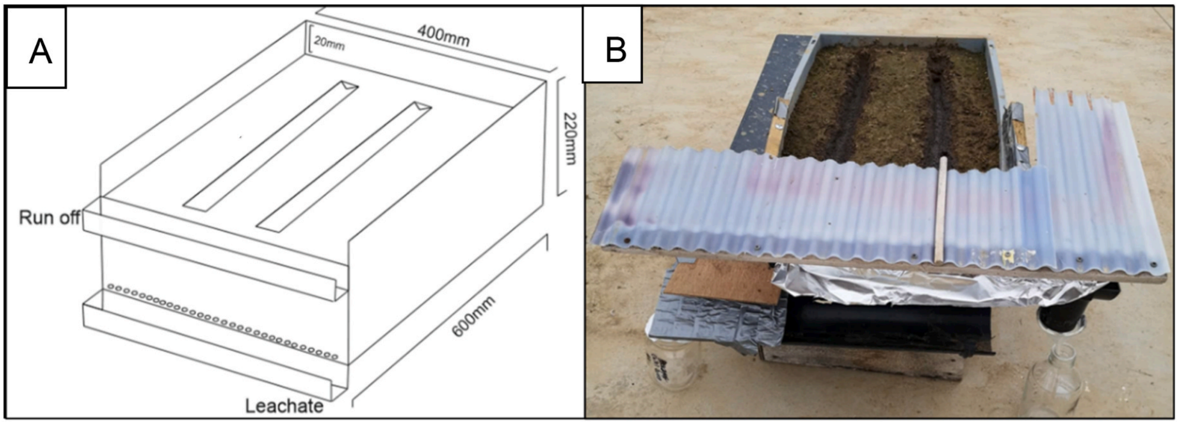

Fig. 1. Schematic drawing of manure application box plots (chisel sweep) (A), and a picture demonstrating the design in real-life. These box plots were placed on wooden frames (100 × 50 and 35 cm) at a 3° incline.

equilibrated into a slurry and the selected temperature was used to reduce the anaerobic content of the slurry and methanogenic bacteria. The pigs had not received any of the selected veterinary medicines that were used within the study. Manures were homogenised and the moisture was corrected to 5% dry weight (EMA, 2011). Please see SI section A1 for the manure characterization methodology and SI Table 2 for the manure properties. The soil utilized within this study was a clay loam from Surrey (UK) which had an organic carbon content of 4.3%; the soil's texture was 22% sand, 50% silt and 29% clay (parameters provided via the retailer Bourne Amenity Ltd).

Prior to dosing the boxes were irrigated with water for 3 h to saturate the soils. Pig slurry containing the veterinary medicines was then applied to the boxes using a range of application methods. The rate of pig slurry that was applied was consistent across all treatments; specifically, manure was applied at 170 kg/N/ha which is typical of arable farming practice within the UK (DEFRA, 2010). This corresponded to 0.72 kg of pig slurry per box; care was taken not to apply slurry close to the edge of the box plot to minimize edge effect (5 cm from the width and 2 cm from the top/bottom) (Williams et al., 2019). The manure application methods were broadcast, chisel sweep and immediate incorporation. The broadcast treatment comprised of uniform application to the plots which was achieved using a watering can. Incorporation utilized a similar method to broadcast, only the slurry was immediately incorporated to 7 cm depth using a trowel. To replicate the chisel sweep (shallow injection) application technique a gouge was drilled into the soil profile using a wooden stake; the dimensions of this were 3.8 cm deep and 3.4 cm wide. The drills were 14.3 cm apart and there were two in total per plot. Irrigation of the plots was initiated 24 h after slurry application (Fig. 1B).

2.4. Irrigation and sampling

The experiment was a semi-field assessment and was conducted within a polytunnel, this enabled the appropriate control that was required for the comparisons between treatments, including removal of external rainfall and irrigation drift. The box plots were irrigated at a rate of 5 mm/h which is typical of heavy rainfall within the UK (DEFRA, 2002), this was achieved in cycles of irrigation (4 min off and 40 s on) and validated utilizing a rain gauge (large plastic rain gauge - Geopacks). A solenoid valve was attached to the water source and was controlled using a time dependent controller circuit. Copper tubing was used to construct the irrigators; these contained a nozzle outlet which created a fine mist. The irrigators were positioned in front of the boxes at height of 1.5 m. Water was distributed evenly between the irrigators using a manifold constructed using copper pipe fittings. The rates of irrigation were validated to ensure that each box received the same rate of rainfall as well as being evenly distributed over the soil profile, this was achieved utilizing 12 plastic cups to catch irrigation water over the course of 5 min, acceptable tolerances were set to 10% (SI Tables 3–4 and SI Fig. 1). Runoff and leachate samples were collected in Schott bottles following three irrigation events (day 1, 2 and 3) and consisted of three sampling points per day post irrigation (30 min, 75 min and 135 min). Samples were then filtered to 0.2 μm using nylon syringe filters and fresh matrix matched standards were prepared. The standards encompassed a range of concentrations (0.004 ng/mL to 0.87 μg/mL), it was crucial to prepare these standards in the exact same matrix but also in parallel with the sample preparation. This provides a more accurate assessment of the concentration within the samples as it corrects for matrix suppression and the potential losses during storage. Samples and freshly prepared calibration standards were then stored at 3 °C prior to LC-MS/MS analyses via direct injection.

2.5. Analytical technique

Veterinary medicine analysis was achieved using LC-MS/MS (SCIEX Triple Quad 5500+ LC-MS/MS system). The method consisted of using a HST3 column at a set temperature of 40 °C and the mobile phases were 0.1% formic acid (aqueous) and 0.1% formic acid with 1 mM ammonium formate (methanol). The method utilized a 30 μl injection volume and the flow rate was set to 0.4 mL/min. The total chromatographic duration was 11 min, and the gradient was reversed phase. This consisted of the following organic percentages; 0mins (0%), 3mins (90%), 8mins (90%), 8.1mins (10%), and 11mins (0%) (see SI Table 5 for full analytical details). Analyst 1.6 was used for data processing and quantification. The analytical method was optimized in order to obtain adequate LODs for this study, due to a singular method being used for the analyses co-eluting pharmaceuticals required separating by altering the gradient as well as sacrificing the sensitivities of good responding compounds to increase the detection of poorer sensitivities (collision energy, and collision cell exit potential). Moreover, calibration standards were only deemed acceptable with a R^2 of 0.99.

2.6. Statistical analyses

Statistical comparisons were carried out using Minitab 18. An analysis of variance (two-way) (ANOVA) was used to statistically compare the application methods and concentration over time (mass = time*-application technique). Tukey post hoc comparisons were utilized within the ANOVA to distinguish differences between the application methods. Statistical significance was reported at the 95% confidence level ($p \leq 0.05$).

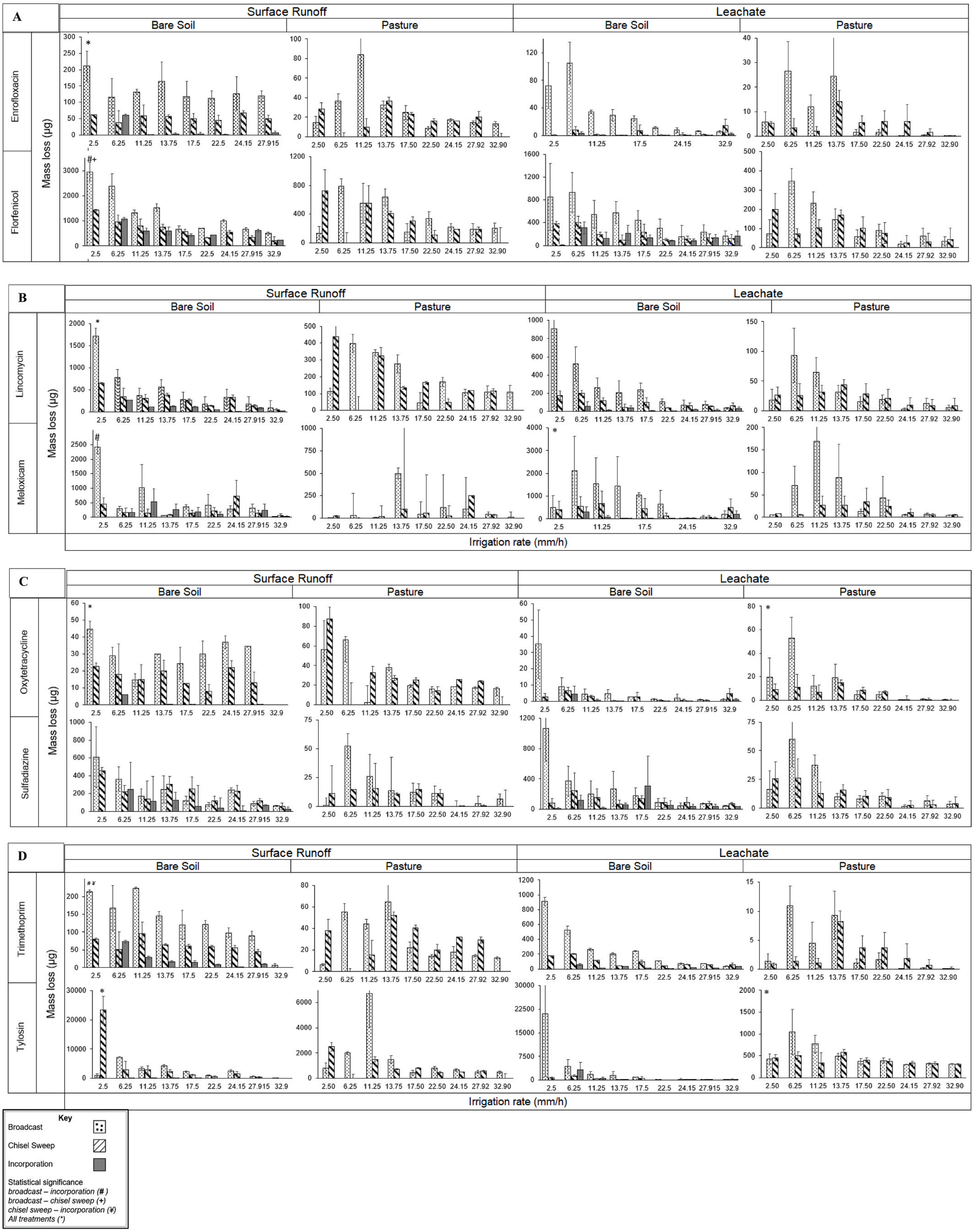

Fig. 2. Mass loss (ug) of veterinary medicines (A, B, C, D) detected within runoff and leachate following differing application methods to bare soils and grasses.

3. Results

All of the veterinary medicines that were dosed into manures were detected within the surface runoff and leachate from both the soil and grass assessments (Fig. 2). The presented results in Fig. 2 refer to the cumulative mass of veterinary medicines rather than concentrations, this interpretation of the dataset was conducted to provide a better comparison between the application methods. The absolute concentrations alone are unable to account for the large differences within the generated sample volumes. This was a result of the differences within soil hydrology's, which drove differences within the sample volumes between the application methods. For example, the incorporation method produced lower leachate and runoff volumes than that of broadcast and chisel sweep; this effect resulted in a high concentration being calculated. The concentrations were still reported as this data provides a better demonstration of the environmental risk but were not used within the statistical analyses, as it does not facilitate true comparisons between the application methods.

3.1. Arable VS grass assessment

The volumes of runoff and leachate were comparable between the same application methods conducted on arable soils and grass plots. The average total volume of runoff generated from broadcast and chisel sweep ranged from 1.0 to 2.1 L and 1.6–2.0 L for bare soils and grasses respectively (SI Figs. 2–3 and SI Tables 6–7). The average total leachate volumes were also comparable amongst replicates; under bare soils broadcast and chisel sweep methods the volume was 2.1–3.6 L and under the grass assessment this was 2.9–3.0 L (SI Figs. 4–5 and SI Tables 6–7). The mass loadings of veterinary medicines that were transported via runoff and leachate were slightly elevated under the bare soil assessment over that of the grasses (Fig. 2). For example, the percentage of the nominal manure concentration that was transported in runoff and leachate ranged from 0.0003 to 0.46% for bare soils and 0.0003–0.1% for grasses under all the assessed application methods (Table 3).

3.2. Surface runoff VS leachate

Following the application of pig slurry and the sequence of irrigation events the volumes of leachate for both the bare soils and grasses was generally higher but more varied than that of surface runoff (SI Figss. 2–5 and SI Tables 6–7). Interestingly the percentage of the nominal manure concentration that was transported in runoff was significantly greater than that of leachate for both bare soils and grasses ($p \leq 0.05$); MLX and TYL were exceptions of this where the concentrations were slightly elevated within leachate over that of the surface runoff via the broadcast method (Fig. 2 and Tables 1 and 2).

3.3. Veterinary medicine mass losses and concentrations under varying application methods

3.3.1. Surface runoff

Following the application of pig slurries to bare soils under varying methods, the concentrations of veterinary medicines detected within surface runoff ranged from 0.49 to 183.46 μg/L (Table 1). The total percentage of the nominal veterinary medicine concentration in manure that was transported via runoff was compound specific and followed in the order of OTC < ENR < TMP < LNC < MLX < SDZ < TYL < FLO. FLO exhibited the greatest percentage loss via runoff from bare soils, this was found to be within a range of 0.08–0.21% for all assessed application methods (Fig. 2 and Table 3). Within the grass assessment the concentrations of veterinary medicines detected within surface runoff ranged from 1.44 to 236.83 μg/L (Table 2). The susceptibility for veterinary medicines to form runoff under the grass plots was similar to that of bare soils, OTC < ENR < TYL < TMP < MLX < LNC < FLO. For both the soil and grass plots under all application methods peak runoff and leachate concentrations were detected within the first day of irrigation; generally, the concentration followed a decreasing trend over time (Fig. 2).

Within the bare soil assessment, the assessed application treatments were observed to alter the soils hydrology and influence the total volumes of runoff that were generated, these were 1.5, 2.1 and 1.0 L for broadcast, chisel sweep, and incorporation respectively. Although the only significant difference was between broadcast and incorporation runoff volumes ($p \leq 0.05$). The manure application treatments not only influenced the soils hydrology but also the mass loadings of veterinary medicines that were detected within surface runoff. Within the bare soil assessment, the greatest veterinary mass loads were detected within surface runoff under the broadcast method, both chisel sweep and incorporation were observed to be significantly lower than that of broadcast ($p \leq 0.05$) (Fig. 2 and Table 8). For ENR, FLO, LNC, and OTC, the cumulative masses within the chisel sweep surface runoff were significantly reduced over that of broadcast ($p \leq 0.05$). For example, ENR and OTC mass loads were reduced by 55% (447.9–990.0 μg) and 83% (127.4–216.4 μg) respectively (SI Tables 8–10). Conversely TYL runoff concentrations were higher under the chisel sweep technique; this is likely a result of the peak in the mass loads at 30 min (23.350 mg). The incorporation of manures substantially reduced the veterinary medicine mass loads within runoff over that of broadcast ($p \leq 0.05$); however, SDZ was observed to be an exception of this. For OTC, ENR and TMP, reductions of 97%, 92% and 89% were observed ($p \leq 0.05$). Incorporating manures resulted in a surface runoff and leachate lag phase, for example no sample was generated until the irrigation rate reached 6.25 mm/h (SI Table 6 and Figss. 2–5).

Similarly, within the grass assessment the total surface runoff volume that was generated under the chisel sweep technique was slightly elevated in comparison to that of broadcast (1.6–2.0 L). However, no significant differences were observed between the veterinary mass loads that were detected within surface runoff from the differing application methods. There were however time specific differences observed between the application methods (Fig. 2). Under the chisel sweep method, the cumulative masses for all assessed veterinary medicines (except for MLX) were elevated at 30 min when compared to broadcast ($p \leq 0.05$). For example, the LNC concentration range was 88.7 to 40 μg/L. Moreover, the broadcast method exhibited greater mass loads over that of chisel sweep when the irrigation rate reached 13.75 mm/h for MLX, 11.25 mm/h for TYL and ENR (Fig. 2) ($p \leq 0.05$).

3.3.2. Leachate

The application methods had little effect on the volumes of leachate that were collected from bare soils, volumes of 3.6, 3.4 and 2.9 L were recorded for broadcast, chisel sweep and incorporation respectively. The concentrations of all the veterinary medicines detected within the bare soil assessment for all application treatments ranged from 0.5 to 309.7 μg/L (Table 1). The ability for veterinary medicines to leach was also compound specific (Table s 1and2 and Fig. 2). TYL, MLX and LNC were readily leached following the application of manure to soil, the percentage of the nominal manure concentration that was transported to leachate were, 0.25%, 0.096% and 0.08% respectively. Comparatively OTC and ENR mass loads were minimal within leachate, the percentages lost were 0.0014% and 0.005% respectively. Similar detections were made under the grass assessment, these ranged from 0.3 to 1255.9 μg/L for all of the assessed veterinary medicines (Table 2). The veterinary medicines most readily leached within the grass assessment were FLO, LNC and TYL, with the average total percentages lost at 0.027%, 0.011% and 0.01% respectively (Table 3). Interestingly, TMP, SDZ and OTC exhibited the lowest proportion to leachate under varying application methods to soils (Table 3 and Fig. 2).

Table 1
The total concentrations of veterinary medicines transported from manured soils into surface runoff and leachate.

Veterinary Medicine	Irrigation Rate (mm/h)	Surface Runoff (μg/L)			Leachate (μg/L)		
		BC	CS	IC	BC	CS	IC
ENR	2.5–11.25	2.34 ± 0.34	0.54 ± 0.13	1.48 ± 0.33	0.47 ± 0.14	0.04 ± 0.007	0.02 ± 0.009
	13.75–22.50	3.00 ± 0.31	0.56 ± 0.06	0.18 ± 0.03	0.07 ± 0.02	0.12 ± 0.04	0.00 ± 0.0
	24.15–32.90	1.72 ± 0.39	0.50 ± 0.12	0.06 ± 0.03	0.05 ± 0.02	0.07 ± 0.02	0.02 ± 0.004
FLO	2.5–11.25	31.77 ± 3.06	13.64 ± 2.93	28.54 ± 6.73	15.34 ± 4.41	9.50 ± 3.79	2.56 ± 0.95
	13.75–22.50	19.58 ± 2.61	7.69 ± 1.87	86.54 ± 11.62	10.46 ± 2.50	3.07 ± 0.64	1.53 ± 0.29
	24.15–32.90	14.39 ± 2.54	7.09 ± 2.19	22.55 ± 7.69	3.19 ± 0.37	3.85 ± 0.91	6.74 ± 2.42
LNC	2.5–11.25	20.73 ± 5.25	6.18 ± 1.35	6.20 ± 1.52	9.69 ± 3.38	4.15 ± 1.59	0.47 ± 0.21
	13.75–22.50	8.98 ± 1.45	3.49 ± 0.65	14.04 ± 2.23	3.10 ± 0.61	1.06 ± 0.21	0.17 ± 0.04
	24.15–32.90	4.23 ± 0.90	3.48 ± 1.15	2.41 ± 2.56	1.00 ± 0.16	1.64 ± 0.40	1.01 ± 0.37
MLX	2.5–11.25	11.69 ± 1.89	4.06 ± 1.15	21.05 ± 7.98	21.12 ± 4.56	17.85 ± 6.9	3.10 ± 1.35
	13.75–22.50	6.88 ± 1.34	2.52 ± 0.30	11.70 ± 1.78	44.17 ± 14.53	2.75 ± 0.49	0.12 ± 0.03
	24.15–32.90	4.61 ± 1.18	6.92 ± 2.59	3.72 ± 1.08	0.90 ± 0.12	2.90 ± 0.64	4.85 ± 1.61
OTC	2.5–11.25	0.55 ± 0.09	0.23 ± 0.04	0.49 ± 0.18	0.34 ± 0.13	0.10 ± 0.04	0.03 ± 0.015
	13.75–22.50	0.52 ± 0.02	0.16 ± 0.02	0.01 ± 0.002	0.05 ± 0.01	0.03 ± 0.007	0.00 ± 0.00
	24.15–32.90	0.48 ± 0.07	0.18 ± 0.05	0.00 ± 0.0008	0.04 ± 0.01	0.02 ± 0.007	0.01 ± 0.002
SDZ	2.5–11.25	13.95 ± 3.85	6.48 ± 1.01	7.57 ± 1.90	6.19 ± 2.12	3.08 ± 1.01	0.83 ± 0.21
	13.75–22.50	8.09 ± 1.59	6.56 ± 1.32	11.92 ± 2.20	2.13 ± 0.49	1.81 ± 0.45	1.33 ± 0.36
	24.15–32.90	3.35 ± 0.93	8.67 ± 3.25	2.22 ± 0.40	0.77 ± 0.10	1.66 ± 0.40	1.00 ± 0.30
TYL	2.5–11.25	11.97 ± 1.54	158.57 ± 64.02	37.71 ± 11.10	283.24 ± 122.3	25.38 ± 9.96	25.55 ± 11.3
	13.75–22.50	6.36 ± 1.21	17.34 ± 3.99	12.50 ± 2.94	23.77 ± 6.45	28.97 ± 12.4	0.13 ± 0.06
	24.15–32.90	2.50 ± 0.80	7.56 ± 2.79	0.00 ± 0	2.65 ± 0.73	1.47 ± 0.40	0.21 ± 0.1
TMP	2.5–11.25	3.54 ± 0.33	0.89 ± 0.13	1.61 ± 0.39	1.48 ± 0.42	0.19 ± 0.04	0.11 ± 0.05
	13.75–22.50	3.02 ± 0.30	0.87 ± 0.13	1.83 ± 0.28	0.40 ± 0.08	0.15 ± 0.04	0.00 ± 0.00
	24.15–32.90	1.35 ± 0.31	1.12 ± 0.38	0.19 ± 0.08	0.12 ± 0.02	0.12 ± 0.04	0.02 ± 0.005

Footnote: Broadcast application (BC), Chisel Sweep (CS), Incorporation (IC). Enrofloxacin (ENR), florfenicol (FLO), lincomycin (LNC), meloxicam (MLX), oxytetracycline (OTC), sulfadiazine (SDZ), tylosin (TYL), trimethoprim (TMP). Irrigation events refer to the quantities of rainfall applied on each day (2.5–11.25 mm/h = day 1, 13.75–22.5 mm/h = day 2, and 24.15–32.9 mm/h = day 3).

The veterinary medicine mass loads that were detected within bare soil leachate were found to be the highest under broadcast application over that of both chisel sweep and incorporation (Fig. 2 and SI Table 8). Chisel sweep was found to reduce the leachate concentrations over that of broadcast, although not all the observed differences were significant. The mass loads of FLO, LNC and TYL within chisel sweep leachate were 60%, 63% and 88% lower than that of broadcast ($p \leq 0.05$). Incorporating manures resulted in a greater reduction in the veterinary medicine masses that were detected within leachate, ENR, LNC, and TMP were significantly reduced and their transfer to leachate was reduced by 94%, 91% and 88% over that of broadcast respectively ($p \leq 0.05$) (SI Table 10). No significant differences were observed between the leachate concentrations that were detected within the chisel sweep and incorporation technique, however by incorporating manures this reduced ENR and LNC concentrations by 83% and 76% over that of chisel sweep (Fig. 2 and Table 2).

Within the grass assessment few differences were observed between the application methods and veterinary medicine mass loads within leachate; the total volume of leachate was similar between both broadcast and chisel sweep (2.9 L and 3.0 L). However, all the assessed veterinary medicines exhibited greater percentages lost under the broadcast treatment over that of chisel sweep, for OTC and TYL the differences in cumulative masses over time was significant ($p \leq 0.05$) (Fig. 2). No difference between the application methods was reported for FLO, although some degree of difference was noted ($p = 0.065$), this is likely attributed to the spiked in cumulative mass under broadcast application that was observed at an irrigation rate of 6.25 mm/h (360.3 μg).

4. Discussion

4.1. Veterinary medicine losses in surface runoff and leachate

Surface runoff concentrations generated in this study were found to vary to those presented within the literature; differences within experimental approach and design are suspected to be drivers of this. Kay et al. (2005a) and Popova et al. (2013) both reported a greater percentage of OTC transported in runoff than that of this study (0.0064%), these values were 0.054% and 2.5% respectively. The differences here are most likely attributed to differences in angle of slope (3 < 6°) (Kay et al., 2005a), irrigation duration and soil type (Popova et al., 2013). Similarly, Barrios et al. (2020) reported a total LNC concentration of 5.83 μg/L and a recovery of 122% following three sets of 30-min irrigations (70 mm/h) which were 24 h apart at 1 day, 1 week, 2 week and 3 weeks.

In the available literature the results for grassland plots are also varied. For example, Kreuzig et al. (2005) and Knäbel et al. (2016) reported greater SDZ loss via surface runoff, the reported values ranged from 0.56 to 28% whereas this study reported a loss of 0.048%. Both studies utilized much greater irrigation rates of 50–70 mm/h and angel of slope (5.1°). Until now direct comparisons between grasses and bare soils have not been achieved, Kreuzig et al. (2005) reported greater losses from grassland plots however their bare soil assessment contained incorporation to 15 cm meaning direct comparisons cannot be made. The presented dataset demonstrates that the risk of veterinary medicine exposure to surface waters is greatest following the broadcasting of slurries to bare soils. Similar findings were reported by Lin et al. (2010) who observed a 75% reduction in sulfamethazine runoff concentration when using tall grasses as a buffer zone over that of bare soils. Factors such as, inhibited water velocity, increased microbial degradation and adsorption within the trapped sediments are likely drivers of this (Krutz et al., 2005; Reichenberger et al., 2007; Liu et al., 2008; and Lin et al., 2010).

4.2. THE influence of manure application methods on veterinary medicine fate

The replicated manure application methods altered the soil profiles which was hypothesised to affect the soils hydrology. This likely resulted in the observed differences between the timing and volume of surface runoff generated from the application methods. This was especially true for comparisons between broadcast and incorporation. The altered soil hydrology alone is unlikely to have driven differences in veterinary medicine concentrations. Other factors such as the increased exposure to

Table 2
The total concentration of veterinary medicines transported from manured grass into surface runoff and leachate.

Veterinary Medicine	Irrigation Event (mm/h)	Surface Runoff (μg/L)		Leachate (μg/L)	
		BC	CS	BC	CS
ENR	2.5–11.25	0.43 ± 0.03	2.18 ± 0.89	0.41 ± 0.10	0.10 ± 0.027
	13.75–22.50	0.72 ± 0.22	0.57 ± 0.16	0.49 ± 0.22	0.36 ± 0.11
	24.15–32.90	0.29 ± 0.06	0.32 ± 0.07	0.00 ± 0.00	0.26 ± 0.12
FLO	2.5–11.25	5.63 ± 0.64	50.16 ± 20.79	6.11 ± 1.41	6.34 ± 2.53
	13.75–22.50	14.68 ± 3.55	6.22 ± 1.49	3.85 ± 1.08	4.74 ± 1.34
	24.15–32.90	4.69 ± 0.93	2.91 ± 0.37	0.66 ± 0.49	0.48 ± 0.02
LNC	2.5–11.25	4.24 ± 0.51	36.80 ± 15.23	1.64 ± 0.35	1.80 ± 0.69
	13.75–22.50	6.40 ± 1.52	2.36 ± 0.50	0.87 ± 0.23	1.25 ± 0.34
	24.15–32.90	2.03 ± 0.30	1.84 ± 0.04	0.11 ± 0.01	0.14 ± 0.01
MLX	2.5–11.25	1.12 ± 0.41	4.55 ± 1.40	1.12 ± 0.23	0.48 ± 0.14
	13.75–22.50	14.82 ± 4.73	13.39 ± 4.52	2.15 ± 0.75	0.86 ± 0.12
	24.15–32.90	8.20 ± 3.57	0.69 ± 0.09	0.11 ± 0.01	0.39 ± 0.15
OTC	2.5–11.25	0.97 ± 0.25	7.40 ± 3.18	1.11 ± 0.34	0.38 ± 0.086
	13.75–22.50	0.97 ± 0.28	0.47 ± 0.11	0.44 ± 0.15	0.33 ± 0.087
	24.15–32.90	0.32 ± 0.06	0.28 ± 0.05	0.01 ± 0.001	0.03 ± 0.004
SDZ	2.5–11.25	1.25 ± 0.16	12.32 ± 5.23	1.11 ± 0.23	0.38 ± 0.43
	13.75–22.50	1.37 ± 0.42	0.39 ± 0.10	0.44 ± 0.06	0.33 ± 0.11
	24.15–32.90	0.33 ± 0.07	0.20 ± 0.03	0.01 ± 0.005	0.03 ± 0.05
TYL	2.5–11.25	30.79 ± 2.25	215.31 ± 93.95	14.40 ± 2.22	10.88 ± 2.58
	13.75–22.50	34.22 ± 8.41	13.52 ± 2.52	15.18 ± 3.24	17.38 ± 4.23
	24.15–32.90	12.71 ± 2.63	7.99 ± 1.07	5.90 ± 0.96	9.53 ± 2.65
TMP	2.5–11.25	0.40 ± 0.04	2.75 ± 1.12	0.16 ± 0.03	0.02 ± 0.03
	13.75–22.50	1.07 ± 0.33	0.82 ± 0.21	0.20 ± 0.08	0.23 ± 0.07
	24.15–32.90	0.42 ± 0.11	0.39 ± 0.08	0.00 ± 0.0003	0.09 ± 0.04

Footnote: Broadcast application (BC), Chisel Sweep (CS), Incorporation (IC). Enrofloxacin (ENR), florfenicol (FLO), lincomycin (LNC), meloxicam (MLX), oxytetracycline (OTC), sulfadiazine (SDZ), tylosin (TYL), trimethoprim (TMP). Irrigation events refer to the quantities of rainfall applied on each day (2.5–11.25 mm/h = day 1, 13.75–22.5 mm/h = day 2, and 24.15–32.9 mm/h = day 3).

soil particulates under the varying application methods most likely drove differences in the rates of adsorption, with similar findings previously reported for pesticides (Mickelson et al., 2001; and Elias et al., 2018). Both ENR and OTC have a high affinity for organic matter and carbon (Kim et al., 2012; and Álvarez-Esmorís et al., 2020) and as expected the differences observed between the treatments was greater. Conversely, lower adsorption coefficients have previously been demonstrated to have an increased potential for surface runoff and leachate transport (Kay et al., 2005a; Dolliver and Gupta, 2008; Kim et al., 2010; Joy et al., 2013; and Popova et al., 2013), and manure application methods were observed to be comparatively less influential but still of great significance.

The presented dataset demonstrates that immediately incorporating slurries into soils prior to a rainfall event is best practice in terms of reducing veterinary medicine exposure to nearby water bodies. Injecting slurries is also an effective means in reducing the transport of veterinary medicines to waters although this was less effective than that of incorporation. Similar findings were reported via Joy et al. (2013), where a reduction in antibiotic runoff concentrations were observed when manures were incorporated or injected over that of broadcast. For example, the authors' reported 0.04% of TYL was transported via runoff under the broadcasting method, this was reduced to 0.028% and 0.011% via injection and incorporation methods. A similar significant effect was reported by Le et al. (2018), the authors reported a, 47, 50, 57, and 88% reduction in sulfamerazine, chlortetracycline, pirlimycin, and tylosin runoff concentrations through subsurface injection over that of broadcast.

Interestingly TYL was observed to deviate from this trend within the bare soil assessment; at 2.5 mm/h there was a spike in runoff concentration under the chisel sweep technique that far surpassed that of broadcast. Moreover, the dataset indicates that at this sampling point the broadcast method TYL was readily leachable which could be related to a reduction in TYL leaching under the chisel sweep application method. It has previously been demonstrated that TYL leaching can be promoted via facilitated transport associated with colloids from manure (Kolz et al., 2005). This is highly possible given that TYL's adsorption coefficient is greater to manure colloidal particulates than that of manure, and greater in manure over soil (Hu and Coats., 2009; and Kim et al., 2010). Therefore, colloidal facilitated transport would be greater under broadcast application, and the chisel sweep technique could enhance runoff via channelization and desorption from manures (Hoese et al., 2009; and Amarakoon et al., 2014).

It is well known that veterinary medicines can leach following land application of animal manures (Kay et al., 2005b; Dolliver and Gupta, 2008; Popova et al., 2013; Spielmeyer et al., 2017, 2020; Pan and Chu, 2017), however, research has seldom assessed the influence of manure application methods on veterinary medicine leaching. For the majority of the assessed veterinary medicines the mass loads detected within leachate were greatest under the broadcast application method over that of chisel weep and incorporation. This was expected when making comparisons to the incorporation technique but there has been concern regarding the influence of injecting slurries (chisel sweep) on leaching rates (Rotz et al., 2011; and Fangueiro et al., 2015). The presented dataset demonstrates that chisel sweep application methods do not enhance leaching rates, despite application into the soils subsurface. A possible explanation for this is capping of the silty clay soil as the drill is implemented into the soil profile. This is a likely explanation of why pig slurries were observed to pool within the injection slots. However, further research is required to assess this relationship for other soil types that may not cap (i.e., sandy or silty soils with lower clay contents). Furthermore, future research efforts are required to comprehensively understand the exposure of veterinary medicines within the environment following the application of manures to land, recommendations include, a range of soil types, differing manure properties or types (cattle), evaluation of processed manures, a range of concentrations, and the inclusion of transformation products.

4.3. Relevance to current agricultural practices and management of manures

The presented study demonstrates the ability for veterinary medicines to be transported via runoff and leachate under a heavy rainfall event within the UK. Numerous farms within a catchment will apply manures within a similar timeframe, the joint contribution from several sources indicates that receiving waters within a catchment are potentially at a greater risk than this study anticipates. The derived fate data indicates the ability of advanced application technologies and immediate incorporation to reduce the risk of veterinary medicine exposure to surface and groundwaters. As we found to be true for both soils and grass

Table 3
Percentage of the applied veterinary medicine mass transported via runoff and leachate under varying application methods on arable soils and grasses.

	Percentage Loss Arable Soils (%)								
	Runoff			Leachate			Total		
	BC	CS	IC	BC	CS	IC	BC	CS	IC
ENR	0.0498	0.0225	0.0039	0.0050	0.0017	0.0003	0.0549	0.0243	0.0042
FLO	0.2142	0.1111	0.0849	0.1051	0.0417	0.0318	0.3193	0.1528	0.1167
LNC	0.1499	0.0941	0.0262	0.0809	0.0303	0.0072	0.2308	0.1244	0.0334
MLX	0.0517	0.0304	0.0174	0.0962	0.0361	0.0086	0.1478	0.0665	0.0260
OTC	0.0060	0.0036	0.0002	0.0014	0.0006	0.0002	0.0074	0.0042	0.0004
SDZ	0.0486	0.0425	0.0293	0.0405	0.0207	0.0137	0.0891	0.0632	0.0430
TMP	0.1098	0.0482	0.0125	0.0298	0.0099	0.0024	0.1396	0.0582	0.0149
TYL	0.2108	0.2949	0.0273	0.2528	0.0291	0.0334	0.4635	0.3240	0.0606
Percentage Loss Grasses (%)									
ENR	0.0096	0.0082		0.0036	0.0022		0.0132	0.0104	
FLO	0.0738	0.0723		0.0279	0.0204		0.1017	0.0927	
LNC	0.0603	0.0556		0.0114	0.0087		0.0717	0.0644	
MLX	0.0256	0.0343		0.0049	0.0019		0.0305	0.0362	
OTC	0.0070	0.0077		0.0035	0.0019		0.0104	0.0096	
SDZ	0.0074	0.0084		0.0035	0.0025		0.0108	0.0109	
TMP	0.0232	0.0269		0.0030	0.0022		0.0261	0.0291	
TYL	0.0133	0.0123		0.0106	0.0003		0.0239	0.0126	

Footnote: Broadcast application (BC), Chisel Sweep (CS), Incorporation (IC).

plots, when possible, farmers should utilize shallow injection technologies (soils and grasslands) or immediately incorporate slurries into soils. Whilst incorporating slurries into soils proved to effectively retain veterinary medicines into soils; the physical turning of the top soil is known to hinder earthworm populations (Kibblewhite et al., 2008; and Crittenden et al., 2014). Therefore, this may not be the best practice environmentally, whereas advanced application methods may limit disturbance and offer a suitable means to retain slurries and their contents (nutrients or contaminants). Moreover, Smith et al. (2000) conducted a survey and reported that only 13–23% of farmers incorporate slurries on the day of application, hereby presenting a greater risk than that of injection technologies. The Nitrate Directive (91/676, EEC, 2000/60/EC) states that slurries/manures should be applied from the 1st of September or 15th October (NVZ specific) to the 15th January or 31st December. Typically these application timings are within the wettest months indicating greater surface runoff and leaching risk (Defra, 2010). It is also debatable whether farmers adhere to current agricultural policies due to problems in practicality, therefore environmental exposure maybe greater than anticipated or calculated under a typical environmental the risk assessment (Young and Mutchler, 1976; and Smith et al., 2000).

The results presented here suggest that the risks towards surface waters are lower when manure is applied to surrounding grasslands. Chisel sweep application methods were found to have very little influence on veterinary medicine runoff concentrations, however a reduction in leaching was observed suggesting this method to be a good measure to protect frequently contaminated groundwater's (Sui et al., 2015; Balzer et al., 2016; Kivits et al., 2018; and Boy-Roura et al., 2018). Slurry acidification is now being utilized within Holland and Denmark to better nutrient management and compliance to the Nitrate Directive, the Dutch authorities are also reducing the requirement to inject or incorporate slurries applied to land when utilizing this manure management technique (Hjorth et al., 2013; and Fangueiro et al., 2015). Recent research has demonstrated the capability of acidifying manures to reduce nitrate leaching when using broadcast application (do Rosário Cameira et al., 2019), however, very little is known regarding the influence of this on veterinary medicine fate and needs to be further investigated (degradation during storage, and mobility when applied to land) (Sassman et al., 2007; Dolliver and Gupta, 2008; Ali et al., 2013; Joy et al., 2013; and Nightingale et al., 2022).

5. Conclusion

The presented semi-field study provides a comprehensive evaluation of common manure application methods and their influence on veterinary medicine fate. The broadcasting of pig slurries with no incorporation was identified to present the greatest risk towards both surface and groundwater's. Comparatively, the incorporation of broadcasted pig slurries was observed to be of best practice in terms of the environmental exposure of veterinary medicines, however this practice requires more of the farmers valuable time and could result in greater soil compaction. Therefore, it is more likely that advanced manure application methods such as injection/chisel sweep will be utilized which were deemed appropriate to reduce the concentrations of veterinary medicines in surface runoff and leachate. The reduction in leachate concentrations using this method were surprising but beneficial given that this method is now widely adopted in modern farming. Moreover, the dataset demonstrates that the risk towards waterbodies is greatest surrounding bare soils over that of grasses, but chisel sweep methods are an effective means to reduce the veterinary medicine exposure to waters on both grasses and soils. The presented fate data is crucial to the management of manures and understanding veterinary medicine risk, however it indicates that further research is required to fully understand the influence of these application methods on variable soil types to be representative of the natural environment.

Credit author statement

John Nightingale: Conceptualization, practical work, experimental work, sample processing, analytical chemistry, writing, statistics, and editing, Laura Carter: Conceptualization, experimental guidance, reviewing data, statistics, and editing, Paul Kay: Funding acquisition, conceptualization, experimental guidance, reviewing data and editing, Chris Sinclair: Funding acquisition, conceptualization, experimental methods and experimental design, Philip Rooney: Conceptualization, expert guidance on manure degradation, system design, and degradation kinetics.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: John Nightingale reports financial support was provided by Natural Environment Research Council.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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