Impact of slurry application method on phosphorus loss in runoff from grassland soils during periods of high soil moisture content

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Abstract

Previous studies have reported that the trailing shoe application technique reduces phosphorus (P) in the runoff post-slurry application when compared to the traditional splash-plate application technique. However, the effectiveness of the trailing-shoe technique as a means of reducing P losses has not been evaluated when slurry is applied during periods of high soil moisture levels and lower herbage covers. To address this issue, three treatments were examined in a 3 × 4 factorial design split-plot experiment, with treatments comprising three slurry treatments: control (no slurry), splash-plate and trailing-shoe, and four slurry application dates: 7 December, 18 January, 1 March and 10 April. Dairy cow slurry was applied at a rate of 20 m³/ha, while simulated runoff was generated 2, 9 and 16 days later and analysed for a range of P fractions. Dissolved reactive P concentrations in runoff at day two was 41% lower when slurry was applied using the trailing-shoe technique, compared to the splash-plate technique (*P* < 0.05). In addition, *P* concentrations in runoff were higher (*P* < 0.05) from slurry applied in December and March compared to slurry applied in January or April, coinciding with periods of higher soil moisture contents. While the latter highlights that 'calendar'-based non-spreading periods might not always achieve the desired consequences, the study demonstrated that further field-scale investigations into the trailing shoe as a mitigation measure to reduced P loss from agricultural soils is warranted.

Introduction

Nutrient losses from livestock systems remain an issue of increasing concern in many countries. Within the European Union (EU), legislation, primarily in the form of the Nitrates Directive (91/676/EEC), has been implemented to reduce losses of nitrates from agricultural soils, while many EU countries have also implemented regulations to manage the use of phosphorus (P) within agriculture. For example, in Northern Ireland (NI), the P Use (in Agriculture) Regulations and the Nitrates Action Programme Regulation (EHS, 2007) seek to limit the application of inorganic P fertiliser to soils. These regulations form the main measures under the EU Water Framework Directive (WFD) (2000/60/EC) to address the contribution of agriculture to the decline in water quality in NI. It is estimated that agriculture contributes > 70% of the annual P load to Lough Neagh and Lough Erne, two significant water bodies that suffer from chronic eutrophication (NIEA 2013, Unpublished report).

Similar to the Republic of Ireland (ROI), the Nitrates Action Programme and P Regulations in NI limit the spatial and temporal application of slurry so as to minimise risks to water quality (Kleinman *et al.,* 2015). Under the action programme,

slurry cannot be spread between October 15 and January 31, while outside of this period, slurry cannot be spread under the following circumstances: 'on waterlogged soils, flooded land, or land liable to flood; on frozen or snow covered ground; and if heavy rain is forecast within 48 hrs' (EHS, 2007). Within NI, grassland occupies approximately 80% of the total land area, and has been estimated to account for almost 60% of terrestrial P inputs to inland waterways (Smith *et al.*, 2005; Jordan *et al.*, 2007). Due to the high rainfall frequency and high soil moisture content that occur during significant parts of the year in NI (Doody *et al.,* 2010), managing slurry applications poses significant challenges in terms of achieving the minimum P standard of 0.25 mg/L (for high status) or 0.35 mg/L in rivers required under the WFD. While reducing the phosphorus content of livestock diets can improve P use efficiency, and reduce P excretion in faeces (Ferris *et al.*, 2010), livestock manures will inevitably contain P. Thus management practices need to be adopted to minimise the risk of P being lost once manure is applied. The system of applying slurry can influence P losses in surface runoff, with Withers *et al.* (2003) highlighting that surface

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runoff can contribute 50–98% of the measured P loads for sites receiving surface applications of manure or fertilisers. While Lalor *et al.* (2011, 2104) have evaluated the impact of the trailing shoe technique under Irish conditions on nitrogen recovery and NH_3 emissions, its impact on P loss was not evaluated. However, in a recent plot scale study by McConnell *et al.* (2013a), dissolved reactive P (DRP) concentrations in runoff were reduced by 37%, following slurry application using the trailing-shoe technique, in comparison to traditional 'splash-plate' spreading.

While a small number of studies have examined the use of trailing shoe technology to reduce P loss to water (McConnell *et al.*, 2013a & b), a number of studies have examined the use of a range of other approaches to reducing the risk of P loss post-slurry application (O'Rourke *et al.*, 2010; Brennan *et al.*, 2011; O'Rourke *et al.*, 2012; Murnane *et al.*, 2015). However, unlike the study of Lalor *et al.* (2011, 2014), these studies were carried out using small-scale rainfall simulations. Rainfall simulation methodologies have provided a useful cost-effective tool for testing hypothesis related a wide range of mitigation strategies (e.g Serrenho *et al.*, 2012; Doody *et al.*, 2014; McConnell *et al.*, 2015). Rourke *et al.* (2012) used rainfall simulation techniques to demonstrate a reduction of P loss in runoff when dairy cows were fed a diet containing reduced P levels, while Brennan *et al.* (2011) used the technique to examine the impact of a range of chemical amendments to slurry on P-suspended sediment and metal loss in runoff from grassland soils. While McConnell *et al.* (2013a) evaluated the use of the trailing shoe to reduce P loss in runoff during the 'summer' months (May/June), the effectiveness of this technique as a means of reducing P losses does not appear to have been tested during periods when soil moisture content is closer to saturation and herbage covers are lower, for example during late winter/early spring. With regards the impact of herbage cover, McConnell *et al.* (2013b) demonstrated increased P losses with decreasing herbage cover. Thus the aim of this study was to examine the effectiveness of the trailing-shoe technique as a means of reducing P losses in surface runoff from slurry applied during the late winter/early spring period, a time when soil moisture contents are normally high and herbage covers are low.

Materials and Methods

Site description

This experiment was conducted at the Agri-Food and Biosciences Institute, Hillsborough, NI (54°27'N; 06°04'W) between 7 December 2009 and 28 April 2010. The 192 m² experiment site was established on a permanent pasture located on a drumlin hill slope (average slope of 4.5%) with a north-easterly aspect (altitude, 120 m). The area soil type was classified as a Soil Water Gley Class 1 overlying Silurian Shale (DANI Soil Survey of Northern Ireland) (FAO classification: Dystric Gleysol). The area has a hydrology of soil types (HOST) classification of 24, which is indicative of poorly drained soils with high runoff rates, with this classification accounting for 46% of the land area in NI (Higgins, 1997). A previous study by Doody *et al.* (2010) at a nearby experimental site demonstrated that saturation excess overland flow dominates on this soil type. The soil is a slightly gleyed sandy clay-loam (48% sand, 31% silt and 21% clay) overlying Silurian shale (greywacke) till (FAO Classification: Dystric Gleysol) (Higgins, 1997). The Ap horizon (0–25 cm) has a sub-angular, coarse blocky clay loam texture and the B horizon (25–45 cm) has a sub-angular sandy loam texture. In both horizons, stones of medium size are common, while the C horizon (>0.45 cm) has a clay loam coarse blocky structure with many stones of medium to very large size. The soil has a hydraulic conductivity of 0.2 m/day (Watson *et al.*, 2000a).

The soil had an average Olsen P content of 57.7 mg/L (Morgan P, 18.8 mg/L), twice the agronomic optimum, and an average bulk density of 0.83 g/cm³ in the 0–5 cm horizon. Average annual rainfall and duration of the growing season at the site was 890 mm and 254 days for the periods 1971–2000 and 1951–1990, respectively (Betts, 1997). Daily meteorological data for the site were supplied by a UK Met Office weather station located 300 m from the field site. Prior to the start of this experiment, grass was harvested from the area on 22 September and again on 29 October 2009 using a hand-operated mower (3600BM, Agria, Möckmühl, Germany) and removed by hand.

Treatments

Treatments examined in this 3 × 4 factorial design experiment comprised three slurry treatments (control, splash-plate and trailing-shoe) and four slurry application dates. The 48 experimental plots (each 0.5 m²) were arranged in four blocks in a split plot design, with each block 'split' into four sub-blocks (4.5 m wide × 1.0 m deep), and with each sub-block comprising three 0.5 m² plots. Plots within each sub-block were situated 1.0 m apart, while each block was separated by a 3.0 m buffer strip. The three plots within each sub-block represented the three slurry treatments, with one of the four sub-blocks within each block treated with slurry on each of the four application dates.

Slurry was only applied on the planned dates if conditions on that day complied with legislation contained within the Nitrates Action Programme (Northern Ireland) Regulations (EHS, 2007), as described earlier. Using these criteria, the following conditions were set to ensure spreading only took place when there was minimal risk of pollution following application:

1. No snow cover
2. Soil temperature above 0°C
3. Forecast rainfall on day of application below 2.5 mm
4. Total forecast rainfall for the following two days below 10 mm
5. Soil moisture levels below or within +2% of field capacity (40.1%)

By adhering to these criteria, the following spreading dates were adopted, thus ensuring that measurements encompassed the late winter and early spring periods: 7 December 2009, 18 January 2010, 1 March 2010 and 12 April 2010, with all intervals between spreading dates being 42 days.

The runoff plots were established based on the methods detailed in the previous studies, including Brennan *et al.* (2011), O Rourke *et al.* (2012), McConnell *et al.* (2013 a&b), Doody *et al.* (2014) and McConnell *et al.* (2015). Two weeks prior to each slurry application (so as to minimise soil disturbance), a shallow trench was excavated along the down-slope edge of each plot and a stainless steel V-shaped collection tray (0.5 × 0.1 × 0.1 m) placed in the trench to act as a runoff collector. The upslope edge of each tray was fitted with a 0.07 m horizontal lip, and this was driven horizontally (to a distance of approximately 0.05 m) into the soil directly underneath each plot, at a depth of approximately 0.03 m below the soil surface. A 0.02 m diameter outlet at the base of the each collection tray allowed runoff collected from each plot to drain into a two-litre high density polyethylene (HDPE) collection container via a 0.5 m length of underground pipe.

The dairy cattle slurry used within this study was collected following the mechanical mixing of an above ground slurry store. Slurry was collected three weeks prior to the first slurry application date and stored at <4°C in HDPE containers throughout the duration of the experiment. No slurry was applied to the control treatment plots on any application date. With the other two treatments slurry was applied by hand at a rate equivalent to 20 m³/ha (one litre per 0.5 m² plot), less than half of the current permissible level in NI at present. This equated to an application rate of 7.58 kg/ha P. Within the plots slurry was not applied within 0.05 m of the plot edges so as to minimise the impact of any disturbance created by the introduction of the plot surrounds following slurry application. Splash-plate spreading was simulated using a plastic jug to pour slurry onto a wooden board, which caused it to splash across the plot area. The trailing-shoe treatment consisted of three slurry tramlines (each 0.9 m long) running in the same direction as the slope, an earlier study having found direction of spreading to have no effect on P losses in runoff (McConnell *et al.*, 2013a). Tramlines were spaced 0.225 m apart, with the two outer tramlines situated 0.025 m away from the sides of the plot and terminating 0.05 m from the top and bottom of each plot. To simulate the trailing-shoe spreading technique, grass was parted by hand and held in place with wooden boards. Slurry was then applied to the base of the sward using a thin spouted plastic jug. All plots were covered with translucent plastic sheeting (positioned approximately 0.2 m above the ground) between slurry application and the first rainfall simulation event, a period of approximately 48 hours. On the same day that slurry was applied, the sub-plots were hydrologically isolated from overland and shallow sub-surface flow by inserting stainless steel surrounds into the soil along the sides and across the up-slope end of each plot to a depth of 0.05 m.

Rainfall simulation

Rainfall simulations were carried out using the same methodology as described in a number of similar studies: Brennan *et al.* (2011), O'Rourke *et al.* (2012), McConnell *et al.* (2013 a,b), Doody *et al.* (2014) and McConnell *et al.* (2015). Rainfall simulations were performed at 2 (RD2) and 9 (RD9) days following the December slurry application, and at 2, 9 and 16 (RD16) days following the January, March and April slurry applications. The selection of the RD2 rainfall simulation day was based on the current regulation within NI that slurry should not be spread with 48 hrs of heavy rain being forecast. The selection of RD9 and RD16 was based on previous studies carried out at this institute (O'Rourke *et al.,* 2012; McConnell *et al.*, 2013a, b) which demonstrated that elevated P concentration from slurry were still detectable up to 20 days post-application. Rainfall simulations were not performed at day-16 following the December slurry application as the ground was frozen at this time, as described later. Two Amsterdam drip-type rainfall simulators (Bowyer-Bower and Burt, 1989) were employed to supply rainfall at a constant rate of 20 mm/hr. The rainfall intensity was selected as preliminary investigations on this soil type have indicated that this was the minimum rainfall intensity required to generate runoff consistently across a range of different soil moisture contents, and within a reasonable time frame. This rainfall intensity has a return period equivalent to a one-in-five-year event for NI (Betts, 1997). Thirty minutes of runoff was collected at each rainfall simulation. Runoff volume and time taken to generate runoff was recorded. Water used in the rainfall simulations was passed through a DC9 general deionising cylinder (Purite Limited) to reduce its P concentration. The cylinder delivered deionised water with an average dissolved reactive P (DRP) and nitrate-N concentration of 9.3 µg/L and 253 µg/L, respectively.

Water quality analysis

Water samples were placed in a fridge at 3°C within 4 hours of sampling. One sub-sample was analysed for DRP, total dissolved P (TDP) and total P (TP) within 24 hours of

sampling. Samples for DRP and TDP were filtered through 0.45 µm filters (MF-Millipore, Billerica, MA) before analysis. Dissolved reactive P was determined colorimetrically using the ascorbic acid reduction technique described by Murphy and Riley (1962). Acid-digestion techniques (Eisenreich *et al.*, 1975) were used to convert TDP and TP content to DRP. These samples were then analysed using the ascorbic acid reduction method outlined above (Murphy and Riley, 1962). Particulate P (PP) was calculated as the difference between TP and TDP.

Sward measurements
On each slurry application date, extended tiller measurements were recorded to the nearest millimetre at 10 randomly selected positions within each 0.5 m^2 plot using a 30 cm ruler.

Soil measurements
Soil moisture readings were taken using a volumetric soil moisture probe (HH2, Delta-T Devices Ltd., Cambridge, UK). Three soil moisture readings were taken per plot at each slurry application. In addition, average daily soil moisture levels were recorded by a continuous data logger attached to a HH2 volumetric soil moisture probe located 300 m from the study site (WS-STD1, Delta-T Devices Ltd., Cambridge, UK) to provide soil moisture reading for the duration of each rainfall simulation event.

Slurry analysis
Slurry was sampled at each application date and analysed for dry matter (DM), nitrogen (total Kjeldahl N), ammonium-N and P content. Dry matter content was determined gravimetrically after oven-drying at 100°C for 48 hours. Slurry nitrogen and ammonium-N content were determined by analysing fresh manure, as described in Jensen (1991). Total P was determined on a dried sample of slurry by the methods described in APHA (1995).

Statistical analysis
Data were analysed using Genstat Version 12 software (VSN International, 2009, UK). Runoff days 2, 9 and 16 were treated as independent events following the completion of regression analysis using Microsoft Excel (Microsoft Corporation, 2003, WA), which determined no significant correlation between the amount of rainfall a plot received prior to a rainfall simulation event, and the subsequent runoff volume generated or the time required to generate runoff, at that event. Subsequently, data from each runoff day were analysed separately using ReML repeated measures analysis, which included both application date and slurry method. This was adopted rather than a two-way analysis of variance to take into consideration the random effect of the main plot in the split plot design. A power city-block distance model was applied to the data. The presence of non-normality in some variables in the data set was addressed by fitting logarithm base 10 transformations to these variables before analysis. Herbage results were also analysed using ReML repeated measures analysis with the application date and spreading method as factors.

Results

Slurry applied during December, January, March and April had a DM content of 68.3, 67.7, 65.9 and 67.6 g/kg, an ammonium-N content of 1.91, 1.92, 1.99 and 2.18 g/kg, a total nitrogen content of 2.98, 2.99, 3.14 and 3.17 g/kg, and a total P content of 5.69, 5.56, 5.74 and 5.52 g/kg DM, respectively. Table 1 summarises the weather and soil conditions, and extended tiller heights at each slurry application.

Following each slurry application, weather conditions were monitored during the 16-day period during which runoff measurements were undertaken (Figure 1). During this period, average VSM contents following the December, January, March, and April slurry applications were 38.8, 39.2, 35.2 and 33.9%, respectively. The 16-day period following the January application was the wettest period during the experiment, with 44.0 mm of rainfall falling during this period. In contrast, 8.6, 0.9 and 9.2 mm of rainfall fell during the 16-day periods following the December, March and April applications, respectively. Following slurry application on 7 December, air temperature fell below freezing on 18 December, the start of a 23-day cold period during which ground remained almost permanently frozen, thus preventing the RD16 rainfall simulations from being undertaken.

Table 1. Weather and soil conditions, and extended tiller heights at each slurry application

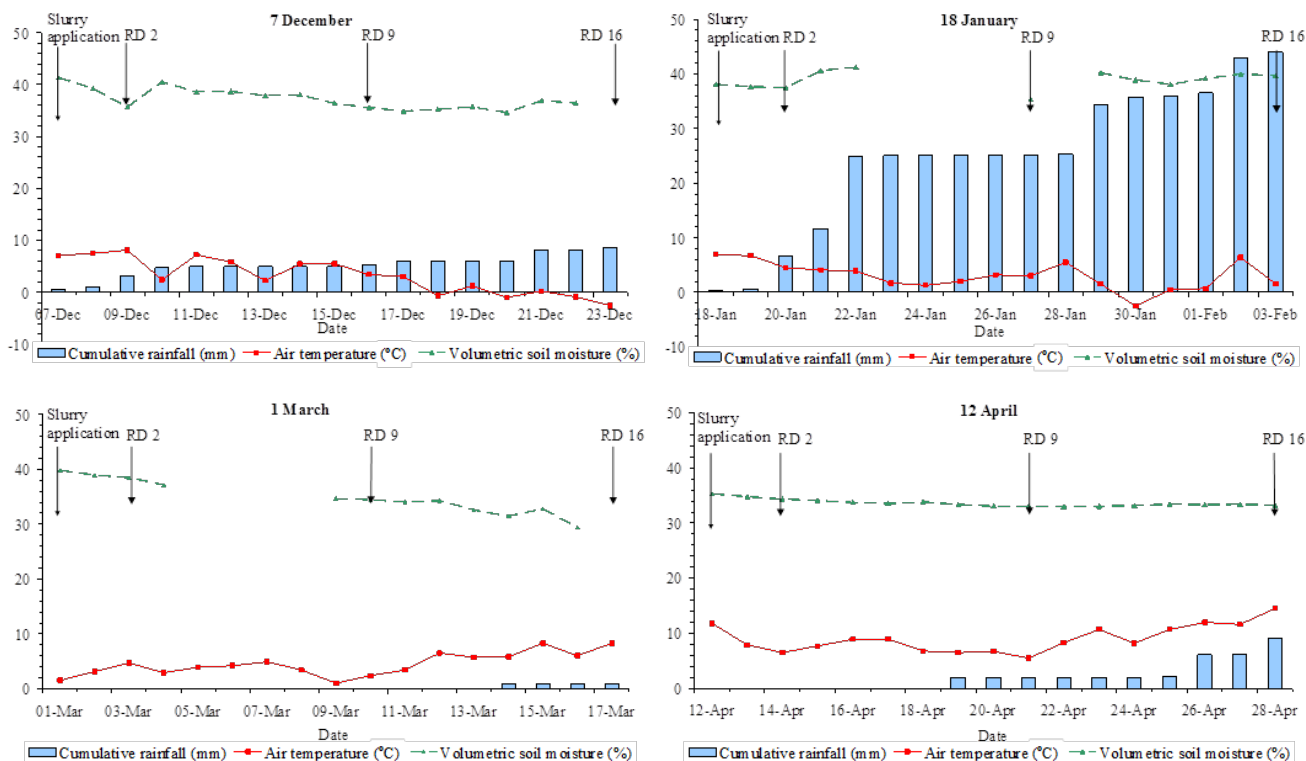| Application date | Rainfall total (mm) | | Temperature (°C) | | | Volumetric soil moisture content (%) | Extended tiller heights (cm) |
| | | | Air | | | | |
	Day	+48 hrs	Max	Min	Soil @10 cm		
7 December	0.6	1.0	8.0	3.4	5.2	41.3	9.6
18 January	0.3	6.3	8.5	3.4	4.8	38.1	9.4
1 March	0.0	0.0	6.4	-2.6	1.5	41.6	8.5
10 April	0.0	0.0	18.0	3.7	7.6	35.3	11.7

Figure 1. Cumulative rainfall totals, average air temperature and average soil moisture content at the study site during the 16-day period following each slurry application date.

Slurry treatment had no significant effect on either runoff generation time or the volume of runoff produced over a 30-minute period at RD2 and RD9 (Table 2). While runoff generation time at RD16 was unaffected by slurry treatment, runoff volume was higher with the trailing-shoe treatment than with the control treatment ($P < 0.05$) at this time. In contrast, runoff generation time differed with application date at RD2 and RD9 ($P < 0.001$), being longest with the April application date. At each of RD2, RD9 and RD16, flow-weighted mean concentrations of DRP, PP and TP in runoff were significantly lower ($P < 0.05$) with the control treatment than with either the splash-plate or trailing-shoe treatments (Table 3). At RD2, concentrations of DRP, PP and TP in runoff were significantly lower ($P < 0.05$) with the trailing-shoe treatment than with the splash-plate treatment, while these differences had largely disappeared at RD9 and RD16. The exception to this was DRP concentrations in runoff at RD16, which was significantly higher ($P < 0.05$) with the trailing-shoe treatment than with the splash-plate treatment. Application date had a significant effect ($P < 0.05$) on DRP, PP and TP concentrations in runoff at each of RD2, RD9 and RD16 (with the exception of PP concentrations in runoff at RD2). There was a significant slurry treatment × application date interaction at each of RD2,

RD9 and RD16, for DRP ($P = 0.028$, $P < 0.001$ and $P = 0.003$, respectively) and TP ($P = 0.018$, $P = 0.029$ and $P < 0.001$, respectively) concentrations in runoff.

At each application date, total P export at RD2 was greater ($P < 0.05$) from the splash-plate treatment than from the trailing-shoe treatment, with TP exports from both slurry treatments higher ($P < 0.05$) than from the control treatment (Figure 2). Total P export rates at RD2 were significantly greater ($P < 0.05$) following the January and March slurry applications than following the December and April slurry applications. Total phosphorus exports at RD9 were higher with the splash-plate and trailing-shoe treatments ($P < 0.05$) than with the control treatment, while TP export at RD9 following the December application was higher ($P < 0.05$) than either the January, March or April applications. By RD16, TP export was significantly greater ($P < 0.05$) from the trailing-shoe treatment than from the splash-plate treatment. Application date also had a significant effect ($P = 0.013$) on TP export at RD16, with the January and March applications having a higher TP export than the April application. Following each slurry application, the majority of the TP exported from the control treatment was in a particulate form, with the proportion of PP exported as TP

Table 2. Effect of slurry treatment and slurry application date on the time taken to generate runoff, the volume of runoff produced, and the average runoff: rainfall ratio throughout the study

		Runoff day 2			Runoff day 9			Runoff day 16		
		Time to generate runoff (seconds)	Runoff volume[†] (litres)	Runoff: rainfall ratio[‡]	Time to generate runoff (seconds)	Runoff volume[†] (litres)	Runoff: rainfall ratio[‡]	Time to generate runoff (seconds)	Runoff volume[†] (litres)	Runoff: rainfall ratio[‡]
Slurry treatment	Control	925	1.84	0.24	1014	1.19	0.15	991	1.48[a]	0.19
	Splash-plate	973	1.83	0.24	975	1.50	0.20	872	1.65[ab]	0.22
	Trailing-shoe	800	1.95	0.27	856	1.69	0.23	764	1.88[b]	0.26
	SED	99.1	0.173		128.1	0.206		98.2	0.136	
	P	NS	NS		NS	NS		NS	0.016	
Application date	7 December	718[a]	1.45[a]	0.21	506[a]	1.78	0.28	-	-	-
	18 January	841[a]	2.18[b]	0.30	937[b]	1.07	0.14	643	2.17	0.32
	1 March	630[a]	2.69[b]	0.40	773[ab]	1.67	0.23	1055	1.67	0.21
	12 April	1408[b]	1.16[a]	0.13	1578[c]	1.31	0.14	928	1.16	0.15
	SED	123.3	0.344		155.3	0.364		175.0	0.408	
	P	<0.001	0.003		<0.001	NS		NS	NS	

[†]Runoff volume collected in the first 30 minutes following the initiation of runoff.
[‡]Runoff: rainfall ratio calculated as the volume of runoff collected during a 30-minute period divided by the total volume of simulated rainfall applied from the start of rainfall until the end of this 30-minute period.
Means with the same superscript within columns, within factors, are not significantly different (P > 0.05).

Table 3. The effect of slurry treatment and slurry application date on flow-weighted mean concentrations of dissolved reactive phosphorus (DRP), particulate phosphorus (PP) and total phosphorus (TP) in runoff throughout the experiment

		Runoff day 2			Runoff day 9			Runoff day 16		
		DRP (mg/L)	PP (mg/L)	TP (mg/L)	DRP (mg/L)	PP (mg/L)	TP (mg/L)	DRP (mg/L)	PP (mg/L)	TP (mg/L)
Slurry treatment	Control	0.16[a‡]	0.91[a]	1.24[a]	0.16[a]	0.39[a]	0.71[a]	0.19[a]	0.29[a]	0.57[a]
	Splash-plate	3.34[c]	4.33[c]	9.10[c]	1.85[b]	1.34[b]	3.93[b]	0.96[b]	0.43[b]	1.63[b]
	Trailing-shoe	1.96[b]	3.26[b]	6.21[b]	1.57[b]	1.14[b]	3.40[b]	1.18[c]	0.48[b]	1.90[b]
	SED	0.128	0.289	0.292	0.040[†]	0.089[†]	0.059[†]	0.038[†]	0.053[†]	0.033[†]
	P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Application date	7 December	1.99[b]	3.48	6.74[c]	1.02[b]	2.00[c]	4.07[c]	-	-	-
	18 January	1.47[a]	2.99	5.14[b]	0.63[a]	1.14[b]	1.99[b]	0.54[a]	0.86[a]	1.52[c]
	1 March	2.14[b]	2.80	5.76[b]	0.78[b]	0.57[a]	1.82[ab]	0.75[b]	0.23[c]	1.18[b]
	12 April	1.68[a]	2.13	4.42[a]	0.72[ab]	0.39[a]	1.37[a]	0.54[a]	0.30[b]	0.98[a]
	SED	0.208	0.461	0.349	0.046[†]	0.102[†]	0.068[†]	0.037[†]	0.037[†]	0.033[†]
	P	0.014	NS	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001
Interaction[§]	P	0.028	NS	0.018	<0.001	NS	0.029	0.003	NS	<0.001

[†]Logarithmic base 10 standard error of difference.
[‡]Means with the same superscript within columns, within factors, are not significantly different (P > 0.05).
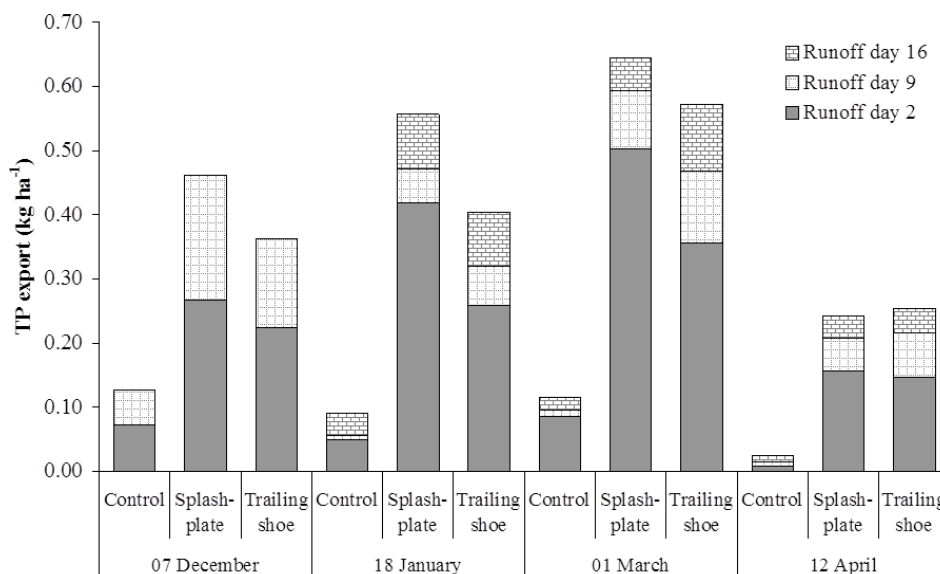[§]Slurry treatment × application date interaction.
NS = P > 0.05

Figure 2. The effect of application date and slurry treatment on total phosphorus (TP) export rates in runoff, collected 2, 9 and 16 days post slurry application.

gradually reduced from 74% in December to 37% in April. In contrast both the splash-plate and trailing-shoe treatments exhibited lower proportions of TP export in particulate form, with PP from the slurry treatments accounting for 46, 51, 58 and 29% of TP following the December, January, March and April applications, respectively.

Discussion

Runoff generation

Slurry was only applied when soil and weather conditions were in agreement with guidance contained within the Code of Good Agricultural Practice (DARD, 2008) and the Nitrates Action Programme (Northern Ireland) Regulations (EHS, 2007). Nevertheless, there was considerable variation in runoff characteristics between the four application dates, and between runoff days 2, 9 and 16. In general, when VSM content was high, runoff volume was also high. Vegetation cover may also have influenced runoff volume, with the low runoff volumes in April coinciding with the maximum grass tiller heights recorded. As plant cover increases, interception by vegetation has a greater effect on lowering the kinetic energy of raindrops, and this is thought to facilitate greater infiltration, thus reducing runoff generation (Barfield *et al.*, 1979). Small-scale changes in soil structure and soil micro-topography between individual rainfall simulation plots may also have caused some variation in runoff generation within each runoff event.

There is conflicting evidence concerning the impact of slurry application on runoff generation. While Smith *et al.* (2001)

and Brennan *et al.* (2012) suggested that slurry can reduce infiltration rates and promote runoff by 'sealing' the soil surface, slurry application had no significant impact on runoff generation in the current experiment, in agreement with findings of similar grassland-based studies (Srinivasan *et al.*, 2007; Johnson *et al.*, 2011).

Effect of slurry treatment on P losses in runoff

As expected, P concentrations in runoff from the slurry treated plots were higher than from the control plots at all runoff day events, with this highlighting the risk of P losses in surface runoff following intensive rainfall events, even up to 16 days post-slurry application. However, this experiment provides clear evidence that the use of the trailing-shoe slurry spreading technique during the winter-early spring period can reduce P concentrations in runoff, relative to traditional splash-plate spreading. For example, DRP, PP and TP concentrations were reduced by 41, 25 and 32% respectively at a rainfall event two days after slurry application. This is likely due to a smaller slurry-rainfall contact area when slurry is applied using the trailing-shoe technique compared to the splash-plate technique. As a consequence of this smaller contact area, the potential for the dissolution of slurry P to runoff is reduced with the trailing-shoe (Leinweber *et al.*, 2002), while the cumulative raindrop impact experienced by the slurry will also be reduced. In addition, when slurry is placed at the base of the sward using the trailing-shoe technique, the grass plants intercept and deflect raindrops, thus reducing their impact on the slurry. Structural breakdown of slurry aggregates by raindrop impact can result in both

particle detachment and the exposure of previously occluded P (Kleinman *et al.*, 2002; Leinweber *et al.*, 2002). As a result of the lower cumulative raindrop impact associated with the trailing-shoe treatment, the potential for both dissolved and particulate P losses is reduced.

These findings are consistent with those reported by McConnell *et al.* (2013a) in a study involving slurry application to a grass stubble during the summer period. In that study, DRP concentration in runoff following a rainfall event two days after slurry application was 37% lower when slurry was applied using the trailing-shoe technique compared to the splash-plate technique. Thus the current study clearly demonstrates that during periods of high antecedent soil moisture levels the trailing-shoe technique can be equally effective as during the summer months in reducing the risk of P losses in runoff at this scale.

A number of recent studies have examined measures to reducing the risk of P loss following slurry application to grassland soils under Irish conditions (O'Rourke *et al.*, 2010; Brennan *et al.*, 2011; O'Rourke *et al.*, 2012; Serrenho *et al.*, 2012; Murnane *et al.*, 2015). For example, Brennan *et al.*, (2011) reported an 86%, 83%, 69% and 67% reduction in DRP in runoff from soil boxes following the application of slurry amended with ploy-aluminium chloride hydroxide, alum, lime and FeCl$_2$, respectively. O'Rourke *et al.* (2010) reported that DRP concentration in runoff was reduced by up to 74% following a reduction of P in dairy cow diets from 5.3 to 3.0 g P/kg. However, the greatest reduction in the latter study related to the time between slurry application and rainfall, with the largest reduction occurring when rainfall was delayed from 2 to 9 days post-slurry application. While the reductions observed in the current study are lower than those reported by Brennan *et al.*, (2011), there are significant challenges that still need to be overcome before chemical amendment of slurry becomes a viable mitigation measure at field scale. Although uncertainty in rainfall predictions impact on the effectiveness of delaying slurry applications, it is hypothesised that this approach, in combination with trailing shoe technology, offers a more cost-effective solution than amendments at this time. However, further research is required to test the cost-effectiveness of this approach at field scale, considering barriers such as the capital investment required from farmers to move from traditional splashplate to the use of trailing shoe technology.

High DRP concentrations in runoff (RD2) following the December and March slurry applications coincided with high VSM levels (above field capacity) at the time of slurry application. Sommer and Jacobsen (1999) noted that at higher soil water contents, the mass flow of liquid from surface broadcast pig slurry into the soil was reduced. Thus the high VSM levels at the time of slurry application in the current study most likely hindered the infiltration of the liquid fraction of slurry into the soil during the first 48 hours after application,

leaving a higher proportion of the applied slurry P on the soil surface. Indeed, McGechan and Lewis (2000) noted that applying slurry to fields with high soil hydraulic conductivities provided one of the greatest opportunities to minimise the loss of P in runoff during the winter period, as this would both aid the infiltration of slurry P and reduce the potential for runoff generation. Similarly, Vadas *et al.* (2011) noted that under drier soil conditions, the time taken to generate runoff at an individual rainfall event increases, resulting in a greater interaction time between slurry and rainfall, thus allowing the rainfall to transfer P to the upper soil horizons where it undergoes rapid sorption by soil particles. The impact of this process was particularly evident following the March application of slurry, where the highest runoff:rainfall ratio (0.40) recorded during the experiment was observed at RD 2. This was reflected in a short-time interval to the start of runoff, minimal translocation of P into the soil and the highest DRP concentrations and exports recorded throughout the experiment. In contrast, a low runoff:rainfall ratio (0.13) and a low VSM content at the time of slurry application (35.3%), as observed following the April slurry application, facilitated rapid translocation of P into the underlying soil, and resulted in lower concentrations and exports of P.

At each application date throughout this experiment, the trailing-shoe technique significantly reduced the magnitude of DRP concentrations in runoff relative to the splash-plate technique, regardless of weather and soil conditions. The absence of significant variation between runoff DRP concentrations from the trailing-shoe treatment across the four application dates suggests that the lower rainfall-slurry contact offered by the trailing-shoe helps mitigate against adverse weather conditions thus minimizing DRP concentrations in runoff. In contrast, the high levels of DRP in runoff from the splash-plate treatment under high VSM levels (December and March), suggests that splash-plate spreading methods can exacerbate the magnitude of runoff P loss under wetter weather conditions.

Although a number of authors (McGechan and Lewis, 2000; Jordan *et al.*, 2007) have highlighted that the 'safe' application of slurry during the winter period can often be limited due to the absence of suitable weather conditions, a study by Holden *et al.* (2004) predicted that in five years out of a ten-year period, suitable weather conditions for slurry spreading would be available for at least 10% of the winter period in Northern Ireland. The findings of the current study clearly demonstrate that provided spreading conditions are suitable, P concentrations in runoff from slurry applied during the 'winter' period (18 January) can be lower than from slurry spread in early Spring (1 March), thus highlighting that calendar-based 'closed periods' might on occasions actually delay slurry applications until a higher risk period. Nevertheless, crop requirements for nutrients during the winter are low. Thus,

while it may be possible to apply slurry during the winter without exacerbating the risk of P loss in runoff compared to slurry applied later in the year, nitrogen use efficiency will be greater if slurry applications are delayed until grass growth has commenced. This was reflected in the trend in yield of herbage harvested from plots in the current experiment on 25 May (1.82, 2.16, 2.46 and 2.50 t DM/ha for the December, January, March and April application dates respectively: SED, 0.1732, P = NS).

Runoff P losses over successive rainfall events

The reductions in runoff P concentrations over the three successive runoff events (RD2, RD9 and RD16) in the current experiment are in line with findings from earlier studies (Kleinman and Sharpley, 2003; O'Rourke et al., 2010; Vadas et al., 2011). While a number of mechanisms may account for the decline in P concentrations in runoff over time, P availability at the soil surface is one of the primary factors controlling P loss (Kleinman and Sharpley, 2003). Phosphorus availability is determined by the extent of P removal during earlier runoff events, and by the translocation of P into the soil via infiltration and bioturbation, whereby rapid sorption of P occurs. Within the current experiment, P removal during previous runoff events most likely contributed in part to the lower P concentrations in runoff at RD9 and RD16. Indeed, higher DRP concentrations in runoff at RD2 from the splash-plate treatment relative to the trailing-shoe treatment indicate a greater depletion of slurry P at the soil surface and most likely resulted in the lower DRP concentrations in runoff from the splash-plate treatment (0.96 mg/L) relative to the trailing-shoe treatment (1.18 mg/L) by RD16. Consequently, though the splash-plate appears to pose a greater short-term threat to water quality, the trailing-shoe may perhaps pose a longer term threat, with the rate of decline of P loss over successive runoff events being lower than that of the splash-plate treatment. However, this is an issue that requires further clarification.

While earlier rainfall events contributed to lower P concentrations at later events in the current experiment, in reality, only a small proportion of the total P applied in slurry (<10%) was lost in this way. Similarly, Kleinman and Sharpley (2003) noted that while runoff DRP concentrations fell by 90% over the course of three rainfall simulation events (at 3, 10 and 24 days after slurry application), the total DRP exported only accounted for 4–13% of the slurry water extractable P applied. Thus a large part of the decrease in concentrations of runoff P over time must be due to the assimilation of slurry P into soil. Up to 60% of P from dairy cow slurry can infiltrate into soil provided the manure has a DM content of

less than 15% (Vadas et al., 2007), with up to two-thirds of infiltration occurring during the first four days after slurry application (Vadas, 2006). Once infiltration takes place the manure P is subject to rapid sorption by soil colloids, thus reducing its availability to runoff water. For example, Sharpley (1997) noted a positive correlation between the initial soil sorption capacity of soil, and the difference in runoff DRP concentrations between the first and final rainfall simulation events after slurry application. The results of the current study demonstrate that those processes remain active during periods of higher antecedent soil moisture conditions.

While the results from this study have demonstrated that the trailing shoe is a potential mitigation measure to reduce P loss in runoff during periods of higher antecedent soil moisture conditions, further research at field scale is required to confirm these results. For example, as the scale increases the potential for attenuation along transport pathways also increases, which could impact on the effectiveness of the use of trailing shoe technology to reduce P loss in runoff. While this study was carried out on a surface water gley, with a HOST classification of 24 representing 46% of soils in NI, variations in soil type, drainage class and position with the landscape need further investigation. In addition, a high rainfall intensity of 20 mm/hr is likely to represent a 'worst case scenario', so evaluation under 'natural' rainfall conditions is advised.

Conclusions

In agreement with previous research undertaken during the summer months, the use of the trailing-shoe technique during periods of high soil moisture content was effective in reducing P losses in runoff from applied slurry, when compared to the splash-plate technique. Phosphorus concentrations in runoff appeared to be primarily driven by soil moisture levels, and not by date of slurry application per se, thus highlighting the importance of considering soil conditions at the time of spreading when seeking to minimise nutrient losses from applied slurry. In addition to optimal timing of slurry application, the use of trailing-shoe during winter and early spring should be considered as a mitigation measure to minimise the risk of nutrient loss during this period. However, further research is required to test the scale dependency of the finding of this study, as factors such as rainfall intensity, boundary effects, attenuation and hydrological processes will vary significantly with experimental scale, and potentially impact the effectiveness of the trailing shoe in reducing P loss post-slurry application.

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