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Chemical amendment of pig slurry: control of runoff related risks due to episodic rainfall events up to 48 h after application

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Abstract

Losses of phosphorus (P) from soil and slurry during episodic rainfall events can contribute to eutrophication of surface water. However, chemical amendments have the potential to decrease P and suspended solids (SS) losses from land application of slurry. Current legislation attempts to avoid losses to a water body by prohibiting slurry spreading when heavy rainfall is forecast within 48 h. Therefore, in some climatic regions, slurry spreading opportunities may be limited. The current study examined the impact of three time intervals (TIs; 12, 24 and 48 h) between pig slurry application and simulated rainfall with an intensity of 11.0±0.59 mm h^{-1}. Intact grassed soil samples, 1 m long, 0.225 m wide and 0.05 m deep, were placed in runoff boxes and pig slurry or amended pig slurry was applied to the soil surface. The amendments examined were: (1) commercial-grade liquid alum (8% Al_2O_3) applied at a rate of 0.88:1 [Al/total phosphorus (TP)] (2) commercial-grade liquid ferric chloride (38% $FeCl_3$) applied at a rate of 0.89:1 [Fe/TP] and (3) commercial-grade liquid poly-aluminium chloride (10 % Al_2O_3) applied at a rate of 0.72:1 [Al/TP]. Results showed that an increased TI between slurry application and rainfall led to decreased P and SS losses in runoff, confirming that the prohibition of land-spreading slurry if heavy rain is forecast in the next 48 h is justified. Averaged over the three TIs, the addition of amendment reduced all types of P losses to concentrations significantly different ($p<0.05$) to those from unamended slurry, with no significant difference between treatments. Losses from amended slurry with a TI of 12 h were less than from unamended slurry with a TI of 48 h, indicating that chemical amendment of slurry may be more effective at ameliorating P loss in runoff than current TI-based legislation. Due to the high cost of amendments, their incorporation into existing management practices can only be justified on a targeted basis where inherent soil characteristics deem their usage suitable to receive amended slurry.

Keywords: pig slurry, runoff, P sorbing amendments, Nitrates Directive, Water Framework Directive, phosphorus, suspended solids

Introduction

During episodic rainfall events, phosphorus (P) and reactive nitrogen (N_r) fluxes from critical (soil) and incidental (e.g. slurry or fertiliser application) sources can contribute to anthropogenic eutrophication of surface water (Preedy et al. 2001; Kleinmann et al. 2006; Wall et al. 2011). European Union (EU) legislation attempts to optimise nutrient use on agricultural land and to avoid losses to water bodies. The Nitrates Directive (OJEC 1991;

Monteney 2001) has been ratified into national legislation in Ireland and limits the magnitude, timing and placement of inorganic and organic fertilizer applications (Jordan et al. 2012). Specifically, it stipulates a mandatory closed period for slurry spreading during winter. Slurry application is limited on soils with a high soil test P (e.g. Morgan's P > 8 mg L^{-1}), thereby restricting the available land for application (Nolan et al. 2012). Additionally, slurry spreading is prohibited when heavy rainfall is forecast within 48 h of application. Therefore, slurry spreading opportunities may be limited, especially in wet years or in areas where soil trafficability is limited due to wet or saturated soil conditions.

Even though there is very clear evidence that P losses in runoff are reduced with increasing time interval (TI) between slurry application and the occurrence of a rainfall-runoff event (Daverede et al. 2004; Hart et al. 2004), most studies have investigated the effect of cumulative rainfall events. Only a few studies have looked at the effect of the TI between slurry application and the first rainfall event (Sharpley 1997; Smith et al. 2007; Allen and Mallarino 2008). Moreover, none of these studies assessed a range of TIs shorter than 48 h, which is the limit set by Irish and UK regulations. Assessing the risk of runoff at TIs within these 48 h is highly relevant, as the occurrence of heavy rain can often not be ruled out in the highly unpredictable North Atlantic climate (McDonald et al. 2007; Creamer et al. 2010). In addition, this would provide evidence that a 48 h limit does not unnecessarily restrict the opportunity of farmers to apply slurry. To our best knowledge, there are no studies that address the validity of adhering to a 48-h dry period between application and the first heavy rainfall event, apart from work by Serrenho et al. (2012), who found that adherence to a minimum TI of 48 h between application of dairy soiled water and rainfall was prudent to reduce incidental P losses in runoff. Investigating the development of P losses during first rainfall events within 48 h after application can shed more light on the validity and effectiveness of this measure.

Measures to effectively control agricultural P transfer from soil to water include chemical amendment of slurry. Alum, aluminium chloride ($AlCl_3$), lime and ferric chloride ($FeCl_3$) have been shown to significantly reduce P losses in surface runoff arising from the land application of dairy cattle slurry (Brennan et al. 2011, 2012), dairy soiled water (Serrenho et al. 2012), poultry litter (Moore et al. 1999, 2000) and pig slurry (Dao 1999; Dou et al. 2003; Smith et al. 2001, 2004; O’ Flynn et al. 2012a, b). In particular, O’ Flynn et al. (2012b) showed that the runoff losses from amended pig slurry 48 h after application could be reduced to levels similar to the soil-only treatment. This warrants the effort of assessing the effectiveness of these additives at TIs of less than 48 h between application and first rainfall event.

Therefore, the aim of this study was to investigate the effect of TI (12, 24 and 48 h) between pig slurry application and first rainfall event on the losses of P and suspended solids (SS) in runoff, and to assess the efficacy of adding chemical amendments in reducing losses at these three TIs.

Materials and Methods

Slurry collection and characterisation

Pig slurry was taken from an integrated pig unit in Teagasc Research Centre, Moorepark, Fermoy, Co. Cork, Ireland in April 2012. The sampling point was a valve on an outflow pipe between two holding tanks, which were sequentially placed after a holding tank under slats on which no bedding materials were used. To ensure a representative sample, this valve was turned on and left to run for a few minutes before taking a sample. The slurry was stored inside a cold-room fridge at 10°C prior to testing. Total P (TP) and total nitrogen (TN) were determined using persulfate digestion. Ammonium-N (NH_4^+-N) was determined by adding 50 ml of slurry to 1 L of 0.1M HCl, shaking for 30 min at 200 rpm, filtering through no. 2 Whatman filter paper, and analysing using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). Slurry pH was determined using a pH probe (WTW, Germany). Dry matter content was determined by drying at 105°C for 24 h. The physical and chemical characteristics of the pig slurry used in this experiment and characteristic values of pig slurry from other farms in Ireland are presented in Table 1.

Pig slurry amendment

Amendments for the present study were chosen based on effectiveness of P sequestration and feasibility criteria (cost and potential for metals release to the environment; Table 2)) as determined by O’ Flynn et al. (2012a, b). The amendment rates, which were applied on a stoichiometric basis were: (1) commercial grade liquid alum (8% Al_2O_3) applied at a rate of 0.88:1 [Al/TP] (2) commercial-grade liquid ferric chloride (38% $FeCl_3$) applied at a rate of 0.89:1 [Fe/TP]; and (3) commercial-grade liquid poly-aluminium chloride (PAC) (10 % Al_2O_3) applied at a rate of 0.72:1 [Al/TP]. The compositions of the amendments used are the same as those used in O’ Flynn et al. (2012a, b).

Soil collection and analysis

Intact grassed soil samples 1.2 m long, 0.3 m wide, 0.1 m deep (n=45) were collected from permanent grassland, which had not received fertiliser applications for more than 10 yr, in Galway City, Ireland (53°16'N, -9°02'E). Samples were cut out of the ground with a spade and, to avoid cracking, placed carefully on 1.5 m long, 0.5 m wide timber boards. Between collection and use, soil samples were stored externally to prevent drying. Soil samples (n=3), taken from the upper 0.1 m from the same location, were oven dried at 40 °C for 72 h, crushed to pass a 2 mm sieve and analysed for Morgan's P (the national test used for the determination of plant available P in Ireland) using Morgan's extracting solution (Morgan 1941). Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water to soil. The particle size distribution was determined using a sieving and pipette method (British Standards Institution 1990a) and the organic content of the soil was determined using the loss on ignition test (British Standards Institution 1990b). The soil used was a well-drained, sandy loam textured, acid brown earth (WRB classification: Cambisol) (58% sand, 29% silt, 14% clay) with a soil test P of 2.8±0.5 mg L^{-1}, making it a P index 1 soil according to The European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2010 (hereafter referred to as S.I. No. 610 of 2010); total potassium of 203 mg L^{-1}, a pH of 6.4±0.3 and an organic matter content of 5±2%.

Rainfall simulation study

The following treatments were examined within 21 days of sample collection: (1) a grassed sod-only treatment with no slurry applied, (2) a grassed sod with unamended slurry (the slurry control) applied at a rate of 19 kg TP ha^{-1} and (3) grassed sods receiving amended slurry applied at a rate of 19 kg TP ha^{-1}. Three replications of each treatment were subject to rainfall at a TI between application and rainfall of either 12 (TI 1), 24 (TI 2) or 48 h (TI 3).

Stainless steel laboratory runoff boxes, constructed by a steel fabricator, 1 m long, 0.225 m wide and 0.075 m deep, with side walls of 0.025 m higher than the grassed sods, were used in this experiment. The runoff boxes were positioned under a rainfall simulator. The rainfall simulator consisted of a single 1/4HH-SS14SQW nozzle (Spraying Systems Co., Wheaton, IL, USA) attached to a 4.5 m high metal frame, and calibrated to achieve an intensity of 11.0±0.59 mm h^{-1} and a droplet impact energy of 260 kJ mm^{-1} ha^{-1} at 85% uniformity after Regan et al. (2010). The source for the water used in the rainfall simulations had a dissolved reactive P (DRP) concentration of less than 0.005 mg L^{-1}, a pH of 7.7±0.2 and an electrical conductivity of 0.44 dS m^{-1}. Each runoff box had 5 mm diameter drainage holes, spaced at distances of 0.3 m centre to centre, positioned in a line and spanning the length of the base, after Regan et al. (2010). Muslin cloth was placed at the base of each runoff box before packing the sods to prevent soil loss. Immediately prior to the start of each experiment, the sods were trimmed and packed in the runoff boxes. To prevent cracking, sods were first trimmed into two 0.5 m lengths and then placed in the runoff box. Each sod was then butted against its adjacent sod to form a continuous surface. Molten candle wax was used to seal any gaps between the soil and the sides of the runoff box, while the joints between adjacent soil samples did not require molten wax. The packed sods were then saturated using a rotating disc, variable-intensity rainfall simulator (after Williams et al. 1997), and left to drain for 24 h by opening the 5 mm diameter drainage holes before continuing with the experiment. At this point, when the soil was at approximately field capacity, slurry and amended slurry were spread on the packed sods and the drainage holes were sealed. They remained sealed for the duration of the experiment. At t = 12, 24 or 48 h, the sods were subjected to a rainfall event, and each event lasted for a duration of 30 min after runoff began. Different sods were used for each rainfall event. Surface runoff samples were collected in 5 min intervals over the 30 min period and in the time period subsequent to the when the rainfall simulator was turned off, until no further runoff samples were available.

Runoff water samples were tested for pH. A subsample was passed through a 0.45 µm filter and analysed colorimetrically for DRP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). Filtered (passed through a 0.45 µm filter) and unfiltered subsamples, collected at 10, 20 and 30 min after runoff began and any subsequent runoff once rainfall ceased, underwent acid persulfate digestion and were analysed colorimetrically for total dissolved P (TDP) and TP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland. Particulate phosphorus (PP) was calculated by subtracting TDP from TP. Dissolved unreactive P was calculated by subtracting DRP from TDP. Suspended solids were tested by vacuum filtration of a well-mixed (previously unfiltered) subsample through Whatman GF/C (pore size, 1.2 µm) filter paper. Prior to filtration, the filter paper was weighed. After filtration, the filter paper was dried at 105^{o}C for 24 h and reweighed.

Statistical analysis

The data was analysed in R (version 2.15.1, 32 bit) and IBM SPSS 20 using analysis of variance implemented via a general linear model. There were five levels of treatment (soil-only, slurry-only (the study control), and slurry treated with alum, PAC and $FeCl_3$) and three levels of the time factor (12, 24 and 48 h). Diagnostic plots indicated that a logarithmic transformation of the response variable was desirable when analysing the effects of the predictor variables on the flow weighted mean concentrations (FWMCs, calculated by dividing the total load over a rainfall event by the total flow) of DRP, dissolved unreactive P, TDP, PP and TP, if the normal distributional assumptions of the analysis were to be met. No transformation was performed for the analysis of SS. Probability values of $p>0.05$ were deemed not to be significant.

Results

Phosphorus in runoff

The FWMC of P in runoff from the soil-only treatment showed no statistically significant differences between TIs, with average TP and TDP FWMCs of 0.35 and 0.21 mg L^{-1} (corresponding to loads of 2.48 and 1.49 mg m^{-2}), respectively (Fig. 1, Table 2). At all TIs, P losses of all forms increased significantly ($p<0.05$) with slurry application compared with the soil only treatment (Fig. 1). The increase in losses was particularly high for PP, and averaged over the three TIs, the PP in runoff from the soil-only contributed 40% of the TP (Table 2) compared to 67% of the runoff from slurry-only. For the slurry-only treatment, losses of P in runoff significantly ($p<0.05$) decreased with increasing TI between application and rainfall. The FWMC of TP and TDP decreased from 8.2 and 3.4 mg L^{-1} (corresponding to loads of 45.7 and 18.9 mg m^{-2}), respectively, at TI 1 to 3.6 and 1.1 mg L^{-1} (23.5 and 7.5 mg m^{-2}) at TI 3 (Fig. 1).

In general, the addition of chemical amendment significantly ($p<0.05$) reduced concentrations of all forms of P lost in runoff at each TI to below the lowest losses from slurry-only, i.e. at a TI of 48 h (Fig. 1). However, with the exception of DRP, all forms of P losses in runoff from amended slurry were significantly ($p<0.05$) different to those from soil-only (Table 2). There were generally no significant differences between amendments for P losses in runoff. Time interval had no significant effect on P losses from amended slurry. There was no evidence of any significant interaction between time and treatment type.

Suspended solids and pH in runoff

Loses of SS in runoff from soil-only did not change significantly with TI, with FWMCs of 15.5, 16.9 and 15.6 mg L^{-1} (corresponding to loads of 134, 116 and 118 mg m^{-2}) after TIs 1, 2 and 3, respectively (Fig. 2). Application of slurry increased SS losses significantly (p<0.001) to levels over 30 times that of soil-only at TI 1 (482 mg L^{-1} or 2780 mg m^{-2}). Similar to the trends observed in P losses for the slurry-only treatment, losses of SS in runoff decreased with increasing TI between slurry application and rainfall, with statistically significant differences (p<0.05) between each TI. Similar to the P observations, losses of SS in runoff from amended slurry at all TIs were less than the lowest losses from unamended slurry at TI 3 (p<0.05). Whilst diagnostic plots were not entirely satisfactory for SS, all results were extremely clear-cut and there can be no doubt concerning the significance, or otherwise, of the results reported. The variable pH proved to be insignificant in all cases.

Discussion

Phosphorus in runoff from soil-only

The soil used in the present study was P deficient (P index 1), which would not normally be expected to pose a danger of P losses to the environment (Schulte et al. 2010) as such a soil requires additional nutrients to build up soil P reserves. Phosphorus concentrations in runoff from the soil only treatment were often above the Irish surface water regulation of 0.035 mg reactive P L^{-1} (S.I. No. 272 of 2009), but overall loads were small and therefore any deleterious effects to a greater scale cannot be inferred. In the field, rainfall would typically be less intense, and the soil would have the capacity for vertical drainage. As a result, the experiment replicated a worst-case scenario in terms of potential P loss from this soil. Therefore, while P losses from the runoff boxes may be used to compare the effects of chemical amendments and TI, they are not an accurate measure of P loss concentration or load to a surface water body that might be expected at field scale.

Phosphorus in runoff from unamended slurry

Decreased losses of P in runoff with increasing TI between application and rainfall have also been found in previous research–but at TIs significantly greater than those examined in the present study. In a plot study, Smith et al. (2007) spread pig slurry at 35 kg P ha^{-1} and found that at 30 min rainfall events, each with an intensity of 100 mm h^{-1}, DRP concentrations in runoff reduced from 8.4 mg DRP L^{-1} at a TI of 1 day to 2.6 mg DRP L^{-1} at a TI of 29 days. Allen and Mallarino (2008) spread pig slurry in a plot study at varying rates up to 108 kg P ha^{-1} and found that during 30-min rainfall events, each with an intensity of 76 mm h^{-1}, DRP and TP loads in runoff were 3.8 and 1.6 times lower at a TI of 10-16 days than at a TI of less than 24 h. The trend of an initial peak followed by a gradual reduction may be due to the interaction of the applied P and the conversion from soluble to increasingly recalcitrant forms over time (Edwards and Daniel 1993). The current study indicates that this process already starts within 24 h after application, and confirms that the prohibition of the land-spreading of slurry, if heavy rain is forecast in the next 48 h (S.I. No. 610 of 2010), is justified.

The extra PP lost in runoff from unamended slurry, associated with sediment and organic material in agricultural runoff, may provide a variable, but long-term, source of P in lakes (Sharpley et al. 1992), and as it is generally bound to the minerals (particularly iron (Fe), Al, and calcium (Ca)) and organic compounds contained in soil, it constitutes a long-term P reserve of low bioavailability (Regan et al. 2010).

The effect of slurry amendment on P losses

The addition of amendment resulted in reduced P losses in runoff compared to unamended slurry, with losses reduced at each TI to below the lowest losses from slurry only. There appeared to be little difference in runoff losses of P between the different amendments (Table 2). Higher losses in runoff from amended slurry than soil-only is because chemical amendment of slurry will only reduce the incidental P losses to the environment, but will not reduce chronic (long-term) P losses from the soil. In a field-based study, Smith et al. (2004) found that $AlCl_3$, added at 0.75% of final slurry volume to slurry from pigs on a phytase-amended diet, could reduce runoff DRP by 73%. In another field-based study, Smith et al. (2001) found that alum and $AlCl_3$, added at a stoichiometric ratio of 0.5:1 Al/TP to pig slurry, achieved reductions of 33 and 45%, respectively, in runoff water, and reductions of 84% in runoff water when adding both alum and $AlCl_3$ at 1:1 Al/TP.

Investigation of chemical amendment effectiveness on two soils using identical amendments, spreading rate and TI (Table 3) produced varied results due to differing soil characteristics. Both soils were of a similar texture but have different levels of soil organic carbon. Even though the current study was conducted on a P index 1 soil and had a lower chronic TP loss than measured by O’ Flynn et al. (2012b), incidental losses from slurry were higher, but not significantly so. Additionally, the effectiveness of the amendments (PAC, in particular) was much lower than reported by O' Flynn et al. (2012b; Table 3). This may be explained by differences in soil characteristics between the two experiments: the soil used by O' Flynn et al. (2012b) had a higher buffering capacity (i.e. more binding sites to retain added P) than that of the current study, due to differences in soil composition, including pH and organic matter. This reduction in effectiveness may also be the cause for little difference in P losses between the different amendments (Table 2). The effectiveness of slurry amendments is hence soil specific and should therefore be examined in future studies.

Based on the results from this study, runoff from amended slurry will have reduced P losses regardless of TI between landspreading and the occurrence of rainfall, indicating that chemical amendment may be more effective in reducing P losses than the current TI-based legislation.

Suspended solids and pH in runoff

As is the case with P, the reduction of SS was also related to the flocculating properties of the amendments. As well as removing PP from suspension, they also aid in adhesion of slurry particles, making them less prone to loss in runoff (Brennan et al. 2011). Apart from soil-only, losses of SS in runoff were all well above 35 mg L^{-1}, the treatment standard necessary for discharge to receiving waters (S.I. No 419 of 1994). However, whilst the results from this laboratory study may be used to compare the effects of chemical amendments and TI, they are not intended as a measure of actual losses to surface water bodies at field-scale.

The effect of amendments on slurry pH is a potential barrier to their implementation as it affects P sorbing ability (Penn et al. 2011) and ammonia (NH_3) emissions from slurry (Lefcourt and Messinger 2001). However, the results from this laboratory experiment, similar to previous studies (Smith et al. 2004; O' Flynn et al. 2012b), showed that there was no effect on the pH of the runoff water due to the use of amendments. However, further investigation would need to be undertaken to confirm that pollution swapping (the increase in one pollutant as a result of a measure introduced to reduce another pollutant (Healy et al. 2012)) does not occur.

Targeted use of amendments

Due to high costs involved (O' Flynn et al. 2012a), use of chemical amendments in slurry for land application can only be justified on a targeted basis, in particular: (1) soils with high mobilisation potential, soil test P and hydrological transfer potential to surface water, i.e. a critical source area and (2) at times when storage capacity becomes the critical factor, i.e. towards the end of the open period when unpredictable weather conditions would normally prohibit slurry spreading. In these cases, the adoption of the use of chemical amendment of slurry as part of a programme of measures would be justified. However, chemical amendments should only be used on soils that have been extensively tested for suitability. The difference in removals experienced in the current study and by O' Flynn et al. (2012b; Table 3) demonstrates the impact that soil type has on the efficacy of chemical amendment of pig slurry. The future uptake of such a mitigation strategy is dependent on the additional cost being considered a worthwhile expense, based on weather conditions and regulatory constraints at the time. If climatic conditions and legislation results in inadequate periods during which to spread slurry, and exerts pressure on slurry storage facilities, then chemical amendment may be seen as the most cost-effective and feasible option.

Conclusions

The excessively high losses of P in runoff at TIs of less than 48 h after slurry application, combined with the strong decrease of P losses within this time frame, confirm that the prohibition of land-spreading slurry if heavy rain is forecast in the next 48 h (S.I. No. 610 of 2010) is justified. Chemical amendment of pig slurry was effective at decreasing P and SS losses from the slurry. Runoff P losses from amended slurry were lower than from unamended slurry regardless of TI between land application and the occurrence of rainfall, indicating that chemical amendment may be more effective at reducing P losses than current TI-based legislation. The cumulative deposition of slurry over time, coupled with unpredictable weather patterns, increases the need for amendment, as leaching and overland flow are all possible vectors for pollution. The tightening of environmental legislation or the rigorous enforcement of current Water Framework Directive (European Commission 2000) legislation means that investment in P reduction will become justified. Due to the high cost of amendments, their incorporation into existing management practices can only be justified on a targeted basis, in particular: (1) critical source areas and (2) towards the end of the open period when unpredictable weather conditions would normally prohibit slurry spreading. However, chemical amendments should only be used on soils that are suitable. There is a pervading difficulty in gaining acceptance for new technologies by farmers, and so strategies such as those suggested by this study may never be implemented at farm scale. Future work must be carried out on the refinement of spreading lands within critical source areas based on soil suitability to receive amended slurry.

Chemical amendment has also been used for the poultry and dairy industries, but may also have the potential to be used in the treatment of wastes from other agricultural industries and sludge from wastewater treatment. If chemical amendment becomes a more prevalent practice, then the cost of employing it as a mitigation measure may decrease, making it an even more attractive option. Although encouraging, the effectiveness of the amendments examined in this study must be validated at field scale.

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Figure Captions

Fig. 1 Histogram of flow-weighted mean concentrations (mg L^{-1}) for dissolved reactive phosphorus (DRP), dissolved un-reactive phosphorus (DUP) and particulate phosphorus (PP) in runoff at time intervals of 12, 24 and 48 h after land application of pig slurry

Fig. 2 Histogram of average flow-weighted mean concentration of suspended solids (SS) (mg L^{-1}) in runoff at time intervals of 12, 24 and 48 h after land application of pig slurry

Table 1 Physical and chemical characteristics[a] of the pig slurry used in this experiment and characteristic values of pig slurry from other farms in Ireland

TP	TN	TK	NH_4^+-N	pH	DM	Reference
	(mg L^{-1})				(%)	
482±37	3,850±20		2250 ±72	7.37 ± 0.07	3.22± 0.15	The present study
800	4,200					S.I. No. 610 of 2010
1630	6,621	2,666			5.77	McCutcheon 1997[b]
900±7	4,600±21	2,600±10			3.2±2.3	O’ Bric 1991[b]

[a] TP total P; TN total N; TK total K; DM dry matter. [b] Values changed to mg L^{-1} assuming densities of 1 kg L^{-1}.

Table 2 Flow-weighted mean concentrations (mg L^{-1}) averaged over three time intervals, application costs per tonne, metal application rate (kg ha^{-1}), and removals (%) for dissolved reactive P (DRP), dissolved un-reactive P (DUP), total dissolved P (TDP), particulate P (PP), total P (TP) and suspended solids (SS)

	DRP mg L^{-1}	Removal %	DUP mg L^{-1}	Removal %	TDP mg L^{-1}	Removal %	PP mg L^{-1}	Removal %	TP mg L^{-1}	Removal %	SS mg L^{-1}	Removal %	Costs € tonne^{-1}	Metals kg ha^{-1}
Soil Only	0.10 ^{a}	-	0.11 ^{a}	-	0.21 ^{a}	-	0.14 ^{a}	-	0.35 ^{a}	-	15.98 ^{a}	-	-	-
Slurry Only	1.34 ^{b}	-	0.60 ^{c}	-	1.94 ^{c}	-	3.85 ^{c}	-	5.78 ^{c}	-	377.60 ^{c}	-	-	-
Alum	0.21 ^{a}	84	0.28 ^{b}	53	0.49 ^{b}	74	1.78 ^{b}	54	2.27 ^{b}	61	101.30 ^{b}	73	150	16.72^{e}
$FeCl_3$	0.21 ^{a}	84	0.19 ^{b}	69	0.40 ^{b}	80	1.48 ^{b}	61	1.88 ^{b}	67	139.94 ^{b}	63	250	16.91^{f}
PAC	0.22 ^{a}	84	0.26 ^{b}	56	0.48 ^{b}	75	2.01 ^{b}	48	2.49 ^{b}	57	135.68 ^{b}	64	280	13.68^{e}

^{abcd} Means in a column, which do not share a superscript, were significantly different ($p < 0.05$). ^{e}Spreading rate of Al. ^{f}Spreading rate of Fe.

Table 3 Comparison of flow-weighted mean concentrations (mg L^{-1}) of TP in runoff from two different soils with identical amendments, spreading rates and TIs[a]

	Soil 1		Soil 2	
Study	Current study		O' Flynn et al. (2012b)	
Soil texture	Sandy loam		Sandy loam	
Organic matter (%)	5±2		13±0.1	
Soil organic carbon (%)	2.8		7.4	
Soil pH	6.4±0.3		7.65±0.06	
Parent material	Granite		Limestone	
P index	1		4	
Morgan's P (mg L^{-1})	2.8±0.5		16.72±3.58	
Runoff results	TP mg L^{-1}	Removal (%)	TP mg L^{-1}	Removal (%)
Soil-only	0.36		0.62	
Slurry-only	3.65		2.68	
PAC	2.77	24%	0.79	71%
Alum	2.08	43%	1.39	48%
$FeCl_3$	2.17	41%	1.14	57%

[a]Runoff results are from rainfall events at TIs of 48 h, which occurred in both studies.

Fig. 1

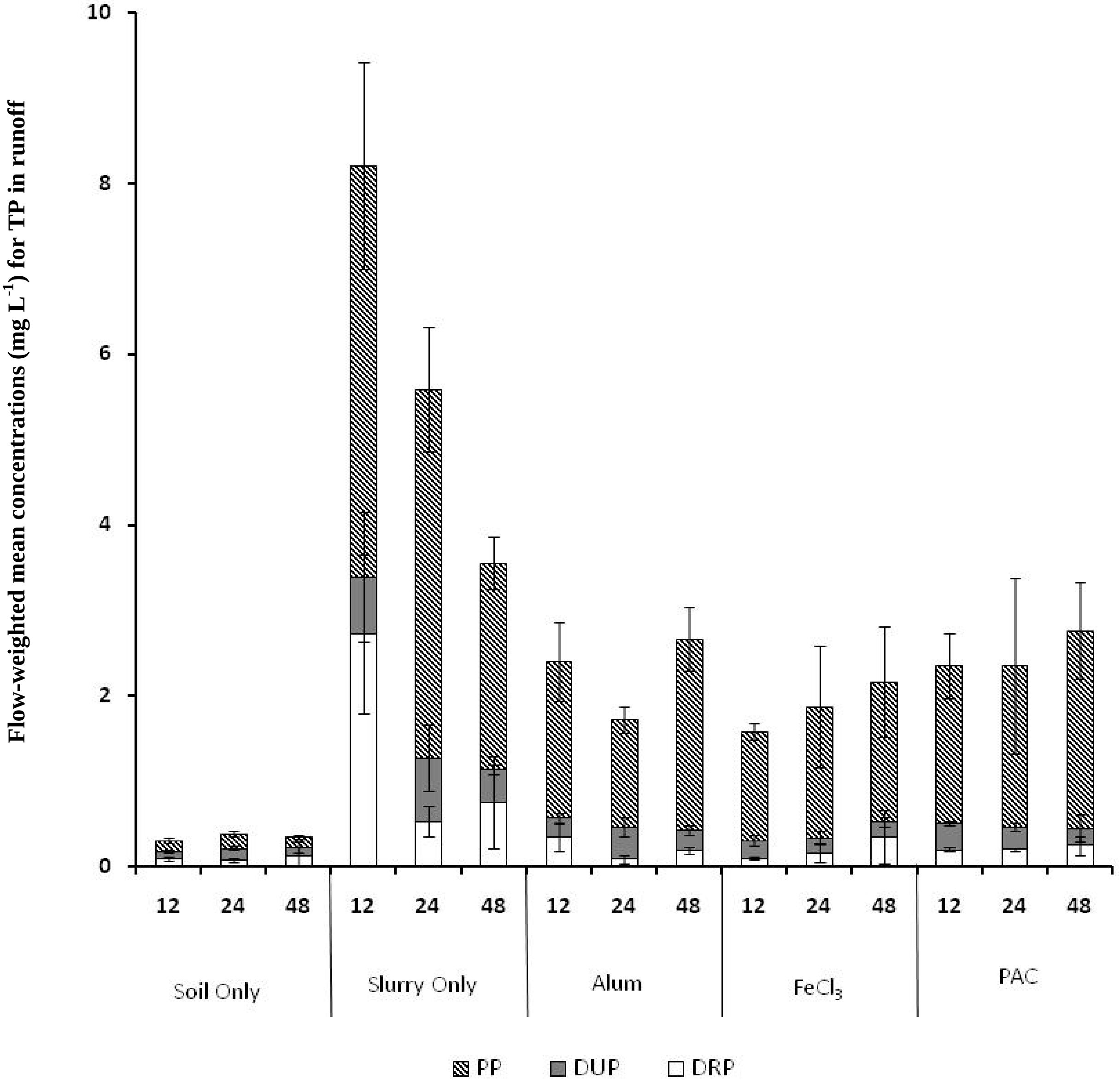
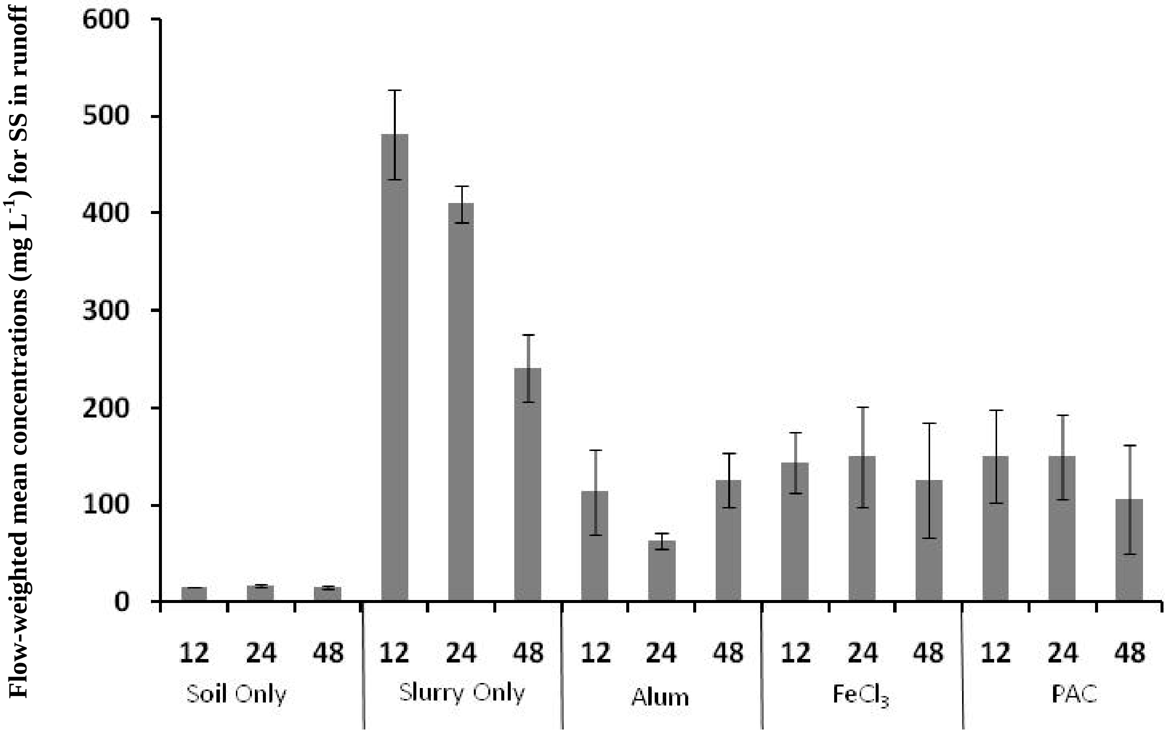

Flow-weighted mean concentrations (mg L^{-1}) for TP in runoff
10
8
6
4
2
0
12
24
48
12
24
48
12
24
48
12
24
48
12
24
48
Soil Only
Slurry Only
Alum
FeCl$_3$
PAC
▨ PP
■ DUP
□ DRP

Fig. 2


Flow-weighted mean concentrations (mg L^{-1}) for SS in runoff
600
500
400
300
200
100
0
12
24
48
12
24
48
12
24
48
12
24
48
12
24
48
Soil Only
Slurry Only
Alum
FeCl$_3$
PAC