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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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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^{-1} 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^{-1} and 0.09-0.14 kg DRP ha^{-1} for the organic and mineral soil, respectively, and 1.5-

32   1.8 kg total phosphorus (TP) ha^{-1} and 1.8-2.9 kg TP ha^{-1} for the organic and mineral soil,

33   respectively). There was high ammonium-N retention within the organic soil (0.2-0.4 kg ha^{-1},

34   compared to 15.0-36.8 ha^{-1} for mineral soils in the leached water). Nitrate-N loads were higher

35   from the organic soil (6.5-105.3 ha^{-1}) than the mineral soil (9.7-17.4 ha^{-1}), although for both

36   soils, loads from the amended columns were lower than the controls (110.7 and 20.1 NO$_3$-N

37   ha^{-1} 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_2O) 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,

94 1941) procedures, respectively. Particle size analysis was determined using the hydrometer

95 method (ASTMD 2002). The Mehlich-3 soil test was used to determine extractable aluminium

96 (Al), calcium (Ca), iron (Fe) and P (Mehlich 1984). As a measure of the degree of P saturation

97 of the soils, the P saturation ratio (PSR) for acidic soils was calculated using:

98 $$[P/(Al+\gamma*Fe)]_{Mehlich-3} \tag{1}$$

99 where P, Al and Fe are Mehlich-3 extractable forms on a molar basis and γ is a weighing factor,

100 set at 1 for the mineral soil and 5 for the organic soil, to compensate for the low extraction

101 efficiency of Fe in organic soils (Guérin et al. 2007).

102 Additionally, P sorption isotherm experiments were conducted to determine the total sorption

103 and bonding capacities of both soils. Twenty-five mL of varying concentrations (0, 5, 10, 30

104 and 60 mg P L^{-1}) of a KH$_2$PO$_4$ stock solution were added to 50 mL polyethylene centrifuge

105 tubes each containing 1 g of soil (n=3). Samples were shaken for 24 h at 250 rpm in a

106 reciprocating shaker, allowed to settle for 1 h, filtered through a 0.45 μm membrane filter, and

107 the filtrate was analysed for dissolved reactive phosphorus (DRP) using a nutrient analyser

108 (Konelab 20, Thermo Clinical Lab systems, Finland). A linearized Langmuir adsorption

109 equation (Kovar and Pierzynski, 2009) was used to fit the data:

110

111 $$\frac{C}{S} = \frac{1}{kS_{max}} + \frac{C}{S_{max}} \tag{2}$$

112

113 where C is the concentration of P after equilibration (in mg L^{-1}) and S is the total amount of P

114 retained (mg kg^{-1}), S_{max} represents the maximum amount of P that can be sorbed by the soil

115 (mg kg^{-1}), and k is a constant related to the bond strength of added P to soil (L mg^{-1} P).

116

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 ± 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 (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° 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 μm) and analysed for DRP and 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 ± 1 ° C) and humidity (85 ± 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^{-1} (11.8

150   mg P column^{-1}) (2) a 15 kg P ha^{-1} applied in two split applications of 7.5 kg P ha^{-1} (5.9 mg P

151   column^{-1}) each (3) one single application of 30 kg P ha^{-1} (23.6 mg P column^{-1}) (4) a 30 kg P

152   ha^{-1} applied in two split applications of 15 kg P ha^{-1} (11.8 mg P column^{-1}) each (5) one single

153   application of 55 kg P ha^{-1} (43.2 mg P column^{-1}) (6) 55 kg P ha^{-1} applied in two split

154   applications of 27.5 kg P ha^{-1} (21.6 mg P column^{-1}) 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^{-1}, 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^{-1} for applications of

158   15, 30 and 55 kg P ha^{-1}, 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^{-1}, 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).

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-μm pore

170 size) were analysed for DRP, NH_4-N, total oxidised nitrogen (TON) and nitrite-N (NO_2-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 (NO_3-N) was calculated as the difference between TON and NO_2-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:

181

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

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 *nlraa* package (Fernando Miguez, 2022).

189   These data were then extrapolated to produce a weekly gravimetric loss per hectare (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 (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^{-1}) was higher than in the mineral

214   soil (896 mg kg^{-1}), 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^{-1})

226   with respect to agronomic recommendations (Mallarino et al. 2013) and very high for the

227   mineral soil (72.3 mg kg^{-1}), 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^{-1} (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^{-1} 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^{-1} 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^{-1} 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^{-1} after three days of continuous leachate from peat soil columns

260   receiving 22 kg P ha^{-1} in the form of composted horse manure. In comparison, TP losses in the

261   current study were lower than 2 kg ha^{-1} 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^{-1} 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 NH_4-N loads between

291 the different treatments and the control in the organic soil, except for the single 55 kg ha^{-1}

292 treatment (Figure 2 - A1). For the mineral soil, single applications of 30 and 55 kg ha^{-1} and the

293 split application of 55 had a statistically significant effect ($p < 0.001$) on the NH_4-N loads

294 compared to the control (Figure 2 - B1), raising them in all cases. Among soils, NH_4-N loads

295 in the leachate water were significantly higher ($p < 0.001$) in the mineral soil than the organic

296 soil. The NH_4-N in the leachate from the mineral soil ranged from 6 to 36 kg ha^{-1} compared to

297 the very low values for the organic soil, which ranged from 0.1 to 0.3 kg ha^{-1}. The NH_4-N

298 released in leached water as a percentage of the NH_4-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 NH_4-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 meq/100 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 meq/100 g) may have

304 facilitated mobilization of the positively charged NH_4-N through the columns.

305 Over the duration of the study, cumulative NO_3-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_3-N were statistically lower in all

311 treatments than from the control, except for the split 30 kg ha^{-1} (Figure 2 - A2). Similarly, NO_3-

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_3-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_3-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_4-N load for the first application of the split 55 kg ha^{-1} treatment four

320 weeks after it was applied.

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_4-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_3-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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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 525
pH		5.5 (0.3)	6.3 (0.1)
OM	g kg^{-1}	54.1 (2.1)	8.0 (0.2) 526
Dry bulk density	g cm^{-3}	0.41 (0.1)	0.99 (0.1)
Particle Size			527
Clay	%	13.9 (1.5)	16.9 (1.3)
Silt	%	27.3 (1.6)	37.4 (0.3) 528
Sand	%	58.8 (0.5)	45.7 (1.0)
Texture (USDA)		Sandy Loam	Loam 529
Total C	mg kg^{-1}	276.8 (7.7)	39.2 (4.1)
Total N	mg kg^{-1}	16.5 (0.1)	3.6 (0.5) 530
Total P	mg kg^{-1}	884.0 (39.5)	770.0 (60.1)
Mehlich III			531
P	mg kg^{-1}	29.3 (3.1)	72.3 (3.1) 532
Al	mg kg^{-1}	328.7 (79.6)	591.7 (15.6)
Fe	mg kg^{-1}	350.7 (46.5)	334.0 (22.6) 533
Ca	mg kg^{-1}	2831.7 (51.7)	3042.0 (289.1)
Cation exchange capacity	cmol kg^{-1}	32.4 (5.6)	17.5 (0.2) 534
Phosphorus saturation ratio		0.022 (0.001)	0.084 (0.002)
Langmuir parameters			535
Maximum adsorption capacity, S$_{max}$	mg kg^{-1}	1278.9	896.5
Bonding energy, k	m^3 g^{-1}	0.09	0.12 536
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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^{-1})	Soil type	
	Organic	Mineral
Single		
15	1.62	0.930
30	0.430	1.99
55	0.710	0.970
Split		
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$_4$-N in leachate, calculated as the difference between the

558   total NH$_4$-N leached in leachate water at each treatment and the control divided by the amount

559   of NH$_4$-N applied in the slurry.

Slurry application (kg ha^{-1})	Soil type	
	Organic	Mineral
Single		
15	0.590	32.5
30	0.310	53.7
55	0.370	33.3
Split		
15	0.580	49.1
30	0.320	17.8
55	0.250	28.6

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Figure captions

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).

576
577 **Figure 2.** Average cumulative leaching of ammonium (NH_4-N) and nitrate (NO_3-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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