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Split phosphorus fertiliser applications as a strategy to reduce incidental phosphorus losses in surface runoff

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Abstract

Organic soils have low sorption capacities for phosphorus (P), and may pose a risk of P loss to water if P applications to these soils coincide with runoff events. Little is known about the magnitude of exports of P in overland flow following application of P fertiliser onto these soils, or on the influence of the frequency on P losses and persistence. The number of P fertiliser applications was surveyed across 39 commercial farms to assess current practice and inform the design of a rainfall runoff experiment to evaluate the effect of frequency of P applications on losses and persistence across time. Superphosphate (16 % P) was applied in single (equivalent to 30 and 55 kg P ha^{-1} applied at day 0) and split (equivalent to 15 and 27.5 kg P ha^{-1} applied in two doses at days 0 and 55) applications to an organic soil inclined at a slope of 6 % in a rainfall simulator experiment. The surface runoff of dissolved reactive phosphorus (DRP) was measured in controlled 30-min rainfall simulations conducted intermittently over an 85-day period. The DRP losses in surface runoff after the first rainfall event were 44.6 and 97.8 mg L^{-1} for single applications of 30 and 55 kg ha^{-1}, respectively, and 13.3 and 21.8 mg L^{-1} for the same rates split in two doses, indicating that single P applications had disproportionately bigger impacts on losses than split applications. This supports the idea that frequent, but smaller, P applications can minimise the impact of fertilisation on waters. Dissolved reactive P concentrations remained significantly higher than those from the control samples until the end the experiment for almost all the P treatments, highlighting the long-lasting effects of added P and the elevated risk of P losses on organic soils. For climates with frequent rainfall events, which are likely to coincide with fertiliser applications, smaller but more frequent P applications can reduce the risk of P transfer as opposed to one single application.

Keywords: frequency, survey, histosols, timing, half-live, histic.

Introduction

Incidental losses of phosphorus (P) to surface waters, originating from recently added fertilisers to agricultural soils, is a significant pressure on water quality that can jeopardise public health and the environment (Hanifzadeh et al., 2017; Delgado and Scalenghe, 2008; Carpenter, 2008; Hart et al., 2004; Haygarth and Jarvis, 1999). The European Union (EU) introduced the Water Framework Directive (WFD) in order to preserve high ecological water status for those water bodies where it already exists, and achieve good ecological status for the remaining water bodies (OJEC, 2000). However, the drive for agricultural intensification across the EU means that marginal soils such as histosols and other peat-derived soils may be brought into production.

Histic soils have a high content of organic matter (OM) and are often derived from partially decomposed wetland vegetation where plant debris accumulated over long periods of time in flooded conditions, before the land was drained for agricultural production (Okruszko and Ilnicki, 2003). These soils are generally moderately acidic with low content of clay minerals and aluminium (Al)/iron (Fe) oxides, and are characterised by poor P sorption and buffering capacities (Daly et al., 2001; Guppy et al., 2005). At European level, they are mainly located in the north-western countries and represent up to 7 % of the total land area (Montanarella et al., 2006). Organic soils account for 1.27 million ha in Ireland, of which more than 65 % are located in upland areas under extensively managed farm enterprises (Renou-Wilson et al., 2011; White et al., 2014). As a result of reclamation of marginal land for grassland production and the application of P fertiliser, P exports from these soils have been reported to be potential major contributors of water deterioration in Ireland (Roberts et al., 2017) and in other parts of the world (Simmonds et al., 2015; Zheng et al., 2014; Guérin et al., 2011; Janardhanan and Daroub, 2010; Castillo and Wright, 2008). However, although some research has been conducted regarding the mechanisms of surface runoff from organic soils (Simmonds et al., 2017; Holden and Burt, 2002), little is known about the potential magnitudes of P loss following P applications nor the mitigation of those losses.

Given the low sorption capacity of organic soils for added P, one of the mechanisms that has been proposed to mitigate P exports is the optimisation of P fertiliser applications in order to better match P requirements with crop demands (Hart et al., 2004). Multiple smaller applications of P fertiliser that account for the same amount of P applied in one single application can both fulfil crop demands and decrease incidental P losses during rainfall-runoff events. However, very little research has reported P losses in this scenario, especially from organic soils. Burkitt et al. (2011) reported this “little and often” approach as a common practice in some parts of Australia, although they did not report consistent data on the number of applications being carried out by landowners. In Ireland, P fertiliser recommendations for mineral soils are based on (1) a national P index that, from an agronomical point of view, classifies soils into *deficient, low, optimum* and *excessive* in available P using Morgan’s P extractant, and (2) the stocking rate, farming system and grassland use of each field (Coulter and Lalor, 2008). Nonetheless, the national P index does not apply for organic soils and they only receive maintenance rates to compensate for P exports in animal and plant products. For both soil types, P can be applied either in one single application or “little and often” through the year.

In this study, we hypothesise that the frequency of P applications on organic/histic soils can reduce the magnitude, decay rate and persistence of P concentrations in runoff following a rainfall event. Therefore, the objectives of this study were to (1) report the results of a farm survey conducted in three different catchments in Ireland on the frequency of P applications that are typically applied (2) using the data from the farm survey, to evaluate P concentrations in runoff from a rainfall simulation experiment where P was applied as single and split applications and at different P doses, and (3) assess the decay rate and persistence of P losses in overland flow derived from the different P applications. To achieve these objectives, a laboratory rainfall-runoff experiment was conducted. Two different P fertiliser applications were applied, in one single dose or split into two, on intact organic soil blocks and subjected to eight simulated rainfall events over a period of 85 days.

Materials and methods

Sites description and farm survey

Farm surveys were carried out in three high status river catchments, namely, the River Urrin in the Southeast, the River Allow in the Southwest, and the River Black in the Midwest of the Republic of Ireland over the 2014/2015 winter period. A total of 39 farms (16, 10 and 13 for the Urrin, Allow and Black catchments, respectively) were surveyed to assess the frequency of P applications of mineral and organic fertilisers across 520 fields. Surveyed data accounted for the number and type of P applications (nitrogen (N)-only fertiliser applications, like CAN or urea, are not included in these data) and the percentage of OM content of each field. As any particular field may have received applications of mineral fertiliser only, organic fertiliser only, or a combination of both types of fertiliser in different proportions, the total numbers of organic and mineral fertiliser applications were calculated. The absolute values were then converted to proportions of the total number of fields with relation to each soil.

Soil sample collection, characterisation and fertiliser application regime

Intact soil blocks, each approximately 0.6 m long, 0.4 m wide and 0.2 m deep, under permanent perennial ryegrass (*Lolium perenne* L.) were collected from a drystock farm in Tuam, Co. Galway (53°3’ N 9° 0’ W) in June 2017. This farm is situated within the River Black catchment, one of the three catchments included in the farm survey (Roberts et al., 2017). Subsamples taken from the same locations as the soil blocks were air dried, sieved through 2-mm mesh, thoroughly homogenised and analysed for physico-chemical properties. Percentage OM was determined using a loss on ignition test at 360° C (Schulte and Hopkins, 1996), particle size analysis was determined with the hydrometer method (ASTMD, 2002), total carbon (C) and N were estimated by combustion (McGeehan and Naylor, 1988), total and plant available P were determined by the acid perchloric digestion (Sommers and Nelson, 1972) and Morgan’s P test (Morgan, 1941) procedures, respectively. Mehlich-3 soil test was used to determine Al, calcium (Ca), Fe and P (Mehlich, 1984). A P saturation ratio (PSR) for organic soils was estimated as $[P/(Al+5*Fe)]_{\text{Mehlich-3}}$, where P, Al and Fe are Mehlich-3 extractable forms on a molar basis (Guérin et al., 2007).

Phosphorus treatments consisted of different rates of P fertiliser in the form of single super-phosphate (16 % P). Artificial fertiliser was chosen as the predominant form of added P over organic fertilisers (slurry) based on the results of the farm survey conducted in this study. Fertiliser recommendations for organic soils in Ireland are limited to maintenance amounts to replace P removed in crop offtakes, which can be up to 30 kg ha^{-1} depending on the stocking rate and/or grazing regime (Coulter and Lalor, 2008). However, in a nutrient management survey published recently (Roberts et al., 2017), added P can be almost 1.5 times higher than the P requirements for organic soils. Based on this, the fertiliser application rates and timings investigated were: one single application of 30 kg P ha^{-1}, a 30 kg P ha^{-1} applied in two split applications of 15 kg P ha^{-1} (one at day 0 and the second at day 55), one single application of 55 kg P ha^{-1} and 55 kg P ha^{-1} applied in two split applications of 27.5 kg P ha^{-1} (one at day 0 and the second at day 55). Each treatment was replicated at n=3, and a study control (soil only, also replicated at three times) was included in the experimental design.

Rainfall simulation setup

The grassed, intact soil cores were trimmed and packed in runoff boxes, each 1 m long by 0.225 m wide by 0.05 m deep, with side walls 2.5 cm higher than the soil surface. Each runoff box was instrumented with three holes, each 0.5 cm in diameter, at the base to facilitate natural drainage of the soil (Regan et al., 2010) and an overflow weir at the end to allow runoff water to be collected in the simulated rainfall experiments. Prior to placing the soil in the runoff boxes, cheese cloth was placed at the base before packing the soil slabs to prevent soil loss through the drainage holes. Typically, two blocks were used to fill each runoff box, and packed to ensure that no gap existed between the cores. Melted candle wax was applied between the walls and the soil surface to seal any gap and avoid runoff losses. The runoff boxes were placed outdoors under natural conditions for two months prior to the start of the experiment to facilitate natural settlement of the cores. Grass in the boxes was trimmed to a length of 4-6 cm before any P treatment application, as typically P fertiliser is applied, along with N fertiliser, after a field has been grazed (Burkitt et al., 2011).

The runoff boxes were placed in a rainfall simulator at a slope of 6 %, similar to the average slope of fields high in OM (> 20 %) of the Roberts et al. (2017) study. The rainfall simulator consisted of a single 1/4HH-SS14SQW nozzle (Spraying Systems Co., Wheaton, IL) attached to a 4.5-m-height metal frame with a rotating disc. The simulator was calibrated to achieve an intensity of 10.2 ± 0.1 mm h^{-1} and a droplet impact energy of 260 kJ mm^{-1} h^{-1} at 90 % uniformity. The water used in the simulations had a dissolved reactive phosphorus (DRP) concentration of less than 0.005 mg L^{-1}. Prior to the start of the experiment, the drainage holes were plugged and the soil was saturated under the simulator until ponding was observed in the surface. The drainage holes were then unplugged to allow the soil to drain freely for 24 h to replicate field conditions before any P application. Due to higher infiltration of water in organic soils compared to mineral soils, drainage holes were plugged at each rainfall simulation to mitigate the direct loss of water in the drainage (Zheng et al., 2014).

After one day, the different P treatments were applied (day 0). Eight rainfall simulations were carried out at days 2, 7, 15, 30, 57, 62, 70 and 85, respectively. Each event lasted for 30 min after continuous runoff was observed. Water in the runoff was collected at 10-min intervals within this 30-min rainfall period and analysed immediately after the end of each simulation. Between each rainfall simulation, the soil boxes were left outdoors under natural weather conditions with the drainage holes unplugged and at a 6 % slope. Temperature and rainfall parameters were recorded from a local weather station (www.iruse.ie).

Water analysis

Water samples were tested for suspended solids (1.2 μm pore size), DRP, total P (TP), total dissolved P (TDP). Suspended solids were measured only for the first three rainfall events and discontinued thereafter as the concentration for all the P treatments (including control) were similar (24.5 ± 5.5 mg L^{-1}) and remained constant over these three first events. Dissolved reactive phosphorus was measured colorimetrically using a nutrient analyser (Konelab 20, Thermo Clinical Laboratories Systems), and TP and TDP were determined after acid persulfate digestion using a BioTector Analyzer (BioTector Analytical Systems Ltd). Dissolved reactive phosphorus and TDP were performed in filtered samples using 0.45-μm filter disks. Particulate P (PP) was calculated by subtracting TDP from TP, and dissolved unreactive P (DUP) was calculated by subtracting DRP from TDP.

Data analysis

Flow weighted mean concentrations (FWMC) were calculated to adjust the variability of the discharge water for each rainfall simulation event using (Cooke et al., 2005):

$$FWMC = \frac{\sum_1^n (v_i \times c_i)}{\sum_1^n v_i} \qquad [1]$$

where v_i is the volume, in litres, in the i^{th} sample and c_i is the concentration, in mg L^{-1}, in the i^{th} sample. A repeated-measures ANOVA was performed in SPSS (IBM SPSS 24 Core Systems) followed by the Tukey's HSD multiple comparison test. Data were log-transformed in order to meet constancy of variance and normality of errors. A monophasic exponential equation was used to model the decay of P concentration in runoff with time:

$$P = \alpha \times e^{-\beta * t} \qquad [2]$$

where P is the concentration of P in runoff (in mg L^{-1}), t is the time in days since P application, and α and β are the equation parameters representing the maximum P (in mg L^{-1}) at time zero and the decay rate of P, respectively. For the split P treatments (2 × 15 kg P ha^{-1} and 2 × 27.5 kg P ha^{-1}), two equations were fit for each portion of the treatments. The regression analyses were conducted using a nonlinear mixed-effects model in *R* statistical software, version 3.4.2 (R Core Team, 2017) using the *nlme* function in the *nlme* package (Pinheiro et al., 2017). From the models generated, the time at which the concentration of P would decrease to 50, 75 and 87.5 % of the maximum (corresponding with the half-life, quarter-life and one-eighth-life of the peak P value, respectively) and the corresponding P concentration were estimated. Additionally, the cumulative P losses (mg L^{-1}) were calculated as the area under the curve for each treatment by integrating Eqn. 2 between time zero and infinity:

$$CP = \frac{\alpha}{\beta} \qquad [3]$$

where α and β are the model parameters in Eqn.2.

Results and discussion

Farm survey

Figure 1 shows the number of fertiliser applications for organic and mineral soils, differentiating between organic and mineral P fertiliser for each application. To our knowledge, this is the first study to survey and report the frequency of P fertiliser applications. From the 520 fields sampled, 456 fields (88 %) were mineral and 64 (12 %) were organic. There were 39 mineral soils (9 %) and 10 organic soils (16 %) that did not receive any P fertiliser application (data not presented in Figure 1). Nearly 40 % of the organic soils received one single application, followed by 28 % and 16 % of the fields receiving two and three applications, respectively, with no further applications beyond this point. Mineral soils had a higher number of P applications, up to seven or eight (with a marginal number of soils receiving nine to eleven applications). These fields were typically under more intense management, with tighter rotational grazing regimes linked to dairy farms and silage and hay production enterprises. By contrast, organic fields were generally under dry stock farms with a more extensive land use.

Regarding the type of fertiliser applied, mineral fertiliser was predominant across the number of fertiliser applications, especially in those soils receiving one single application. This trend was observed in both soil types. For fields receiving two or three applications, the proportion in the use of mineral and organic fertilisers was more balanced. The mineral fertiliser used in the fields receiving two or more applications was typically a combination of different nutrients (NPK) to balance plant offtakes (Roberts et al., 2017).

Organic soils have been reported to have low sorption capacities for P (Guppy et al., 2005; Daly et al., 2001). Therefore, the risk of P losses to adjacent water bodies is high when these soils are placed into agricultural production and receive external P applications to increase grass yields. Phosphorus applied in excess of crop requirements in these soils remains in the soil solution (González Jiménez et al., 2018), so the likelihood of P loss is increased during rainfall events. However, P losses from these soils may be minimised using a combination of timing and rates of P fertiliser applications (González Jiménez et al., 2018; González Jiménez et al., 2019; Roberts et al., 2017).

Soil general properties

Based on the soil profile and the OM content, the soil used in this study was classified as a humic lithosol in the Irish Soil Information System (Creamer et al., 2014), corresponding to a Lithic Leptosol (Humic Eutric) in the FAO World Reference Base System (IUSS Working Group WRB, 2014). Table 1 shows the main physicochemical parameters. The pH was acidic (5.5), likely due to the presence of organic acids arising from the abundant content of OM in the soil (54 %). The PSR of the soil (0.02) was below the 0.05 value at which it is considered to be a threshold for P concentration in runoff (Guérin et al., 2007). The Morgan's P value implies that the soil can be classified as P index 4 (excessive) in the Irish agronomic P index system (Coulter and Lalor, 2008). However, Morgan's extractant has been shown to overestimate P availability in organic soils, likely due to hydrolysation of organic P forms by the acid matrix of the reagent, and hence is not suitable for these types of soils (Roberts et al., 2017).

Phosphorus forms and concentrations in runoff

Among the different forms of P measured in the runoff, DRP was predominant, and on average comprised 89 % of the TP for the P-receiving treatments (65 % for the control). These proportions are consistent with previous studies reporting soluble P in grassland soils, which ranged from 60 to up to 96 % of TP (Kleinman et al., 2002, Nash et al., 2000; Fleming and Cox, 1998; Greenhill et al., 1983). Other studies reported PP as the main form in water runoff using organic P fertiliser such as dairy (Murnane et al., 2015; Brennan et al., 2011) or pig slurry (O'Flynn et al., 2012). The moderately smooth slope at which runoff boxes were subjected in this study, along with the use of soluble commercial P fertiliser and the absence of animals causing damage to the soil, are likely responsible for the low particulate P losses in the overland flow observed (Hart et al., 2004).

Phosphorus treatments, timing of rainfall and their interactions had a significant ($p < 0.001$) effect on the concentration of DRP in the runoff. Among the treatments, FWMC DRP losses in the runoff during the first rainfall event from the single application of 30 kg ha^{-1} (44.6 mg L^{-1}) were more than three times greater than for the first application of its split application, 15 kg ha^{-1} (13.3 mg L^{-1}) (Figure 2). Similarly, FWMC DRP losses were almost five times greater for the single application of 55 kg ha^{-1} (97.8 mg L^{-1}) than from its split application of 27.7 kg ha^{-1} (21.8 mg L^{-1}). This highlights that P applications and losses of P in the runoff were not linearly related. Rather, the concentration of P increased exponentially at higher P applications. Other studies also reported a nonlinear relationship between P applications and P concentration in the overland flow (Burkitt et al., 2011; McDowell and Catto, 2005). This is better illustrated when the parameters of the models generated for each treatment were calculated (Table 2): whilst the maximum FWMC DRP at time zero (α) increased with higher P applications, the decay rate (β) remained relatively constant for the different P applications. For example, the FWMC DRP at day 15 was very similar for all the P applications, despite the large differences in the FWMC DRP between P applications at days 2 and 7. We hypothesise that decay rates may differ among soils of different pedogenesis, depending on the mineralogy and hydrological parameters affecting the P sorption capacity of each soil type.

When the simulated cumulative DRP concentrations are considered (CP in Table 2), the maximum values correspond to the highest P treatments. The CP was higher for the single applications than for the sum of the split treatments (577.0 and 264.7 mg L^{-1} versus 305.7 and 132.3 mg L^{-1} for the 55 and 30 kg ha^{-1} applications, respectively). As FWMC DRP losses in single applications were higher than those obtained from the split applications, the relevance of multiple, but smaller, applications instead of the same total P in one single fertiliser application, may be proposed as a strategy to improve P management and reduce P losses.

The comparison of the results obtained in this study with others is hampered by the lack of previous studies on organic soils reporting P loads in surface runoff following P applications. When compared to analogous studies on mineral soils receiving similar P applications, the P loads from organic soils in the current study were higher. For instance, Burkitt et al. (2011) measured DRP losses in surface runoff of approximately 10 and 4 mg L^{-1} after three days of P application in an oxyaquic hydrosol receiving 40 and 13.3 kg ha^{-1} P fertiliser, respectively, at a rainfall intensity of 50 mm h^{-1}. The results of this research support previous studies indicating that organic soils are regarded as having poor adsorbancy of P (Simmonds et al., 2015; Guppy et al., 2005; Daly et al., 2001). To our knowledge, no study to date has examined incidental P losses in surface runoff after P fertiliser applications in soils with high content of OM, either in field or in laboratory conditions. Hence, this study can be regarded as starting point for further experiments investigating incidental P losses under field conditions following recently applied P fertiliser.

The rainfall regime for a specific region/country that may affect any P application is an important point to consider in any P risk assessments and consequently in the P use management in fields. In Ireland, for example, frequent rainfall events occur across the whole year, with April, May, June and July being the months of least rainfall (national average of 80 mm per month). This increases to 100 mm in February, March, August and September (Walsh, 2012). Additionally, rainfall events are higher in the west of the country, where the majority of peat-derived and other organic soils are located (Hammond, 1981). Therefore, it is likely that a rainfall event will occur close to the time of a P fertiliser application, especially at the beginning of the growing season when the temperature starts to rise

(February-March) and farmers begin to apply organic P (accumulated from the preceding winter session) and/or artificial fertilisers to enhance grass growth. In this scenario, a "little and often" approach may be more desirable as the losses are smaller than in a single application. In regions where there are well-defined dry-rainfall seasons such as those with Mediterranean climates, the likelihood that a rainfall/runoff event will occur outside the dry season may be regarded as low and therefore single applications may be favoured as opposed to split applications.

Decay rate and persistence of phosphorus in runoff

The time to reduce FWMC DRP to half the initial values in the different P treatments ranged between two and three days. In a similar manner, it would take between four and six days and between six and nine days to reduce P concentrations to 75% and 85 % of the initial peak value (Table 2). The estimated FWMC DRP at these decay times were all high, indicating that more time would be required to return to baseline concentrations similar to those measured in the control (no P added) soils. Although P concentrations in surface runoff are not equivalent to those for freshwater quality standards, they may be regarded as guidelines in risk assessment plans (Tierney and O'Boyle, 2018). Despite its potential utility, few studies have reported half times in runoff studies, varying between one and four days (Burkitt et al., 2011; Nash et al., 2005). Nevertheless, decay times, such as the ones estimated in the current study, can be seen as guidelines to ascertain the risk of P losses when the probability of rainfall events is taken into account in local recommendation guidelines.

Dissolved reactive P from the different treatments remained significantly different ($p < 0.01$) over the duration of the experiment when compared with the control, except for the single 30 kg ha^{-1} application on day 85 ($p = 0.08$). Relatively low P applications such as those at 30 kg ha^{-1} had a significant effect on DRP exports which lasted more than 70 days, highlighting the persistent effect that P applications can have on surface runoff. For the split applications, DRP losses were significant for more than 30 days. Hart et al. (2004) reported that the most significant proportion of P exports in runoff on mineral soils may last up to 50 days after P applications. The longer periods of time over which P applications had significant effects in the current study compared to those reported in Hart et al. (2004) may be explained by the low P retention abilities of the organic soil used in this experiment. As previously mentioned, in countries such as Ireland, the probability for a relevant rainfall event to occur close to the time of fertiliser application is high, highlighting the elevated risk of P transfer when P applications are made in one dose compared to a smaller but more frequent approach.

Conclusions

Our initial hypothesis in which frequency of P applications would decrease P loads in runoff was supported by our results, where significantly reduced P concentrations in surface runoff were obtained from split applications compared to the same P amount applied in one single application. This suggests that, in soils with low P sorption abilities such as histic and other peat-derived soils, the ‘little and often’ approach may be regarded as a good strategy to minimise P exports in surface runoff from organic soils following P fertiliser application. In this scenario, the risk of P loss in runoff is closely linked to climatology, so that rainfall events occurring all year around, such as in Ireland and other temperate countries, can drastically affect incidental P losses when they are applied in one single dose rather than smaller, but multiple, applications. However, it has been shown that decay rates at which P was exported in the surface runoff were similar across different P application rates and timings, suggesting that is a characteristic related to the specific ability of the soil to retain P in the overland flow and not added P rates, and therefore the study needs to be extended for other soil types to see the effects of split P fertiliser applications on P exports in surface runoff.

Our results also showed that the time required to reduce P concentration in overland flow to a baseline value can take two to three months, and is likely associated with the limited ability of organic soils to retain added P. The time to reduce peak concentrations to 75 or 85 % ranged between six and nine days from the time of fertiliser application. Knowledge of the time periods of elevated P concentrations in runoff following P fertiliser applications may be used to assess the potential risk of P losses in the event of a forecasted rain event and should be considered in the local nutrient management advice for farms.

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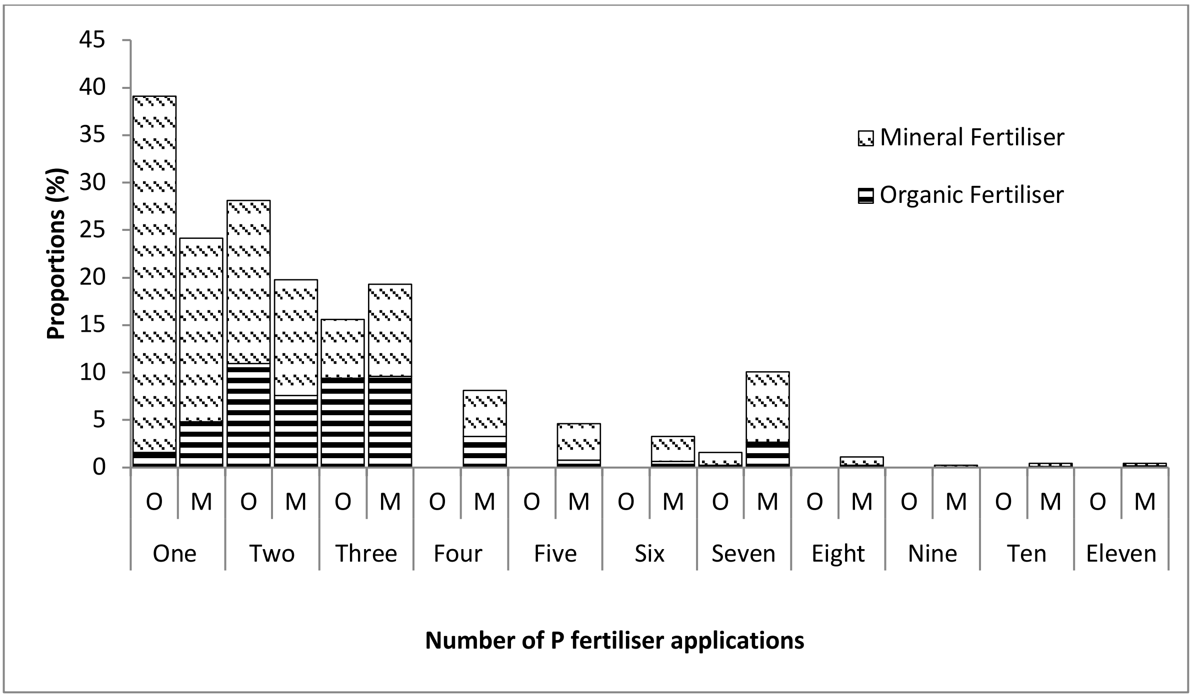

Figure 1. Number of fields (proportion in relation to the total number of organic (n=64) and mineral (n=456) soils) receiving increasing number of P fertiliser applications of organic and/or mineral fertiliser. O = organic soils, M = mineral soils.

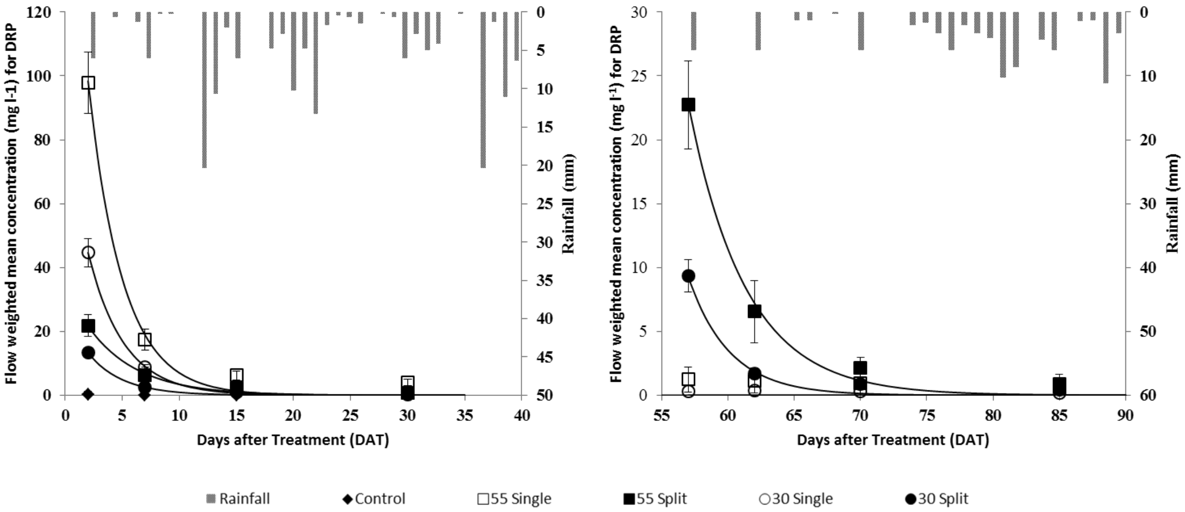

Figure 2. Rainfall (right y-axis) and DRP concentration (left y-axis) in runoff (including standard deviations) for each P fertiliser treatment over a period of 85 days. Fertiliser applications correspond with days 2 (left graph) and 57 (right graph) after treatment.

Table 1. Selected chemical and physical properties of the soil in the rainfall simulations study. Numbers in parenthesis represent standard deviations (n=3)

pH	OM	Particle Size			Texture	Mehlich-3				Total C	Total N	Total P	Morgan's P	PSR[1]
		Clay	Silt	Sand		Al	Fe	Ca	P					
	%					mg Kg^{-1}							mg L^{-1}	
5.5	54.1	13.9	27.3	58.8	Sandy Loam	328.7	350.7	3771.0	29.3	276.8	16.5	884.0	9.1 (2.2)	0.022
(0.3)	(2.1)	(1.5)	(1.6)	(0.5)		(79.6)	(46.5)	(289.1)	(3.1)	(7.7)	(0.1)	(39.5)		(0.001)

[1] Phosphorus saturation ratio

Table 2. Model parameters, time to reach 50, 75 and 87.5 % of the maximum P concentration (as DRP) in runoff, along with the P concentration (as DRP) at these referred times, for the different P fertiliser applications. Numbers in parenthesis represent standard deviations (n=3).

Treatments	**α[1]** mg L^{-1}	**β[2]**	**CP[3]** mg L^{-1}	**t (50 %)** days	**P conc.** mg L^{-1}	**t (75%)** days	**P conc.** mg L^{-1}	**t (87.5%)** days	**P conc.** mg L^{-1}
Single 55 kg ha^{-1}	190.4 (12.7)	0.33 (0.02)	577.0	2.1	95.2	4.2	47.6	6.3	23.8
1st 27.5 kg ha^{-1}	34.2 (2.9)	0.23 (0.02)	148.7	3.0	17.1	6.0	8.5	9.1	4.3
2nd 27.5 kg ha^{-1}	36.1 (4.1)	0.23 (0.02)	157.0	3.0	18	6.0	9.0	8.9	4.5
Single 30 kg ha^{-1}	84.7 (2.1)	0.32 (0.01)	264.7	2.2	42.3	4.3	21.1	6.5	10.6
1st 15 kg ha^{-1}	25.6 (2.2)	0.33 (0.03)	77.6	2.1	12.8	4.2	6.4	6.3	3.2
2nd 15 kg ha^{-1}	17.5 (1.6)	0.32 (0.03)	54.7	2.2	8.8	4.4	4.4	6.6	2.2

[1] α = maximum P (in mg L^{-1}) at time zero. [2] β = decay rate of P. [3] CP= cumulative P, the area under the simulated curve.