



## **Phosphorus and nitrogen leaching from an organic and a mineral soil receiving single and split dairy slurry applications: A laboratory column experiment**

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4 **Phosphorus and nitrogen leaching from an organic and a mineral soil**  
5 **receiving single and split dairy slurry applications: A laboratory column**  
6 **experiment**

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14  
15 **Abstract**

16 Purpose:

17 Intensification of farming means that organic soils, of low phosphorus (P) holding capacity,  
18 are being brought into production. Consequently, farmers may have to adjust their fertiliser  
19 application regimes to reduce environmental risk. The aim of this paper is to test the hypothesis  
20 that overall loads of P and nitrogen are smaller when applications are split in two compared to  
21 a single application.

22 Materials and Methods:

23 A laboratory column experiment was conducted in which two soils, one organic and one  
24 mineral, were exposed to dairy slurry applications of 15, 30 and 55 kg P ha<sup>-1</sup> applied in one  
25 single application or split into two applications. The columns were uniformly irrigated weekly  
26 with 160 mL of distilled water (equivalent to average precipitation in Ireland) and the leached  
27 water was analysed for nutrients.

28 Results and Discussion:

29 There were no significant cumulative P loads in the leached water for any soil type or treatment  
30 (minimum and maximum values ranging from 0.04-0.12 kg dissolved reactive phosphorus  
31 (DRP) ha<sup>-1</sup> and 0.09-0.14 kg DRP ha<sup>-1</sup> for the organic and mineral soil, respectively, and 1.5-  
32 1.8 kg total phosphorus (TP) ha<sup>-1</sup> and 1.8-2.9 kg TP ha<sup>-1</sup> for the organic and mineral soil,  
33 respectively). There was high ammonium-N retention within the organic soil (0.2-0.4 kg ha<sup>-1</sup>,  
34 compared to 15.0-36.8 ha<sup>-1</sup> for mineral soils in the leached water). Nitrate-N loads were higher  
35 from the organic soil (6.5-105.3 ha<sup>-1</sup>) than the mineral soil (9.7-17.4 ha<sup>-1</sup>), although for both  
36 soils, loads from the amended columns were lower than the controls (110.7 and 20.1 NO<sub>3</sub>-N  
37 ha<sup>-1</sup> for the organic and mineral soil, respectively).

38 Conclusions:

39 The overall finding of this study was that split slurry applications had little effect on nutrient  
40 exports when compared to single applications, making the amounts of slurry applied, and not  
41 the application regime, the predominant factor in nutrient loss.

42

43 **Keywords:** Phosphorus; nitrogen; leaching; organic soil; mineral soil.

44

45 **1. Introduction**

46 Land application of animal-derived manures such as dairy slurry is a common practice to  
47 improve soil fertility, but it may also pose a risk of phosphorus (P) and nitrogen (N) losses to  
48 the surrounding waters (Wang et al. 2019). Although surface runoff is considered to be the  
49 main pathway of nutrient losses from fertiliser applications, especially followed by rainfall  
50 events, leachate or subsurface processes may also play an important role in these incidental,  
51 diffuse transfers of P and N from agricultural soils to waters (Hart et al. 2004).

52 With intensification of agricultural practices across Europe, marginal soils such as peat soils  
53 and other peat-derived soils are being cultivated to meet food demands. Organic soils have low  
54 P retention properties due to intense competition reactions of organic acids for the scarce  
55 cationic sorption sites of the mineral fraction (Gerke 2010). Moreover, organic soils have a low  
56 bulk density and can develop significant preferential subsurface flow pathways due to their  
57 high hydrophobicity when they are exposed to drying and wetting processes (Riddle et al. 2018;  
58 Simmonds et al. 2017).

59 Organic soils account for approximately 7 % of the total land area in Europe, of which the  
60 Scandinavian countries and north-west Europe are among the countries with the highest  
61 representation of these soils in their territories. Different management strategies to mitigate P  
62 transport from the source to the surrounding water bodies have been proposed, such as  
63 environmental soil P testing, matching P applications with crop requirements, and timing of  
64 fertilisation to avoid the concurrence of elevated moist soil conditions with fertiliser  
65 applications (Macintosh et al. 2018). Similarly, various strategies have been employed to  
66 reduce N leaching and runoff such as reduced N fertilisation (Constantin et al. 2010). Smaller,  
67 but more frequent applications, of fertiliser has been proposed as a measure to reduce P exports  
68 from the soil in temperate regions where frequent rainfalls are likely to occur throughout the  
69 whole year (González Jiménez et al. 2019). However, few studies have been conducted in  
70 organic soils receiving frequent but smaller fertiliser applications, and the potential impact of

71 subsurface transfer of P and N in these soils under this management strategy remains poorly  
72 understood.

73 The hypothesis of this paper is that soils with elevated organic matter (OM) content have higher  
74 P and N loads in leached water than mineral soils when dairy slurry is applied. Therefore, the  
75 aim was to examine losses of P and N in leached water from a laboratory-scale column  
76 experiment following single and split applications of dairy slurry at different doses to soils of  
77 contrasting OM content. To test this hypothesis and address the study objectives, a laboratory  
78 leachate column experiment was conducted. Three rates of dairy slurry were applied in one  
79 single dose and in split doses on disturbed soil columns containing either a mineral or organic  
80 soil.

## 81 **2. Materials and methods**

### 82 *2.1 Soil collection and analysis*

83 Organic and mineral soils were collected from two dry-stock farms located in a “high status”  
84 catchment in the south east of Ireland (52° 17' N, 6° 29' W). Approximately 150 kg of each  
85 soil type was collected from the top 0.2 m, air-dried, manually sieved to pass a 2 mm sieve,  
86 and thoroughly mixed. A subsample from each soil type was analysed for physico-chemical  
87 properties. At the time of soil collection, intact soil cores (n=3) were taken to determine fresh  
88 bulk density and gravimetric water content, according to British standards (BS 1377-2 1990).

89 Cation exchange capacity (CEC) was estimated using the method described by Ross (1995).  
90 pH (1:1 in H<sub>2</sub>O) was determined according to McLean (1982). Total OM was determined using  
91 the loss on ignition test at 360° C (Schulte and Hopkins 1996). Total C and N were estimated  
92 by combustion (McGeehan and Naylor 1988). Total and plant available P were determined by  
93 the acid perchloric digestion (Sommers and Nelson 1972) and the Morgan's P test (Morgan,

1941) procedures, respectively. Particle size analysis was determined using the hydrometer method (ASTMD 2002). The Mehlich-3 soil test was used to determine extractable aluminium (Al), calcium (Ca), iron (Fe) and P (Mehlich 1984). As a measure of the degree of P saturation of the soils, the P saturation ratio (PSR) for acidic soils was calculated using:

$$[P/(Al+\gamma*Fe)]_{\text{Mehlich-3}} \quad [1]$$

where P, Al and Fe are Mehlich-3 extractable forms on a molar basis and  $\gamma$  is a weighing factor, set at 1 for the mineral soil and 5 for the organic soil, to compensate for the low extraction efficiency of Fe in organic soils (Gu erin et al. 2007).

Additionally, P sorption isotherm experiments were conducted to determine the total sorption and bonding capacities of both soils. Twenty-five mL of varying concentrations (0, 5, 10, 30 and 60 mg P L<sup>-1</sup>) of a KH<sub>2</sub>PO<sub>4</sub> stock solution were added to 50 mL polyethylene centrifuge tubes each containing 1 g of soil (n=3). Samples were shaken for 24 h at 250 rpm in a reciprocating shaker, allowed to settle for 1 h, filtered through a 0.45  m membrane filter, and the filtrate was analysed for dissolved reactive phosphorus (DRP) using a nutrient analyser (Konelab 20, Thermo Clinical Lab systems, Finland). A linearized Langmuir adsorption equation (Kovar and Pierzynski, 2009) was used to fit the data:

$$\frac{C}{S} = \frac{1}{kS_{max}} + \frac{C}{S_{max}} \quad [2]$$

where  $C$  is the concentration of P after equilibration (in mg L<sup>-1</sup>) and  $S$  is the total amount of P retained (mg kg<sup>-1</sup>),  $S_{max}$  represents the maximum amount of P that can be sorbed by the soil (mg kg<sup>-1</sup>), and  $k$  is a constant related to the bond strength of added P to soil (L mg<sup>-1</sup> P).

## 117 2.2 Slurry collection and analysis

118 Dairy slurry was collected in one 20 L capacity drum from the Teagasc Agricultural Research  
119 Centre, Moorepark, Fermoy, Co. Cork, and kept refrigerated ( $10 \pm 1$  °C) prior to the start of  
120 the experiment. Homogenised subsamples were tested in triplicate for total P (TP), total N  
121 (TN), DRP, ammonium ( $\text{NH}_4$ ), pH and dry matter (DM). Total P and TN were measured using  
122 acid persulfate digestion and by combustion oxidation, respectively. Dry matter was measured  
123 by drying at  $105^\circ\text{C}$  for 24 h and pH was determined using a pH probe (WTW). A subsample  
124 of fresh slurry was centrifuged before being filtered ( $0.45\ \mu\text{m}$ ) and analysed for DRP and  $\text{NH}_4$ .  
125 All the parameters were determined using the standard methods (APHA 2005).

## 126 2.3 Soil columns setup

127 Prior to placement in the columns, the gravimetric water content of the two soils was modified  
128 using distilled water to attain the same value as that measured at the time of sampling. The soil  
129 was packed in forty-two 0.3-m deep and 0.104-m internal diameter PVC columns (21 for each  
130 soil type), each with perforated bases to allow free drainage. A 0.05-m layer of gravel was  
131 placed at the bottom of the columns, which was overlain by 0.2 m of soil, compacted in 0.05  
132 m depth intervals, to attain the same fresh bulk density as obtained in the field. At each depth  
133 interval, the soil was pressed against the column to avoid the occurrence of preferential flow  
134 paths. Re-packed soil columns are commonly used in research studies (Hou et al. 2018;  
135 Mazloomi and Jalali 2019; Miri et al. 2022). Although intact, undisturbed soil columns are  
136 preferable, compression of the soil (and, in particular, organic soils) is probable without  
137 specialised equipment. Therefore, re-packed soil columns, in which the soil is allowed  
138 adequate time to consolidate before the experiment begins, are used.

139 The experiment was conducted in a temperature ( $10 \pm 1$  °C) and humidity ( $85 \pm 8$  %)-  
140 controlled room, representative of average climatic conditions in Ireland (Walsh 2012). Each

141 column was irrigated weekly with 160 mL of distilled water, applied homogeneously onto the  
142 surface in two aliquots each of 80 mL over a 2-h period. This rate of water addition was  
143 representative of the yearly average precipitation in Ireland (19 mm per week, 988 mm per  
144 year; Walsh 2012). Distilled water was used to ensure consistency in water chemistry, as the  
145 chemistry of rainwater changes over time due to anthropogenic and terrestrial effects  
146 (Keresztesi et al., 2020). Prior to the start of the experiment, the columns were allowed to  
147 incubate for a period of 16 weeks to stabilise the pulse in N mineralisation following drying  
148 and wetting processes in the soil.

149 The treatments (each at n=3) examined were: (1) one single application of 15 kg P ha<sup>-1</sup> (11.8  
150 mg P column<sup>-1</sup>) (2) a 15 kg P ha<sup>-1</sup> applied in two split applications of 7.5 kg P ha<sup>-1</sup> (5.9 mg P  
151 column<sup>-1</sup>) each (3) one single application of 30 kg P ha<sup>-1</sup> (23.6 mg P column<sup>-1</sup>) (4) a 30 kg P  
152 ha<sup>-1</sup> applied in two split applications of 15 kg P ha<sup>-1</sup> (11.8 mg P column<sup>-1</sup>) each (5) one single  
153 application of 55 kg P ha<sup>-1</sup> (43.2 mg P column<sup>-1</sup>) (6) 55 kg P ha<sup>-1</sup> applied in two split  
154 applications of 27.5 kg P ha<sup>-1</sup> (21.6 mg P column<sup>-1</sup>) each, and (7) a study control (soil only).  
155 Based on the content of TP of the dairy slurry, the amounts of slurry applied were 36, 72 and  
156 132 g for the single 15, 30 and 55 kg ha<sup>-1</sup>, respectively, and 18, 36 and 66 g for the split  
157 applications. The amount of TN added was 64.6, 129.2 and 236.9 kg ha<sup>-1</sup> for applications of  
158 15, 30 and 55 kg P ha<sup>-1</sup>, respectively. The duration of the experiment was 34 weeks.

159 Single applications were made after the incubation period, at week 17, and split applications  
160 on week 17 and 25, respectively. The doses were selected based on current fertiliser  
161 recommendations on organic soils in Ireland, where the maximum allowance for P is 30 kg P  
162 ha<sup>-1</sup>, depending on the stocking rate and/or grazing regime (Wall and Plunkett 2021). However,  
163 a recent survey of farms with these soil types reported that the actual P applied may be up to  
164 1.5 times higher than the advised amounts for organic soils (Roberts et al. 2017).



165 *2.4 Leachate collection and analysis*

166 Leached water was collected in plastic containers using funnels placed beneath each column.  
167 Volumes of leached water were measured and homogenised before subsampling. Unfiltered  
168 subsamples were analysed for TP using a Biotector Analyser (Biotector Analytical Systems  
169 Ltd) and the pH was measured using a pH probe (WTW). Filtered subsamples (0.45- $\mu\text{m}$  pore  
170 size) were analysed for DRP,  $\text{NH}_4\text{-N}$ , total oxidised nitrogen (TON) and nitrite-N ( $\text{NO}_2\text{-N}$ )  
171 using a nutrient analyser (Konelab 20, Thermo Clinical Laboratories Systems, Finland), and  
172 total dissolved P (TDP) using a Biotector analyser (Biotector Analytical Systems Ltd). Nitrate-  
173 N ( $\text{NO}_3\text{-N}$ ) was calculated as the difference between TON and  $\text{NO}_2\text{-N}$ , dissolved unreactive P  
174 (DUP) as the difference between TDP and DRP, and total particulate P (TPP) as the difference  
175 between TP and TDP (APHA 2005; Murnane et al. 2018).

176 *2.5 Data analysis*

177 Each week, the cumulative mass of leached water from every column was measured and tested  
178 for the water quality parameters of interest. This enabled the mass release from each column  
179 to be measured and expressed as a loss per unit surface area of each column. Each cumulative  
180 curve was fitted using a 3-parameter logistic function:

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182 
$$y = \frac{a}{1+be^{-cx}} \quad [3]$$

183 where a, b and c are the function parameters. In addition, a 95 % confidence band was  
184 calculated using the delta method (Bates & Watts, 2011) and added to each of the curves to  
185 express uncertainty in the estimates. The regression analyses were performed following the  
186 non-linear least squares method using the function *nls* in R statistical software, version 4.0.5

187 (R Core Team, 2021), whereas the confidence bands were calculated using the *predict2\_nls*  
188 function of the *nltraa* package (Fernando Miguez, 2022).

189 These data were then extrapolated to produce a weekly gravimetric loss per hectare ( $\text{kg ha}^{-1}$ )  
190 for each treatment. Additionally, in order to estimate the percentage of the nutrients applied  
191 that was released in the leached water, a mass balance was estimated for P and N as the  
192 difference between the cumulative losses of each nutrient and the control soil divided by the  
193 amount of the nutrient applied at each slurry treatment. Despite the repeated nature of the  
194 measurements, the use of the maximum (total) cumulative values of each nutrient as a single  
195 meaningful measure reduced the multivariate response to an univariate response, thus enabling  
196 the use of classical analysis methods (Davis 2002). The data were subjected to normality using  
197 a Shapiro-Wilk test and homogeneity of variance using Levine's test. Differences in the loads  
198 in leachate ( $\text{kg ha}^{-1}$ ) within and between factors (soil type and slurry applications) were  
199 evaluated using a two-way (model 2) ANOVA, and simple effects analyses were performed by  
200 the Bonferroni test at  $\alpha=0.05$  when the main and/or interaction effects were significant ( $p <$   
201  $0.05$ ). Data analyses were performed in SPSS (IBM SPSS 24 Core Systems) using the GLM-  
202 Univariate procedure.

203

### 204 **3. Results and discussion**

#### 205 *3.1 Soil and slurry characteristics*

206 Table 1 shows selected physical and chemical properties of both soils and their Langmuir  
207 equation parameters. The organic and mineral soils were classified as a humic lithosol and  
208 typical brown earth, respectively, under the Irish soil classification system (Creamer et al.  
209 2014), whose equivalents to the FAO soil classification system (IUSS Working Group WRB,

210 2014) are lithic leptosol and haplic phaeozem. The organic soil had nearly seven times more  
211 OM content than the mineral soil, although the Mehlich-III extractable Ca was slightly lower,  
212 yielding a moderately acidic pH for the former (5.5) and near-to neutral pH for the latter (6.3).  
213 The P sorption ability ( $S_{max}$ ) of the organic soil (1278 mg kg<sup>-1</sup>) was higher than in the mineral  
214 soil (896 mg kg<sup>-1</sup>), whilst the constant  $k$ , related to the bonding energy of added P to soil  
215 sorption sites, was similar in both soils (Table 1). The lower  $S_{max}$  of the mineral soil may have  
216 been partly attributable to its higher pH compared to the organic soil. pH has been shown to be  
217 inversely related to the  $S_{max}$  due to the alteration of the forms of P-fixing compounds such as  
218 clays and Al and Fe oxides that lead to desorption processes; lower soil pH favours the presence  
219 of free iron and aluminium oxides in soil matrix, whereas higher pH (6.5 – 7.5) exerts an  
220 opposite effect, lowering the concentration of free iron and aluminium oxides (Roy and De  
221 Datta, 1985). However, it is likely that the main reason for the higher P-sorption ability of the  
222 organic soil over the mineral soil is due to the activation of new sorption sites that were  
223 occluded by the native OM of the soil by the breaking of the soil structure when it was sieved  
224 prior packing in the columns, as it will be explained in the next subsection.

225 Mehlich-3 extractable P concentrations were low-to-optimum for the organic soil (29.3 mg kg<sup>-1</sup>)  
226 <sup>1</sup>) with respect to agronomic recommendations (Mallarino et al. 2013) and very high for the  
227 mineral soil (72.3 mg kg<sup>-1</sup>), possibly due to excessive fertiliser applications in the years prior  
228 to sample collection. The PSR of the mineral soil (0.084) was above the critical threshold of  
229 0.05, indicating a potential source of P losses (Guérin et al. 2007). Despite  $S_{max}$  in the organic  
230 soil being higher than in the mineral soil, the degree of P saturation (as measured by the PSR)  
231 was more elevated for the latter, indicating that P was less strongly retained by the mineral soil  
232 (Beauchemin and Simard, 1999). This seems to be in contradiction with the  $k$  values obtained  
233 from the Langmuir equation, where mineral soil had a slightly higher bonding energy compared  
234 to the organic soil (Table 1). As defined in equation [2],  $k$  is a constant derived from the

235 sorption isotherms where increasing amounts of P are added to the soil, thus reflecting the  
236 overall binding energy across all the saturation process derived from the sorption isotherm  
237 trials. However, this constant may not necessarily reflect the binding energy of P to the soil at  
238 a specific, intermediate phase of the saturation process.

239 The ratio of TP to DRP in the dairy slurry was approximately 11:1, which implies that most of  
240 the P in the slurry was in the form of TPP and/or DUP. A low concentration of soluble P relative  
241 to the total P in dairy cattle slurry has been observed elsewhere (Brennan et al. 2014, 2011).

### 242 *3.2 Phosphorus in leachate*

243 Considering the organic soil, with the exception of the single application of 55 kg ha<sup>-1</sup> (Figure  
244 1 - A1), there was no statistically significant difference ( $p > 0.05$ ) in the mass of DRP released  
245 between the slurry treatments and the study control. Similarly, there were no statistically  
246 significant differences in the DRP mass released across all treatments from the mineral soil  
247 (Figure 1 - B1). Comparing the mass of DRP released from both soils when subjected to the  
248 same application rate, there were no statistically significant differences for the control, single  
249 55 and split 55 kg ha<sup>-1</sup> applications ( $p > 0.05$ ), suggesting that DRP losses in the leachate at  
250 these slurry applications (no slurry application in the case of the control) were of the same  
251 magnitude for both soils. However, mineral soil had significantly higher DRP releases in the  
252 single 15, single 30, split 15 and split 30 kg ha<sup>-1</sup> treatments than the equivalent treatments in  
253 the organic soil.

254 With regard to TP, treatment had no impact on the mass release from the organic soil (Figure  
255 1 - A2), whereas there were significant differences between the control and the single 30 and  
256 single 55 kg ha<sup>-1</sup> treatments in the mineral soil (Figure 1 - B2). In general, the amounts of P  
257 losses observed in this study are somewhat lower than other similar leachate studies in which  
258 undisturbed organic and mineral soils columns were used. For example, Parvage et al. (2015)

259 reported TP losses of 6.72 kg ha<sup>-1</sup> after three days of continuous leachate from peat soil columns  
260 receiving 22 kg P ha<sup>-1</sup> in the form of composted horse manure. In comparison, TP losses in the  
261 current study were lower than 2 kg ha<sup>-1</sup> after a much longer period of 19 weeks. Despite the  
262 higher  $S_{max}$  of the organic soil compared to the mineral soil in this experiment, the maximum  
263 amount of P that can be retained by each soil is higher for the mineral soil than for the organic  
264 soil due to the higher bulk density of the mineral soil compared to the organic soils. Thus, for  
265 the organic soil, the proportion of P applied in the slurry was 1.94, 3.88 and 7.11 % of the  $S_{max}$   
266 for the 15, 30 and 55 kg ha<sup>-1</sup> treatments, respectively. For the mineral soil, the proportions were  
267 0.98, 1.78 and 3.26 % of the  $S_{max}$ . When the amount of TP released in leachate is calculated  
268 as the percentage of what was applied in the slurry (Table 2), most of the TP applied was  
269 retained in the soils, with percentages lower than 2 % for the organic soil. For the mineral soil  
270 the values were similar, although a 7.3 % recovery was obtained for the 15 split applications.

271 Although organic soils are considered to have low sorption capacities for P due to competition  
272 between phosphate anions and humic/fulvic acids and occlusion of OM for sorption sites  
273 (Guppy et al. 2005), the amounts of P obtained in leachate highlight the elevated ability of the  
274 organic soil used in this study to retain freshly added P. The disruption of the soil structure  
275 when packing the columns, with the breakage of soil aggregates, likely enhanced the ability of  
276 the soil to immobilise soluble P applied in the slurry by the activation of sorption sites that  
277 were occluded by the native OM of the soil (Margenot et al. 2017; Muukkonen et al. 2009).  
278 Disturbed soil columns may have created new reaction surfaces and, consequently, increased  
279 the soils' ability to sorb: the presence of new carbonates (Sø et al. 2011), clay minerals (Gérard  
280 2016), and Al and Fe oxide (Antelo et al. 2007) sorption sites from the breakage of the soil  
281 aggregates may have further promoted the P retention capacity. In the case of Al and Fe oxides,  
282 this enhanced sorption ability may have been promoted by the formation of tertiary compounds  
283 between the metals and organic acids, especially abundant in soils with high OM content

284 (Riddle et al. 2018). Additionally, in organic soils, subsurface flow is the predominant path of  
285 P transport due to the tendency to develop macropores and cracks following drying and wetting  
286 cycles under natural conditions as a consequence of its hydrophobicity (Simmonds et al. 2017;  
287 Litaor et al. 2006). Disturbed organic soils likely destroyed the pore network, and therefore  
288 contributed to the observed small mass release of P in the leachate.

### 289 *3.3 Nitrogen in leachate*

290 The ANOVA analysis showed no statistical difference ( $p > 0.05$ ) in the  $\text{NH}_4\text{-N}$  loads between  
291 the different treatments and the control in the organic soil, except for the single  $55 \text{ kg ha}^{-1}$   
292 treatment (Figure 2 - A1). For the mineral soil, single applications of 30 and  $55 \text{ kg ha}^{-1}$  and the  
293 split application of 55 had a statistically significant effect ( $p < 0.001$ ) on the  $\text{NH}_4\text{-N}$  loads  
294 compared to the control (Figure 2 - B1), raising them in all cases. Among soils,  $\text{NH}_4\text{-N}$  loads  
295 in the leachate water were significantly higher ( $p < 0.001$ ) in the mineral soil than the organic  
296 soil. The  $\text{NH}_4\text{-N}$  in the leachate from the mineral soil ranged from 6 to  $36 \text{ kg ha}^{-1}$  compared to  
297 the very low values for the organic soil, which ranged from 0.1 to  $0.3 \text{ kg ha}^{-1}$ . The  $\text{NH}_4\text{-N}$   
298 released in leached water as a percentage of the  $\text{NH}_4\text{-N}$  applied in the slurry was lower than 1  
299 % in the organic soil, but ranged from 18 to 54 % in the mineral soil (Table 3). Therefore, it is  
300 likely that  $\text{NH}_4\text{-N}$  applied in the slurry, which was equivalent to 38 % of the TN, was partially  
301 held in the cationic sorption soil sites of the organic soil due to its relatively high CEC ( $32.4$   
302  $\text{meq}/100 \text{ g}$ ) and subjected to a more intense nitrification process than in the mineral soil  
303 (Vymazal, 2007). By contrast, the lower CEC of the mineral soil ( $17 \text{ meq}/100 \text{ g}$ ) may have  
304 facilitated mobilization of the positively charged  $\text{NH}_4\text{-N}$  through the columns.

305 Over the duration of the study, cumulative  $\text{NO}_3\text{-N}$  losses from all treatments were substantially  
306 higher from the organic soil columns than from the mineral soil columns, indicating a more  
307 efficient nitrification process. In the mineral soil, the nitrification process may have occurred

308 to a lesser extent than in the organic soil, possibly due to the lower C/N ratio as a consequence  
309 of the smaller initial amount of OM in the soil compared to the organic soil (Chen et al. 2015;  
310 Zhang et al. 2015). For the organic soil, leached losses of NO<sub>3</sub>-N were statistically lower in all  
311 treatments than from the control, except for the split 30 kg ha<sup>-1</sup> (Figure 2 - A2). Similarly, NO<sub>3</sub>-  
312 N releases were lower in the amended columns than the control columns, although they were  
313 not statistically different (Figure 2 - B2). The higher concentration of NO<sub>3</sub>-N in the control  
314 columns in both soils may be due to a denitrification process of the native OM of the soils and  
315 the organic N in the slurry. Although gaseous N was not measured, denitrification may be the  
316 only process explaining the lower NO<sub>3</sub>-N loads in amended columns compared to unamended  
317 (control) columns. As was the case for the P, split slurry applications did not have a significant  
318 impact in the mass released in leachate over the period of study. Only the mineral soil showed  
319 an increase in the NH<sub>4</sub>-N load for the first application of the split 55 kg ha<sup>-1</sup> treatment four  
320 weeks after it was applied.

#### 321 **4. Conclusions**

322 This study found that split applications did not produce a significantly lower P release in the  
323 leachate when compared with their single counterparts, although this lack of effect may have  
324 been masked by the artificially enhanced ability of the soils used here to retain P. Although  
325 NH<sub>4</sub>-N loads in leachate increased proportionally with the slurry application rate in the mineral  
326 soil, the losses for the organic soil were negligible. However, the NO<sub>3</sub>-N released in leachate  
327 from the organic soil was greater than from the mineral soil at all the treatments. Split  
328 applications of fertiliser had little effect on N released in leached water, suggesting that these  
329 fertiliser management practices may have little impact on N losses in subsurface transportation.  
330 This indicates that the amount of fertiliser, as opposed to its application regime, would seem  
331 to exert the highest effect in nutrient losses.

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522 **Table 1.** Selected physico-chemical characteristics ( standard deviations) of the two soils used  
 523 in this study.

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Soil properties		Soil type	
		Organic	Mineral
pH		5.5 (0.3)	6.3 (0.1)
OM	g kg <sup>-1</sup>	54.1 (2.1)	8.0 (0.2)
Dry bulk density	g cm <sup>-3</sup>	0.41 (0.1)	0.99 (0.1)
Particle Size			
Clay	%	13.9 (1.5)	16.9 (1.3)
Silt	%	27.3 (1.6)	37.4 (0.3)
Sand	%	58.8 (0.5)	45.7 (1.0)
Texture (USDA)		Sandy Loam	Loam
Total C	mg kg <sup>-1</sup>	276.8 (7.7)	39.2 (4.1)
Total N	mg kg <sup>-1</sup>	16.5 (0.1)	3.6 (0.5)
Total P	mg kg <sup>-1</sup>	884.0 (39.5)	770.0 (60.1)
Mehlich III			
P	mg kg <sup>-1</sup>	29.3 (3.1)	72.3 (3.1)
Al	mg kg <sup>-1</sup>	328.7 (79.6)	591.7 (15.6)
Fe	mg kg <sup>-1</sup>	350.7 (46.5)	334.0 (22.6)
Ca	mg kg <sup>-1</sup>	2831.7 (51.7)	3042.0 (289.1)
Cation exchange capacity	cmol kg <sup>-1</sup>	32.4 (5.6)	17.5 (0.2)
Phosphorus saturation ratio		0.022 (0.001)	0.084 (0.002)
Langmuir parameters			
Maximum adsorption capacity, S <sub>max</sub>	mg kg <sup>-1</sup>	1278.9	896.5
Bonding energy, k	m <sup>3</sup> g <sup>-1</sup>	0.09	0.12

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553 **Table 2.** Percentage recovery of TP in leachate, calculated as the difference between the total  
 554 P leached at each treatment and the control divided by the amount of P applied in the slurry.

Slurry application (kg ha <sup>-1</sup> )	Soil type	
	Organic	Mineral
<b>Single</b>		
15	1.62	0.930
30	0.430	1.99
55	0.710	0.970
<b>Split</b>		
15	1.55	7.32
30	0.610	0.690
55	0.160	1.06

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557 **Table 3.** Percentage recovery of NH<sub>4</sub>-N in leachate, calculated as the difference between the  
 558 total NH<sub>4</sub>-N leached in leachate water at each treatment and the control divided by the amount  
 559 of NH<sub>4</sub>-N applied in the slurry.

Slurry application (kg ha <sup>-1</sup> )	Soil type	
	Organic	Mineral
<b>Single</b>		
15	0.590	32.5
30	0.310	53.7
55	0.370	33.3
<b>Split</b>		
15	0.580	49.1
30	0.320	17.8
55	0.250	28.6

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571 **Figure captions**

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573 **Figure 1.** Average cumulative leaching of dissolved reactive P (DRP) and total P (TP) for  
574 each treatment and soil type. Error bars represent one standard deviation. Hatched lines  
575 indicate slurry application times (17 wk and 25 wk).

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577 **Figure 2.** Average cumulative leaching of ammonium (NH<sub>4</sub>-N) and nitrate (NO<sub>3</sub>-N) for each  
578 treatment and soil type. Error bars represent one standard deviation. Hatched lines indicate  
579 slurry application times (17 wk and 25 wk).

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