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4
5 **Split phosphorus fertiliser applications as a strategy to reduce incidental**
6 **phosphorus losses in surface runoff**

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13
14 **Abstract**

15 Organic soils have low sorption capacities for phosphorus (P), and may pose a risk of P loss
16 to water if P applications to these soils coincide with runoff events. Little is known about the
17 magnitude of exports of P in overland flow following application of P fertiliser onto these
18 soils, or on the influence of the frequency on P losses and persistence. The number of P
19 fertiliser applications was surveyed across 39 commercial farms to assess current practice and
20 inform the design of a rainfall runoff experiment to evaluate the effect of frequency of P
21 applications on losses and persistence across time. Superphosphate (16 % P) was applied in
22 single (equivalent to 30 and 55 kg P ha⁻¹ applied at day 0) and split (equivalent to 15 and 27.5
23 kg P ha⁻¹ applied in two doses at days 0 and 55) applications to an organic soil inclined at a
24 slope of 6 % in a rainfall simulator experiment. The surface runoff of dissolved reactive
25 phosphorus (DRP) was measured in controlled 30-min rainfall simulations conducted

26 intermittently over an 85-day period. The DRP losses in surface runoff after the first rainfall
27 event were 44.6 and 97.8 mg L⁻¹ for single applications of 30 and 55 kg ha⁻¹, respectively,
28 and 13.3 and 21.8 mg L⁻¹ for the same rates split in two doses, indicating that single P
29 applications had disproportionately bigger impacts on losses than split applications. This
30 supports the idea that frequent, but smaller, P applications can minimise the impact of
31 fertilisation on waters. Dissolved reactive P concentrations remained significantly higher than
32 those from the control samples until the end the experiment for almost all the P treatments,
33 highlighting the long-lasting effects of added P and the elevated risk of P losses on organic
34 soils. For climates with frequent rainfall events, which are likely to coincide with fertiliser
35 applications, smaller but more frequent P applications can reduce the risk of P transfer as
36 opposed to one single application.

37

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

39

40 **Introduction**

41 Incidental losses of phosphorus (P) to surface waters, originating from recently added
42 fertilisers to agricultural soils, is a significant pressure on water quality that can jeopardise
43 public health and the environment (Hanifzadeh et al., 2017; Delgado and Scalenghe, 2008;
44 Carpenter, 2008; Hart et al., 2004; Haygarth and Jarvis, 1999). The European Union (EU)
45 introduced the Water Framework Directive (WFD) in order to preserve high ecological water
46 status for those water bodies where it already exists, and achieve good ecological status for
47 the remaining water bodies (OJEC, 2000). However, the drive for agricultural intensification

48 across the EU means that marginal soils such as histosols and other peat-derived soils may be
49 brought into production.

50 Histic soils have a high content of organic matter (OM) and are often derived from partially
51 decomposed wetland vegetation where plant debris accumulated over long periods of time in
52 flooded conditions, before the land was drained for agricultural production (Okruszko and
53 Ilnicki, 2003). These soils are generally moderately acidic with low content of clay minerals
54 and aluminium (Al)/iron (Fe) oxides, and are characterised by poor P sorption and buffering
55 capacities (Daly et al., 2001; Guppy et al., 2005). At European level, they are mainly located
56 in the north-western countries and represent up to 7 % of the total land area (Montanarella et
57 al., 2006). Organic soils account for 1.27 million ha in Ireland, of which more than 65 % are
58 located in upland areas under extensively managed farm enterprises (Renou-Wilson et al.,
59 2011; White et al., 2014). As a result of reclamation of marginal land for grassland
60 production and the application of P fertiliser, P exports from these soils have been reported to
61 be potential major contributors of water deterioration in Ireland (Roberts et al., 2017) and in
62 other parts of the world (Simmonds et al., 2015; Zheng et al., 2014; Guérin et al., 2011;
63 Janardhanan and Daroub, 2010; Castillo and Wright, 2008). However, although some
64 research has been conducted regarding the mechanisms of surface runoff from organic soils
65 (Simmonds et al., 2017; Holden and Burt, 2002), little is known about the potential
66 magnitudes of P loss following P applications nor the mitigation of those losses.

67 Given the low sorption capacity of organic soils for added P, one of the mechanisms that has
68 been proposed to mitigate P exports is the optimisation of P fertiliser applications in order to
69 better match P requirements with crop demands (Hart et al., 2004). Multiple smaller
70 applications of P fertiliser that account for the same amount of P applied in one single
71 application can both fulfil crop demands and decrease incidental P losses during rainfall-
72 runoff events. However, very little research has reported P losses in this scenario, especially

73 from organic soils. Burkitt et al. (2011) reported this “little and often” approach as a common
74 practice in some parts of Australia, although they did not report consistent data on the number
75 of applications being carried out by landowners. In Ireland, P fertiliser recommendations for
76 mineral soils are based on (1) a national P index that, from an agronomical point of view,
77 classifies soils into *deficient*, *low*, *optimum* and *excessive* in available P using Morgan’s P
78 extractant, and (2) the stocking rate, farming system and grassland use of each field (Coulter
79 and Lalor, 2008). Nonetheless, the national P index does not apply for organic soils and they
80 only receive maintenance rates to compensate for P exports in animal and plant products. For
81 both soil types, P can be applied either in one single application or “little and often” through
82 the year.

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

94

95 **Materials and methods**

96 *Sites description and farm survey*

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

108

109 *Soil sample collection, characterisation and fertiliser application regime*

110 Intact soil blocks, each approximately 0.6 m long, 0.4 m wide and 0.2 m deep, under
111 permanent perennial ryegrass (*Lolium perenne* L.) were collected from a drystock farm in
112 Tuam, Co. Galway (53°3' N 9° 0' W) in June 2017. This farm is situated within the River
113 Black catchment, one of the three catchments included in the farm survey (Roberts et al.,
114 2017). Subsamples taken from the same locations as the soil blocks were air dried, sieved
115 through 2-mm mesh, thoroughly homogenised and analysed for physico-chemical properties.
116 Percentage OM was determined using a loss on ignition test at 360° C (Schulte and Hopkins,
117 1996), particle size analysis was determined with the hydrometer method (ASTMD, 2002),
118 total carbon (C) and N were estimated by combustion (McGeehan and Naylor, 1988), total
119 and plant available P were determined by the acid perchloric digestion (Sommers and Nelson,
120 1972) and Morgan's P test (Morgan, 1941) procedures, respectively. Mehlich-3 soil test was

121 used to determine Al, calcium (Ca), Fe and P (Mehlich, 1984). A P saturation ratio (PSR) for
122 organic soils was estimated as $[P/(Al+5*Fe)]_{\text{Mehlich-3}}$, where P, Al and Fe are Mehlich-3
123 extractable forms on a molar basis (Guérin et al., 2007).

124 Phosphorus treatments consisted of different rates of P fertiliser in the form of single super-
125 phosphate (16 % P). Artificial fertiliser was chosen as the predominant form of added P over
126 organic fertilisers (slurry) based on the results of the farm survey conducted in this study.
127 Fertiliser recommendations for organic soils in Ireland are limited to maintenance amounts to
128 replace P removed in crop offtakes, which can be up to 30 kg ha⁻¹ depending on the stocking
129 rate and/or grazing regime (Coulter and Lalor, 2008). However, in a nutrient management
130 survey published recently (Roberts et al., 2017), added P can be almost 1.5 times higher than
131 the P requirements for organic soils. Based on this, the fertiliser application rates and timings
132 investigated were: one single application of 30 kg P ha⁻¹, a 30 kg P ha⁻¹ applied in two split
133 applications of 15 kg P ha⁻¹ (one at day 0 and the second at day 55), one single application of
134 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
135 and the second at day 55). Each treatment was replicated at n=3, and a study control (soil
136 only, also replicated at three times) was included in the experimental design.

137

138 *Rainfall simulation setup*

139 The grassed, intact soil cores were trimmed and packed in runoff boxes, each 1 m long by
140 0.225 m wide by 0.05 m deep, with side walls 2.5 cm higher than the soil surface. Each
141 runoff box was instrumented with three holes, each 0.5 cm in diameter, at the base to
142 facilitate natural drainage of the soil (Regan et al., 2010) and an overflow weir at the end to
143 allow runoff water to be collected in the simulated rainfall experiments. Prior to placing the
144 soil in the runoff boxes, cheese cloth was placed at the base before packing the soil slabs to

145 prevent soil loss through the drainage holes. Typically, two blocks were used to fill each
146 runoff box, and packed to ensure that no gap existed between the cores. Melted candle wax
147 was applied between the walls and the soil surface to seal any gap and avoid runoff losses.
148 The runoff boxes were placed outdoors under natural conditions for two months prior to the
149 start of the experiment to facilitate natural settlement of the cores. Grass in the boxes was
150 trimmed to a length of 4-6 cm before any P treatment application, as typically P fertiliser is
151 applied, along with N fertiliser, after a field has been grazed (Burkitt et al., 2011).

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

164 After one day, the different P treatments were applied (day 0). Eight rainfall simulations were
165 carried out at days 2, 7, 15, 30, 57, 62, 70 and 85, respectively. Each event lasted for 30 min
166 after continuous runoff was observed. Water in the runoff was collected at 10-min intervals
167 within this 30-min rainfall period and analysed immediately after the end of each simulation.
168 Between each rainfall simulation, the soil boxes were left outdoors under natural weather

169 conditions with the drainage holes unplugged and at a 6 % slope. Temperature and rainfall
170 parameters were recorded from a local weather station (www.iruse.ie).

171

172 *Water analysis*

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

183

184 *Data analysis*

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

$$187 \quad FWMC = \frac{\sum_1^n (v_i \times c_i)}{\sum_1^n v_i} \quad [1]$$

188 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
189 i^{th} sample. A repeated-measures ANOVA was performed in SPSS (IBM SPSS 24 Core
190 Systems) followed by the Tukey's HSD multiple comparison test. Data were log-transformed

191 in order to meet constancy of variance and normality of errors. A monophasic exponential
192 equation was used to model the decay of P concentration in runoff with time:

$$193 \quad P = \alpha \times e^{-\beta * t} \quad [2]$$

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

$$206 \quad CP = \frac{\alpha}{\beta} \quad [3]$$

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

208

209 **Results and discussion**

210 *Farm survey*

211 Figure 1 shows the number of fertiliser applications for organic and mineral soils,
212 differentiating between organic and mineral P fertiliser for each application. To our

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

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

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

238

239 *Soil general properties*

240 Based on the soil profile and the OM content, the soil used in this study was classified as a
241 humic lithosol in the Irish Soil Information System (Creamer et al., 2014), corresponding to a
242 Lithic Leptosol (Humic Eutric) in the FAO World Reference Base System (IUSS Working
243 Group WRB, 2014). Table 1 shows the main physicochemical parameters. The pH was acidic
244 (5.5), likely due to the presence of organic acids arising from the abundant content of OM in
245 the soil (54 %). The PSR of the soil (0.02) was below the 0.05 value at which it is considered
246 to be a threshold for P concentration in runoff (Guérin et al., 2007). The Morgan's P value
247 implies that the soil can be classified as P index 4 (excessive) in the Irish agronomic P index
248 system (Coulter and Lalor, 2008). However, Morgan's extractant has been shown to
249 overestimate P availability in organic soils, likely due to hydrolysis of organic P forms by
250 the acid matrix of the reagent, and hence is not suitable for these types of soils (Roberts et al.,
251 2017).

252

253 *Phosphorus forms and concentrations in runoff*

254 Among the different forms of P measured in the runoff, DRP was predominant, and on
255 average comprised 89 % of the TP for the P-receiving treatments (65 % for the control).
256 These proportions are consistent with previous studies reporting soluble P in grassland soils,
257 which ranged from 60 to up to 96 % of TP (Kleinman et al., 2002, Nash et al., 2000; Fleming
258 and Cox, 1998; Greenhill et al., 1983). Other studies reported PP as the main form in water
259 runoff using organic P fertiliser such as dairy (Murnane et al., 2015; Brennan et al., 2011) or
260 pig slurry (O'Flynn et al., 2012). The moderately smooth slope at which runoff boxes were

261 subjected in this study, along with the use of soluble commercial P fertiliser and the absence
262 of animals causing damage to the soil, are likely responsible for the low particulate P losses
263 in the overland flow observed (Hart et al., 2004).

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

282 When the simulated cumulative DRP concentrations are considered (CP in Table 2), the
283 maximum values correspond to the highest P treatments. The CP was higher for the single
284 applications than for the sum of the split treatments (577.0 and 264.7 mg L⁻¹ versus 305.7 and
285 132.3 mg L⁻¹ for the 55 and 30 kg ha⁻¹ applications, respectively). As FWMC DRP losses in

286 single applications were higher than those obtained from the split applications, the relevance
287 of multiple, but smaller, applications instead of the same total P in one single fertiliser
288 application, may be proposed as a strategy to improve P management and reduce P losses.

289 The comparison of the results obtained in this study with others is hampered by the lack of
290 previous studies on organic soils reporting P loads in surface runoff following P applications.
291 When compared to analogous studies on mineral soils receiving similar P applications, the P
292 loads from organic soils in the current study were higher. For instance, Burkitt et al. (2011)
293 measured DRP losses in surface runoff of approximately 10 and 4 mg L⁻¹ after three days of
294 P application in an oxyaquic hydrosol receiving 40 and 13.3 kg ha⁻¹ P fertiliser, respectively,
295 at a rainfall intensity of 50 mm h⁻¹. The results of this research support previous studies
296 indicating that organic soils are regarded as having poor adsorbancy of P (Simmonds et al.,
297 2015; Guppy et al., 2005; Daly et al., 2001). To our knowledge, no study to date has
298 examined incidental P losses in surface runoff after P fertiliser applications in soils with high
299 content of OM, either in field or in laboratory conditions. Hence, this study can be regarded
300 as starting point for further experiments investigating incidental P losses under field
301 conditions following recently applied P fertiliser.

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

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

318

319 *Decay rate and persistence of phosphorus in runoff*

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

332 Dissolved reactive P from the different treatments remained significantly different ($p < 0.01$)
333 over the duration of the experiment when compared with the control, except for the single 30
334 kg ha⁻¹ application on day 85 ($p = 0.08$). Relatively low P applications such as those at 30 kg

335 ha⁻¹ had a significant effect on DRP exports which lasted more than 70 days, highlighting the
336 persistent effect that P applications can have on surface runoff. For the split applications,
337 DRP losses were significant for more than 30 days. Hart et al. (2004) reported that the most
338 significant proportion of P exports in runoff on mineral soils may last up to 50 days after P
339 applications. The longer periods of time over which P applications had significant effects in
340 the current study compared to those reported in Hart et al. (2004) may be explained by the
341 low P retention abilities of the organic soil used in this experiment. As previously mentioned,
342 in countries such as Ireland, the probability for a relevant rainfall event to occur close to the
343 time of fertiliser application is high, highlighting the elevated risk of P transfer when P
344 applications are made in one dose compared to a smaller but more frequent approach.

345

346 **Conclusions**

347 Our initial hypothesis in which frequency of P applications would decrease P loads in runoff
348 was supported by our results, where significantly reduced P concentrations in surface runoff
349 were obtained from split applications compared to the same P amount applied in one single
350 application. This suggests that, in soils with low P sorption abilities such as histic and other
351 peat-derived soils, the ‘little and often’ approach may be regarded as a good strategy to
352 minimise P exports in surface runoff from organic soils following P fertiliser application. In
353 this scenario, the risk of P loss in runoff is closely linked to climatology, so that rainfall
354 events occurring all year around, such as in Ireland and other temperate countries, can
355 drastically affect incidental P losses when they are applied in one single dose rather than
356 smaller, but multiple, applications. However, it has been shown that decay rates at which P
357 was exported in the surface runoff were similar across different P application rates and
358 timings, suggesting that is a characteristic related to the specific ability of the soil to retain P

359 in the overland flow and not added P rates, and therefore the study needs to be extended for
360 other soil types to see the effects of split P fertiliser applications on P exports in surface
361 runoff.

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

369

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378

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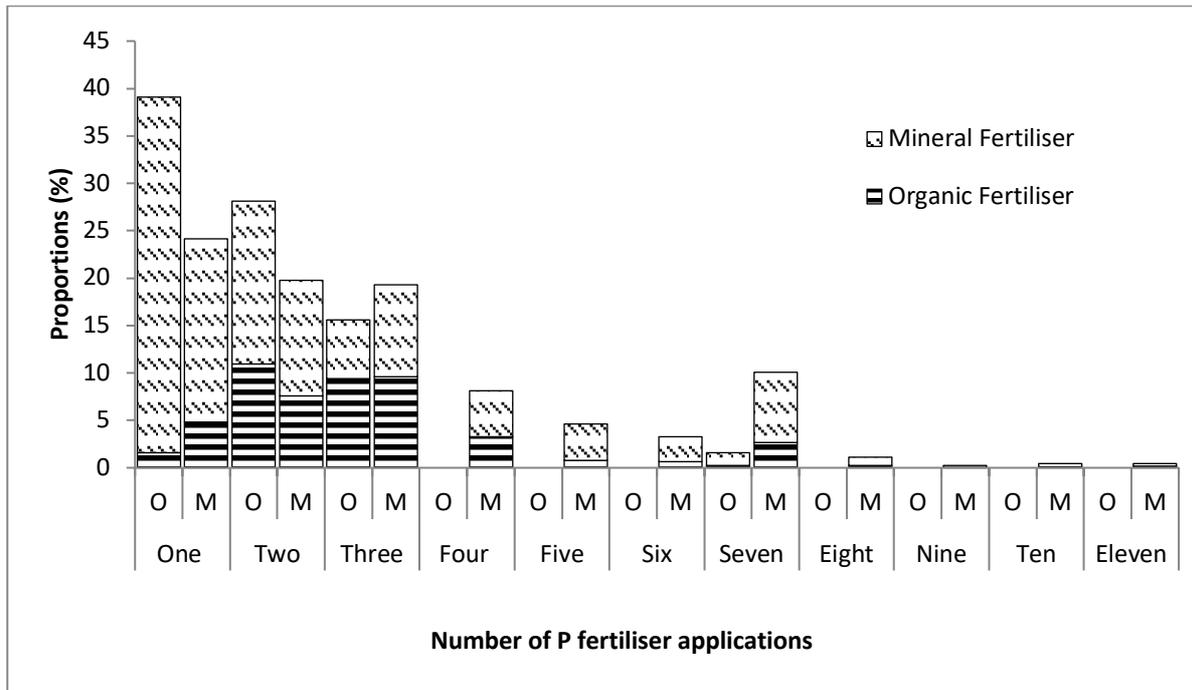
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531 **Figure 1.** Number of fields (proportion in relation to the total number of organic (n=64) and
 532 mineral (n=456) soils) receiving increasing number of P fertiliser applications of organic
 533 and/or mineral fertiliser. O = organic soils,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

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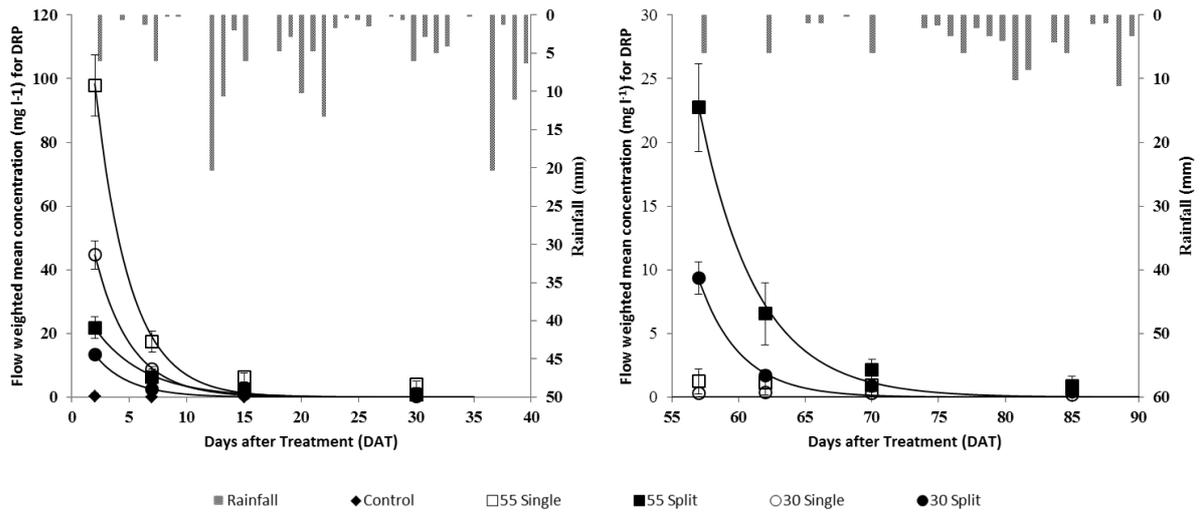
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550 **Figure 2.** Rainfall (right y-axis) and DRP concentration (left y-axis) in runoff (including
 551 standard deviations) for each P fertiliser treatment over a period of 85 days. Fertiliser
 552 applications correspond with days 2 (left graph)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

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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 (0.3)	54.1 (2.1)	13.9 (1.5)	27.3 (1.6)	58.8 (0.5)	Sandy Loam	328.7 (79.6)	350.7 (46.5)	3771.0 (289.1)	29.3 (3.1)	276.8 (7.7)	16.5 (0.1)	884.0 (39.5)	9.1 (2.2)	0.022 (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
1 st 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
2 nd 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
1 st 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
2 nd 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.