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Title	Use of amendments in a peat soil to reduce phosphorus losses from forestry operations
Author(s)	Callery, Oisin; Brennan, Raymond B.; Healy, Mark G.
Publication Date	2015-10-18
Publication Information	Callery, O., Brennan, R. B., & Healy, M. G. (2015). Use of amendments in a peat soil to reduce phosphorus losses from forestry operations. <i>Ecological Engineering</i> , 85, 193-200. doi: http://dx.doi.org/10.1016/j.ecoleng.2015.10.016
Publisher	Elsevier
Link to publisher's version	https://doi.org/10.1016/j.ecoleng.2015.10.016
Item record	http://hdl.handle.net/10379/6671
DOI	http://dx.doi.org/10.1016/j.ecoleng.2015.10.016

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1 *Published as: Callery, O., Brennan, R.B., Healy, M.G. 2015. Use of amendments in a peat*
2 *soil to reduce phosphorus losses from forestry operations. Ecological Engineering 85: 193 –*
3 *200. <http://dx.doi.org/10.1016/j.ecoleng.2015.10.016>*
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5 **Use of amendments in a peat soil to reduce phosphorus losses from forestry operations**

6

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14

15 **Abbreviations:** Al-WTR, aluminum water treatment residual

16 **Abstract**

17 Forestry harvesting on peats is known to result in significant losses of soil phosphorus (P) to
18 adjacent waters, and the issue is becoming an increasingly serious concern as peatland forest
19 stocks mature and reach harvestable age. One potential solution could be the use of low-cost
20 P recovery techniques based on the chemical precipitation and/or adsorption of the dissolved
21 fraction of soil P, which would otherwise be lost. Such recovery techniques have shown
22 promise in similar applications on mineral soils. However, the interaction of peat with P
23 adsorbing materials can significantly alter their adsorptive characteristics, and it is
24 consequentially not known what materials might be suitable for this application. This study
25 compared the performance of six potential soil amendments (aluminum water treatment
26 residual (Al-WTR), crushed concrete, gypsum, magnesium hydroxide, magnesium oxide, and
27 steel wool) in removing P from aqueous solution in the presence of a typical forest peat soil.
28 Comparison of adsorption isotherms plotted from these batch adsorption studies showed that
29 the observed P adsorption maxima of Al-WTR and steel wool were increased by the presence
30 of peat, from 10.6 mg g⁻¹ and 20.4 mg g⁻¹, to 11.8 mg g⁻¹ and 52.5 mg g⁻¹, respectively. In
31 contrast, the observed P adsorption maxima of crushed concrete, gypsum, and magnesium
32 oxide were reduced in the presence of peat, by 44%, 87%, and 37%, respectively. The
33 maximum P adsorption achieved by magnesium hydroxide was increased from 29.8 mg g⁻¹ to
34 59 mg g⁻¹ at an amendment to peat-solid ratio of 1:4, but decreased from 73.9 mg g⁻¹ to 23.6
35 mg g⁻¹ at an amendment to peat-solid ratio of 1:10. It was concluded that Al-WTR, in
36 particular, shows considerable promise for use as a soil amendment for P immobilization in a
37 peat environment.

38

39 **Keywords:** Phosphorus; forestry; peat; clearfelling; harvesting; buffer zones; adsorption

40 **Introduction**

41 Ireland's forestry stock of 731,000 ha covers about 10.5% of the country, of which 44% is
42 planted on peats (National Forest Inventory, 2012). Peats, especially ombrotrophic upland
43 blanket peats, are generally lacking in minerals like aluminum (Al) and iron (Fe), and
44 consequently have extremely low soil phosphorus (P) sorption capacities (Renou et al.,
45 2000). As a result, any P released by the forestry operations, such as clearfelling and
46 afforestation, is liable to leach unimpeded into adjacent receiving waters, even with the
47 application of current best management practices targeted at preventing such pollution
48 (Finnegan et al., 2014).

49 Nutrient enrichment, or eutrophication, of inland waters is recognized as Ireland's most
50 serious environmental pollution problem (Department of the Environment, 2002). As P has
51 been identified as the primary nutrient limiting eutrophication in freshwaters (Carpenter et al.,
52 1998; Boesch et al., 2001), preventing its migration from soil to aquatic environments is
53 paramount. The oligotrophic nature of Ireland's upland catchments, and the unique flora and
54 fauna present in these waters, make them particularly sensitive to eutrophication (Mainstone
55 and Parr, 2002; Hutton et al., 2008). These forested peat catchments are headwaters for many
56 of Ireland's river systems, a great number of which contain important salmonid populations
57 (Giller and O'Halloran, 2004), as well as other species protected under European Union (EU)
58 legislation (O'Driscoll et al., 2012; Reid et al., 2013). Consequentially, pollution from
59 diffuse, low concentration sources of P, such as forestry, is capable of causing considerable
60 environmental damage to an area much larger than that which is forested.

61 The sustained release of P following forestry harvesting has been highlighted as an issue of
62 particular concern, as much of Ireland's current peatland forestry stock was planted between
63 the 1950s and the 1990s (Renou and Farrell, 2005) and has now reached, or is reaching,

64 harvestable age (Rodgers et al., 2010). Clearfelling is the harvesting technique most prevalent
65 in Ireland, and accounted for 76.6% of timber felled between 2006 and 2012 (National Forest
66 Inventory, 2012). Clearfelling involves the removal from site of the commercially-viable
67 portions of the forestry crop (i.e. tree trunks), leaving large amounts of P to remain onsite,
68 present both in the soil and in the non-commercial logging residues, or 'brash'. This brash
69 accounts for a considerable percentage of the above ground nutrients contained in a typical
70 coniferous tree (Moffat et al., 2006), and it has been shown to release these nutrients for
71 many years following its deposition (Titus and Malcolm, 1999; Hyvönen et al., 2000). To
72 compound the issue, the use of brash mats to form temporary driving surfaces for heavy
73 felling machinery is an essential management practice, as it prevents serious damage to the
74 underlying soil (Moffat et al., 2006). Clearfelling completely disrupts natural P cycling in a
75 forest ecosystem, with the deposition of brash mats resulting in increased P availability, while
76 the concurrent removal of trees from site results in decreased P uptake and sequestration - a
77 situation which greatly increases the threat of P leaching to aquatic ecosystems (Schaller et
78 al., 2015).

79 While rates of afforestation on blanket peats have been in decline in recent years (National
80 Forest Inventory, 2012), the harvesting of presently established forest is inevitable, as are the
81 resulting water quality issues, if effective pollution mitigation measures are not implemented.
82 Current best management practices advocate the use of riparian buffer strips between forestry
83 and adjacent aquatic zones (Forest Service, 2000). Previous research has found the use of
84 suitably large riparian buffer zones on peat soils to be largely successful in protecting surface
85 waters from influxes of suspended sediments and associated particulate nutrients (Nieminen
86 et al., 2005). However, with peat's low P adsorption capacity, the performance of these buffer
87 zones in satisfactorily mitigating the flow of dissolved P off site varies greatly. Moreover, it
88 has been found that these buffer zones' effect can be anywhere from positive, with total

89 retention of released P (Vaananen et al., 2008), to negative, compounding the issue with
90 additional P release (Vasander et al., 2003; Liljaniemi et al., 2003).

91 There has been increasing interest in the use of soil amendments to control P losses from
92 diffuse sources, such as land spreading of manure from dairy cattle (Brennan et al., 2011a,b)
93 and pigs (O' Flynn et al., 2012), land spreading of dairy waste water from washing of milking
94 parlors (Serrenho et al., 2012), and construction of wetlands on sites previously used for
95 agriculture (Ann et al., 1999). The use of chemical amendments has shown much promise in
96 these instances, though there has been little to no investigation into the practice's potential in
97 abating the loss of P from peatland forestry. The performance of chemical amendments in
98 this context has the potential to be quite different, as the interaction of amendments with the
99 complex chemistry of peat can significantly alter their P removal performance (James et al.,
100 1992).

101 This study tested the hypothesis that chemical amendments could immobilize P in a forest
102 peat soil. To address this hypothesis, the aim of this study was to identify and compare
103 potential soil amendments which function well in a peat chemistry environment and, when
104 mixed with peat onsite, could increase the adsorptive capacity of the soil to the point where P
105 losses from a forestry site would no longer pose a risk to receiving surface waters.

106 Specifically, the objectives of this study were to: (1) identify chemical amendments capable
107 of removing P from an aqueous solution which mimics the chemistry of runoff/ground water
108 on a forested peat site (2) compare the performance of each amendment and identify the
109 amendment most ideally suited to application in a forested peat site (3) analyze the effect of
110 peat on the performance of each amendment in terms of its adsorptive capacity.

111 **Materials and Methods**

112 **Collection and characterization of peat samples**

113 Samples of blanket peat were collected from a recently clearfelled riparian buffer zone,
114 located near the town of Oughterard, County Galway, Ireland (approx. coordinates 53.375N,
115 -9.419E). The peat was collected from a stratum of homogeneous composition, at a depth of
116 5-25cm from the surface (the surface layer of vegetation and semi-decayed sphagnum moss
117 was discarded, along with any larger roots and plant fibers). Before testing, the samples were
118 homogenized by repeatedly folding and kneading the peat until its texture and water content
119 were entirely uniform. Once homogenized, peat samples were sealed in airtight Ziploc® bags
120 and stored in a temperature-controlled room at 11°C until testing commenced. The water
121 content of the homogenized peat was determined to be 89.7%±0.08% by oven drying the peat
122 for 24 h at 105°C (BSI, 1990).

123 **Sourcing and characterization of amendments**

124 The following amendments were used in this study (Table 1): dewatered aluminum sulphate
125 water treatment residual (Al-WTR; oven dried for 24 h at 105°C and ground to pass a 0.5 mm
126 sieve), crushed concrete cubes (pulverized with a mortar and pestle and ground to pass a 0.5
127 mm sieve), gypsum (sourced from recycled plasterboard, supplied as a powder, and passed
128 through a 0.5 mm sieve to ensure uniformity), magnesium oxide (MgO; sourced from
129 seawater, supplied as a powder, and passed through a 0.5 mm sieve to ensure uniformity),
130 magnesium hydroxide (Mg(OH)₂; sourced from seawater, supplied as a paste, and passed
131 through a 0.5 mm sieve to ensure uniformity) and steel wool (grade 00, fiber diameter
132 approx. 0.04 mm).

133 **Batch test procedure**

134 Samples were prepared comprising two grams (wet weight) of the homogenized peat, mixed
135 with each of the six amendments, at amendment to peat-solid ratios of 1:10, 1:4 and 1:2.
136 These masses provided a material to solution ratio that was small enough to ensure non-zero
137 equilibrium concentrations, thus allowing the determination of the entire isotherm curve. The
138 material to solution ratio used in the current study was comparable to ratios used in similar
139 studies (Li et al., 2006; Chardon et al., 2012). The samples were placed in separate 50 ml
140 conical flasks and overlain by 25 ml of deionized water, with ortho-phosphorus (PO₄-P)
141 concentrations (prepared by adding various amounts of K₂HPO₄ to deionized water) of 0, 25,
142 50, 75, 100, and 150 mg P L⁻¹. This range of P concentrations was determined to be
143 sufficiently wide to account for the variation in the amendments' adsorptive capacities, and
144 the dependence of adsorption capacity on the initial concentration (Seo et al., 2005). The
145 flasks were sealed with Parafilm and shaken in a reciprocal shaker (250 rpm) at room
146 temperature (25°C) for 24 h. After 24 h had elapsed, the samples were centrifuged at 14,500
147 rpm for 5 min, and the supernatant water was passed through a 0.45 µm filter. Dissolved P
148 concentrations of the supernatant water were determined using a nutrient analyzer (Konelab
149 20, Thermo Clinical Lab systems, Finland) after APHA (1998). Experiments were conducted
150 at neutral pH to ensure that all observed changes in pH could be attributed to the addition of
151 peat to the solution. The same procedure was also carried out using identical masses of
152 amendment but without the addition of peat.

153 **Analysis of experimental data**

154 The mass of P adsorbed per gram of adsorbent, q_e , at equilibrium was calculated by:

$$155 \quad q_e = \frac{V(C_o - C_e)}{m} \quad (1)$$

156 where C_o and C_e are the initial and final PO₄-P concentrations of the solution (mg L⁻¹), V is
157 the volume of solution (L), and m is the dry weight of adsorbent (g). For the purpose of these

158 calculations, the PO₄-P adsorbency of the peat was considered to be negligible, and for
159 solutions containing peat and amendment, only the dry weight of the amendment was
160 considered in Eqn 1.

161 The C_e and q_e data obtained from the batch tests were fitted to the Koble-Corrigan equation,
162 which was chosen for its ability to model adsorption over a wide range of data, as well as for
163 its being more universally applicable than the commonly used Langmuir and Freundlich
164 equations (Koble and Corrigan, 1952). The Koble-Corrigan equation is as follows:

$$165 \quad q_e = \frac{A_{KC}C_e^p}{1+B_{KC}C_e^p} \quad (2)$$

166 where A_{KC}, B_{KC} and p are the Koble-Corrigan isotherm constants determined by using an
167 iterative approach to minimize the value returned by the hybrid fractional error function
168 (HYBRID), an error function used to fit Eqn. 2 to the observed data (Porter et al., 1999):

$$169 \quad \frac{100}{n-p} \sum_{i=1}^n \frac{(q_{e,i,meas} - q_{e,i,calc})^2}{q_{e,i,meas}} \quad (3)$$

170 where n is the number of experimental data points, p is the number of isotherm constants in
171 the Koble-Corrigan equation (Eqn. 2), q_{e,i,meas} is the value of q_e obtained from Eqn. (1), and
172 q_{e,i,calc} is the value of q_e obtained from Eqn. (2). By fitting the experimental data for each
173 adsorbent to the Koble-Corrigan equation, it was possible to make predictions for values of
174 C_e and q_e for any given C_o. Substituting Eqn. 1 into Eqn. 2 gives:

$$175 \quad \frac{V(c_o - c_e)}{m} = \frac{A_{KC}C_e^p}{1+B_{KC}C_e^p} \quad (4)$$

176 An iterative approach, using Microsoft Excel's SolverTM, was then used to determine values
177 of C_e for any given value of C_o. The impact of peat on the amendments' performance was
178 evaluated using:

179

$$\phi = \frac{q_{e,a}^{\text{calc}}}{q_{e,b}^{\text{calc}}} \quad (5)$$

180 where $q_{e,a}^{\text{calc}}$ is the modelled mass of P adsorbed by the amendment in a solution containing
181 peat, and $q_{e,b}^{\text{calc}}$ is the modelled mass of P adsorbed by the amendment in a solution containing
182 no peat. Calculated values of $\Phi > 1$ indicate a synergistic effect was obtained by exposing an
183 amendment to peat, i.e. the influence of peat chemistry was favorable for P adsorption, while
184 values of $\Phi < 1$ suggest the opposite, i.e. that the effect was antagonistic. In this way, ϕ could
185 be considered to be a coefficient of synergy.

186 **Results and Discussion**

187 All of the amendments were effective at removing P from aqueous solution, both with and
188 without the presence of peat in solution. The addition of peat did, however, influence the
189 behavior of all amendments, leading to either improved or diminished adsorptive
190 performance.

191 **Equilibrium adsorption isotherms**

192 Figure 1 shows the adsorption isotherms obtained by fitting the Koble-Corrigan model to
193 each of the peat amendment-mixtures. The Koble-Corrigan fitting coefficients (A_{kc} , B_{kc} , and
194 p) as well as slope, and R^2 values obtained from plots of $q_{e\text{ calc}}$ (calculated using the Koble-
195 Corrigan equation) vs $q_{e\text{ exp}}$, are shown in Table 2. The Koble-Corrigan model fitted the
196 experimental data well, and there was a very good correlation (average $R^2 = 0.94 \pm 0.1$)
197 between predicted and experimental values. In general, higher values of q_e were observed
198 when the ratio of adsorbent to solution was smaller. This is in agreement with a review
199 conducted by Cucarella and Renman (2009), who reported that smaller adsorbent-to-solution
200 ratios may lead to higher concentrations of P sorbed to the adsorbent material. Al-WTR, in
201 particular, showed a much larger increase in P adsorption capacity (maximum observed $q_e =$
202 11.8 mg g^{-1}) when added to peat-containing solutions at an amendment to peat-solid ratio of
203 1:10, compared to amendment to peat-solid ratios of 1:4 and 1:2 (maximum observed $q_e = 3.3$
204 mg g^{-1} and 3.6 mg g^{-1} , respectively).

205 Maximum q_e values observed for concrete were 15 mg g^{-1} , 8.9 mg g^{-1} , and 6.8 mg g^{-1} at
206 amendment to peat-solid ratios of 1:10, 1:4, and 1:2, which were similar to q_e values of 26.8
207 mg g^{-1} , 15.1 mg g^{-1} , and 6.6 mg g^{-1} observed for the same masses of concrete, but without the
208 addition of peat. These values are all comparable to the q_e range of $5.1\text{--}19.6\text{ mg g}^{-1}$ observed
209 by Egemose et al. (2012). With respect to gypsum, the presence of peat in solution resulted in

210 greatly reduced maximum observed q_e values of 10.8 mg g^{-1} , 4.4 mg g^{-1} , and 3.6 mg g^{-1} at
211 amendment to peat-solid ratios of 1:10, 1:4, and 1:2, compared to values of 84.8 mg g^{-1} , 58.4
212 mg g^{-1} , and 34 mg g^{-1} observed for the same masses without the addition of peat.

213 Magnesium oxide and Mg(OH)_2 displayed the highest P adsorption capacities, with MgO
214 having the greatest of the two, with a maximum q_e of 102.7 mg g^{-1} observed at an amendment
215 to peat-solid ratio of 1:10. Liu et al. (2011) found that removal of As(III) from aqueous
216 solution by MgO was due to the *in situ* formation of Mg(OH)_2 by reaction of the MgO with
217 water, followed by subsequent adsorption/reaction of the newly formed Mg(OH)_2 with the
218 As(III) anion. Liu et al. (2011) also reported that the adsorptive performance of Mg(OH)_2
219 formed *in situ* was greater than that of pre-formed Mg(OH)_2 , at least partially as a result of
220 the former's larger specific surface area, which was almost 5.5 times greater than that of the
221 latter ($58.4 \text{ m}^2\text{g}^{-1}$ vs. $10.7 \text{ m}^2\text{g}^{-1}$, respectively). The results of our study indicate that Mg(OH)_2
222 formed *in situ* also had a greater adsorptive capacity for $\text{PO}_4\text{-P}$ compared to that of pre-
223 formed Mg(OH)_2 . Stoichiometrically, MgO contains approximately 45% more Mg per unit
224 weight than Mg(OH)_2 ; however, its P adsorption capacity was observed to be up to 120%
225 greater than that of preformed Mg(OH)_2 in solutions where peat was absent (data not shown).

226

227 When steel wool was examined, P adsorption was observed to be inhibited at high initial
228 $\text{PO}_4\text{-P}$ concentrations (C_o), both with and without the addition of peat. This appeared to be
229 the result of high $\text{PO}_4\text{-P}$ concentrations inhibiting the formation of the iron oxides/hydroxides
230 responsible for P removal, and it was observed that much less of the steel wool had rusted in
231 these comparatively high concentration solutions. Similar observations were made by Pryor
232 and Cohen (1953), who found that solutions of orthophosphate passivate iron; i.e. iron
233 became less reactive due to presence of a micro coating in the presence of dissolved air, and

234 Harahuc et al. (2000), who found that phosphate at or above concentrations of 25 mmol
235 inhibited the solubilization of iron.

236 **pH effects**

237 Figure 2 summarizes the effect the addition of peat had on the pH of the solution at
238 equilibrium (after 24 h). The peat displayed a strong buffering capacity, and its addition
239 altered the final pH of the solution at equilibrium in all cases. In real-world applications, an
240 amendment that has a strong effect on pH may not be desirable, as large fluctuations in pH
241 may have a deleterious impact on the environment. For example, the addition of an
242 amendment which increases the soil's pH may increase soil nitrate (NO_3) concentrations, and
243 the risk of NO_3 leaching could be particularly great during the clearfelling of forestry
244 (Wickström, 2002). After shaking for 24h, the pH of samples containing peat mixed with Al-
245 WTR was found to be closest to those of a solution containing peat only. The performances
246 of P adsorbent materials are known to be strongly affected by pH, and in acidic soils such as
247 peats, Al and Fe are known to be responsible for the sorption of P (Sato et al., 2005), while
248 binding by calcium (Ca) and magnesium (Mg) is responsible for P immobilization in alkaline
249 soils (Faulkner and Richardson, 1989; Reddy et al., 1999).

250 **Synergistic Effects**

251 The results indicate that, at certain initial $\text{PO}_4\text{-P}$ concentrations, a degree of synergy exists
252 between the peat and certain amendments; i.e. their adsorption performance was better in an
253 environment whose chemistry was influenced by peat (Figure 3). Al-WTR and steel wool, in
254 particular, showed improved performance across a large range of concentrations, while
255 concrete, gypsum, and MgO showed largely diminished efficacy. The effect of peat on P
256 adsorption by $\text{Mg}(\text{OH})_2$ varied from beneficial to detrimental, depending on the ratio of peat
257 to amendment in solution.

258 One mechanism by which an amendment's P sorption performance may improve when in a
259 peat environment is as a result of the interaction of humic substances with soluble metal ions.
260 Humic substances facilitate the removal of P through reactions with Al and Fe ions, which
261 results in the formation of insoluble phosphate complexes (Bloom, 1981; Renou et al., 2000).
262 Conversely, humic materials inhibit the removal of P by precipitation with Ca by competing
263 with the phosphate anion for Ca, with this effect being more exaggerated at lower pH
264 (Alvarez et al., 2004; Song et al., 2006; Cao et al., 2007). The formation of humic complexes
265 may therefore contribute both to the observed improvement in Al-WTR and steel wool's
266 adsorptive performance, as well as the diminished performance of concrete and gypsum.
267 Phosphorus sorption by gypsum, for example, is directly related to its solubility, as its P
268 removal is largely due to precipitation reactions (Penn et al., 2007) and thus the availability
269 of Ca for the formation of calcium phosphates (Kordlaghari and Rowell, 2006).

270 The concrete used in this study had significantly higher levels of Al and Fe present than the
271 gypsum (Table 1), which may explain why its P removal performance was not as adversely
272 affected as gypsum's. Oğuz et al. (2003) found that P removal by concrete was by
273 precipitation of metallic PO_4 salts, which were adsorbed onto the surface of the concrete, and
274 $AlPO_4$ appeared to be the main product adsorbed onto the surface of the gas concrete
275 examined in their study. This result suggests that the Al and Fe content of the concrete
276 examined in this study, perhaps more so than its Ca content, plays a crucial role in P
277 adsorption. Berg et al. (2005) reported that P removal by crushed gas concrete was not
278 affected by the presence of organic matter in the form of dissolved organic carbon. However,
279 as concrete's adsorption of P is strongly related to pH, and improves with increasing pH
280 (Oğuz et al., 2003), it appears that the acidification of the solution by the peat is at least
281 partially responsible for the observed reduction in performance.

282 The pH buffering action of the peat is also likely to have contributed to the observed
283 synergistic effects by lowering the solution pH, which can improve Al-WTR's P adsorption,
284 as observed by Yang et al. (2006), and promote corrosion of the steel wool to form P
285 adsorbing iron oxide/hydroxides. Consequently, the peat had a stronger effect on pH at this
286 rate, with the final solution pH ranging from 8.3-8.6, compared to 9.8-10.2 and 9.9-10.5 at
287 amendment to peat-solid ratios of 1:4 and 1:2, respectively. It was also observed that when
288 $Mg(OH)_2$ was added at an amendment to peat-solid ratio of 1:10, recorded q_e values were
289 much lower than solutions containing $Mg(OH)_2$ at amendment to peat-solid ratios of 1:4 and
290 1:2. While the reason for this is not entirely clear, the marked difference in pH accompanied
291 by the significant drop in P adsorption strongly suggests that the pH buffering effect of the
292 peat may also be responsible for reducing the P adsorbency of $Mg(OH)_2$ at this lowest rate of
293 amendment. Xie et al. (2013) reported that fulvic and humic acids had a slight negative effect
294 on PO_4 adsorption by a magnesium oxide nanoflake-modified diatomite adsorbent, and
295 attributed this observation to the effects of competitive adsorption. It is quite possible that at
296 low $Mg(OH)_2$ to peat ratios this effect is more exaggerated.

297 **Conclusions**

298 This study found that the presence of peat in solution increased the P adsorption capacities of
299 Al-WTR and steel wool, while the adsorptive capacities of crushed concrete, gypsum, and
300 magnesium oxide were decreased. Magnesium hydroxide showed both increased and
301 decreased adsorptive capacity, depending on the ratio of peat to amendment in solution.
302 Throughout the study, peat displayed considerable ability to buffer the peat-amendment
303 mixture pH. However, the equilibrium pH of solutions containing Al-WTR and gypsum were
304 observed to be closest to the peat's natural pH, indicating that these amendments were best
305 suited to the peat environment. Taking these factors into consideration, the results of this
306 study indicate that Al-WTR, in particular, holds great promise for utilization in the mitigation
307 of P runoff caused by forestry operations on blanket peat sites. Previous research into the use
308 of Al-WTR has shown it to be effective in preventing P runoff when used as a soil
309 amendment in an agricultural context, and this study's findings demonstrate that the
310 chemistry of a peat forest environment is likely to interact with Al-WTR in such a manner as
311 to improve its P removal performance at low P concentrations. As a waste material, an
312 additional benefit lies in the fact that it does not have the production costs associated with
313 other high performing amendments studied, i.e. steel wool and $Mg(OH)_2$.

314

315 **Acknowledgements**

316

317 The first author would like to acknowledge the Irish Research Council for funding.

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469 **Legend**

470 **Figure 1.** Best fit Koble-Corrigan adsorption isotherm models derived using non-linear
471 regression methods for (a) magnesium oxide, (b) gypsum, (c) steel wool, (d) crushed
472 concrete, (e) magnesium hydroxide, and (f) Al-WTR, at amendment to peat-solid ratios of
473 1:10, 1:4, and 1:2.

474 **Figure 2.** Effect of peat on pH at equilibrium

475 **Figure 3.** Synergistic effect of peat on P adsorption (Refer to Eqn. 5)

476 **Table 1.** Peat and amendment characteristics

Material	Total exchange capacity (meq 100 g ⁻¹)	pH	Organic matter (%)	P† (mg kg ⁻¹)	Bray II P (mg kg ⁻¹)	Ca† (mg kg ⁻¹)	Mg† (mg kg ⁻¹)	Fe† (mg kg ⁻¹)	Al† (mg kg ⁻¹)
Peat	11.45	3.8	100	5	3	228	142	152	47
Al-WTR	16.78	7	21.62	2	< 1	2983	32	154	2159
Gypsum	64.3	8.8	1.85	6	14	11858	296	111	66
Crushed Concrete	145.15	11.7	0.82	< 1	< 1	27593	622	405	441
MgO	267.55	10	1.04	< 1	< 1	2734	29760	77	< 1
Mg(OH) ₂	247.78	9.8	23.53	< 1	< 1	739	28660	57	< 1

477 †Mehlich -3 extractable

478 **Table 2.** Koble-Corrigan fitting coefficients, HYBRID errors, and values of slope and R²

479 obtained from plots of $q_{e \text{ calc}}$ vs $q_{e \text{ exp}}$ for all amendments studied.

Amendment	Mass of amendment (g)	Mass of Peat (g)	Koble-Corrigan Parameters			Hybrid Error	$q_{e \text{ calc}}$ vs $q_{e \text{ exp}}$	
			A _{kc}	B _{kc}	P		R ²	Slope
Al-WTR	0.021	-	0.004	0.000	1.748	26.161	0.980	0.994
	0.051	-	0.002	0.001	1.844	21.142	0.870	1.016
	0.103	-	0.029	0.010	1.090	8.652	0.814	0.988
	0.021	2.000	0.710	0.032	0.795	4.725	0.995	1.001
	0.051	2.000	0.669	0.259	1.201	15.625	0.822	1.039
	0.103	2.000	0.001	-0.999	0.000	5.526	0.911	1.041
Crushed Concrete	0.021	-	1.031	-0.072	0.446	0.045	1.000	1.000
	0.051	-	0.510	0.020	0.873	33.659	0.881	1.016
	0.103	-	1.929	0.205	0.514	8.719	0.903	1.003
	0.021	2.000	3.964	-0.099	0.210	3.408	0.969	0.998
	0.051	2.000	1.087	0.109	0.935	0.187	0.997	1.000
	0.103	2.000	1.625	0.169	0.585	0.230	0.996	1.000
Gypsum	0.021	-	0.191	0.002	1.722	1.816	1.000	1.000
	0.051	-	0.004	0.000	2.841	8.108	0.998	0.999
	0.103	-	0.089	-0.950	0.016	72.056	0.963	1.007
	0.021	2.000	0.504	-0.381	0.176	23.740	0.963	0.981
	0.051	2.000	0.000	-0.999	0.000	10.299	0.962	1.011
	0.103	2.000	0.000	-0.999	0.000	0.826	0.994	0.998
Magnesium Oxide	0.021	-	1.686	0.012	2.406	742.198	0.895	1.036
	0.051	-	27.452	0.442	1.438	41.918	0.975	1.008
	0.103	-	17.694	0.252	0.520	17.290	0.986	1.000
	0.021	2.000	23.555	0.177	0.827	4.847	1.000	1.000
	0.051	2.000	24.286	0.407	1.197	34.473	0.994	1.000
	0.103	2.000	18.636	0.895	0.774	3.136	0.996	1.000
Magnesium Hydroxide	0.021	-	1.214	-0.159	0.379	287.793	0.933	0.999
	0.051	-	0.055	0.001	1.474	60.942	0.949	1.007
	0.103	-	0.152	-0.939	0.011	21.583	0.933	1.006
	0.021	2.000	0.047	-0.009	1.011	35.254	0.997	0.992
	0.051	2.000	7.849	0.098	1.065	408.260	0.937	0.932
	0.103	2.000	2.075	0.047	1.473	0.003	1.000	1.000
Steel wool	0.021	-	2.921	0.159	1.484	42.332	0.968	1.009
	0.051	-	4.128	0.411	0.996	0.870	0.999	1.001
	0.103	-	1.181	0.156	1.001	617.693	0.520	1.453
	0.021	2.000	434.832	9.756	1.352	137.919	0.715	1.003
	0.051	2.000	41.715	0.926	1.313	32.093	0.980	0.996
	0.103	2.000	68.370	2.490	0.728	62.409	0.959	0.975

Figure 1.

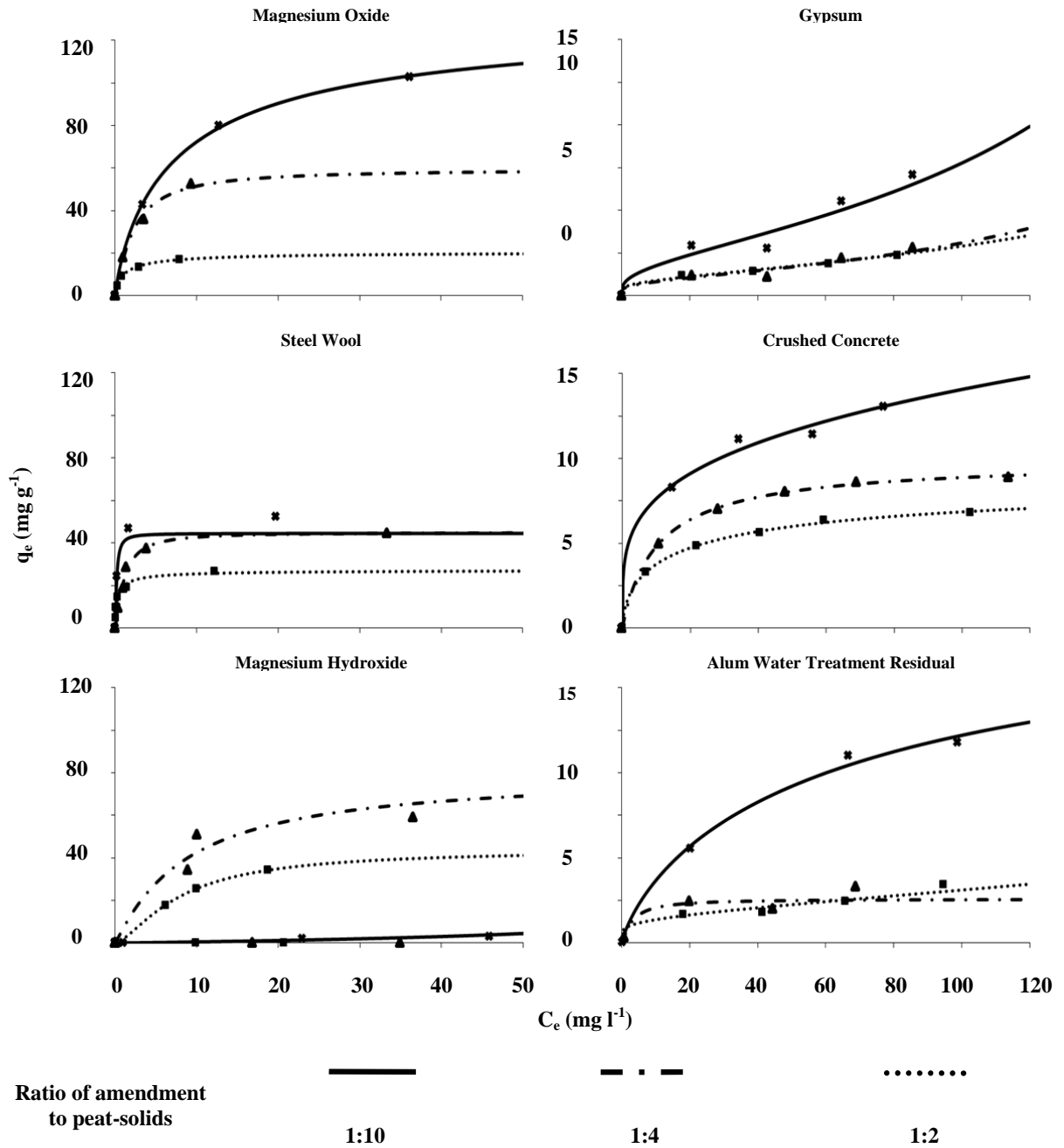
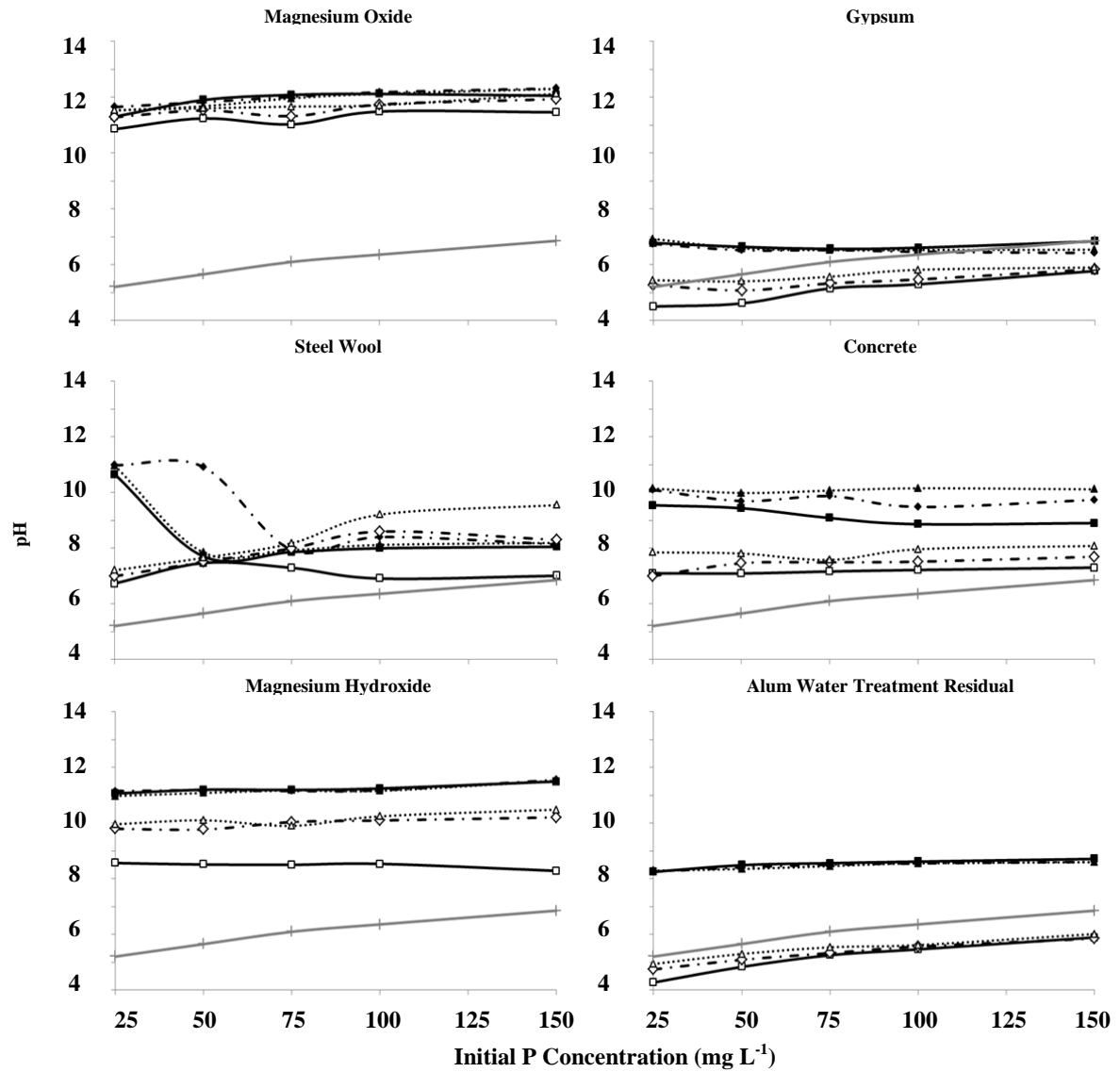


Figure 2.



Mass of amendment 0.021g 0.051g 0.103g

No peat in solution —■— —◆— ...▲...

Peat in solution —□— —◇— ...△...

Peat without amendment —+—

Figure 3.

