

1 **A potential solution to mitigate phosphorus release following clearfelling in peatland forest**
2 **catchments**

3
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10

11 **ABSTRACT**

12

13 Since the 1950s, large areas of upland peat have been afforested in northern European countries.
14 Due to the poor phosphorus (P) adsorption capacity and low hydraulic permeability in blanket
15 peat soil and increased labile P sources, harvesting these blanket peat forests can significantly
16 increase P concentrations in the receiving aquatic systems. This paper briefly reviews the current
17 management practices on the control of P releases from forestry in Ireland and the UK, and
18 proposes a possible novel practice – grass seeding clearfelled areas immediately after harvesting,
19 which should reduce P release from blanket peat forest harvesting. The study was conducted in
20 the Burrishoole Catchment in the west of Ireland. A field trial was carried out to identify the
21 successful native grass species that could grow quickly in the blanket peat forest. The two
22 successful grass species - *Holcus lanatus* and *Agrostis capillaris* – were sown in three blanket
23 peat forest study plots with areas of 100 m², 360 m² and 660 m² immediately after harvesting.
24 Areas without grass seeding were used as controls. One year later, the P content in the above
25 ground vegetation biomass of the three study plots were 2.83 kg P ha⁻¹, 0.65 kg P ha⁻¹ and 3.07
26 kg P ha⁻¹, respectively, which were significantly higher than the value of 0.02 kg P ha⁻¹ in the
27 control areas. The water extractable phosphorus (WEP) in the three study plots were 8.44 mg (kg
28 dry soil)⁻¹, 9.83 mg (kg dry soil)⁻¹ and 6.04 mg (kg dry soil)⁻¹, respectively, which were lower
29 than the value of 25.72 mg (kg dry soil)⁻¹ in the control sites. The results indicate that grass
30 seeding of the peatland immediately after harvesting can quickly immobilize significant amounts

31 of P and warrants additional research as a new Best Management Practice following harvesting
32 in the blanket peatland forest to mitigate P release.

33
34 Key words: P release. Blanket peat. Forest harvesting. Grass seeding. *Holcus lanatus*. *Agrostis*
35 *capillaris*

37 INTRODUCTION

38
39 Forest harvesting disrupts the phosphorus (P) cycle of forest ecosystems and increases labile P
40 sources in the soil, which could result in an increase of P release. P at concentrations of $30 \mu\text{g l}^{-1}$
41 could trigger eutrophication in freshwaters (Boesch et al. 2001). Eutrophication has been
42 identified as the most important water quality problem in the UK and Ireland (EPA 2004),
43 particularly for the generally oligotrophic salmonid rivers and lakes, which are very sensitive to
44 pollution. Therefore, P release after harvesting is of significant concern in upland blanket peat
45 forest catchments, such as the Burrishoole catchment in the west of Ireland, which contains
46 salmonids and has a great risk of P release due to the poor phosphorus (P) adsorption capacity
47 and low hydraulic permeability of the peat soil. Since the 1950s, large areas of upland peat have
48 been afforested in northern European countries. Previous studies have documented the effects of
49 peatland forest harvesting on P release. In Southern Finland, Nieminen (2003) found an increase
50 in phosphorus release at three out of four peatland forest study sites after harvesting. In the west
51 of Ireland, Cummins and Farrell (2003) investigated the biogeochemical impacts of clearfelling
52 with regard to phosphorus on blanket peatland streams and noted that in three drains the
53 molybdate-reactive phosphorus (MRP) increased from $9 \mu\text{g l}^{-1}$, $13 \mu\text{g l}^{-1}$ and $93 \mu\text{g l}^{-1}$ before
54 harvesting to $265 \mu\text{g l}^{-1}$, $3530 \mu\text{g l}^{-1}$, and $4164 \mu\text{g l}^{-1}$, respectively, one year after harvesting.
55 Recently, Rodgers et al. (2010) carried out a study in the Burrishoole catchment in the west of
56 Ireland and found that the daily mean total reactive phosphorus (TRP) concentration in a study
57 stream increased from about $6 \mu\text{g l}^{-1}$ pre-harvesting to $429 \mu\text{g l}^{-1}$ one year after harvesting, even
58 though best management practices were strictly implemented. Four years after clearfelling, the P
59 concentrations returned to the pre-harvesting concentrations. In the first three years after
60 harvesting, up to 5.15 kg ha^{-1} of TRP was released from the harvested catchment to the receiving
61 water; in the second year alone, 2.3 kg ha^{-1} of TRP was released. These results indicated that the

62 water quality of lakes, rivers and streams in the blanket peat forest catchments could be
63 threatened by possible increases of P in runoff water arising from forest harvesting.

64

65 **Current mitigation methods**

66

67 Buffer zones, which can filter the runoff before it reaches the receiving water, are widely used by
68 forestry practitioners in the management of freshwater aquatic systems. They can protect aquatic
69 systems by controlling runoff: (i) mechanically, by increasing deposition through the slowing
70 down of flow; (ii) chemically, through reactions between incoming nutrients and soil matrices
71 and residual elements; and (iii) biologically, through plant and microbial nutrient processes.
72 Buffer zones have been recognized as an efficient method to remove suspended solids and
73 attached P and could remove 14% to 91.8% of total phosphorus (TP) (Table 1). However, its
74 effectiveness on dissolved reactive phosphorus (DRP) removal has been controversial. In their
75 study, Vought et al. (1994) found that buffer strips were very efficient in DRP removal, with the
76 removal efficiency of 95%. In contrast, Uusi-Kämpä (2005) found that their naturally vegetated
77 buffer zone became a P release source, responsible for 70% of DRP release. Stutter et al. (2009)
78 indicated that vegetated buffer zones increased soil P solubility and the potential amount P
79 release. In Ireland and the UK, many of the earlier afforested upland blanket peat catchments
80 were established without any riparian buffer areas, with trees planted to the stream edge (Ryder
81 et al., 2010). Ryder et al. (2010) carried out a study on the creation of riparian buffer zones in
82 three blanket peat forest in the west of Ireland and concluded that it was a technically challenging
83 felling operation. In their study, Rodgers et al. (2010) found that in the Burrishoole catchment
84 most of the P release after harvesting occurred in soluble form during storm events, raising
85 concerns about the effectiveness of buffer zones in blanket peatland catchments.

86

87 In order to reduce nutrient sources, whole-tree harvesting (WTH) is recommended (Nisbet et al.
88 1997). In the UK, WTH is usually achieved by removing the whole tree (i.e. all parts of the tree
89 above the ground) from the site in a single operation (Nisbet et al. 1997). In Ireland, in
90 experimental trials conducted by Coillte, an adapted WTH procedure was adopted where the
91 forest harvest residues are bundled and removed from the selected site after the conventional
92 harvesting of stem wood (personal communication, Dr. Philip O’Dea, Coillte Teoranta, 2010).

93 Needles and branches have much higher nutrient concentrations than stem wood and whole-tree
94 harvesting may reduce nutrient sources by 2 to 3 times more than bole-only harvesting (Nisbet et
95 al. 1997). Rodgers et al. (2010) found higher water extractable P content in the areas below
96 windrow/brush material than the brush-free areas in the harvested upland peat forest catchment
97 and indicated that whole-tree harvesting could be used as a mean to decrease P release. Yanai
98 (1998) reported negligible P loss to streams over three years from harvesting using the whole-
99 tree harvesting method (all parts of tree above the ground) at the Hubbard Brook Experimental
100 forest in New Hampshire. However, whole tree harvesting can remove most of the nutrients as
101 well as base cations (Nisbet et al. 1997), which could have a negative impact on the next crop
102 rotation, especially in blanket peat catchments. Walmsley et al. (2009) found that removal of
103 forest residues can reduce second rotation productivity through nutrient shortage.

104
105 Phased felling is recommended in the UK (Forest Commission 1988) and Ireland (Forest Service
106 2000) to diminish the negative impact of harvesting on water quality. Harvesting appropriately
107 sized coupes in a catchment at any one time can minimise the nutrient concentrations in the main
108 rivers (Rodgers et al. 2010). In their study, Cummins and Farrell (2003) found higher P
109 concentrations in the smaller drains, which covered higher proportion of harvesting area.
110 Rodgers et al. (2010) carried out a study on the impact of harvesting on the downstream
111 receiving river. The study stream and the main river have the areas of about 25 ha and 200 ha,
112 respectively. They found that although the P concentrations in the study stream were up to about
113 $420 \mu\text{g TRP l}^{-1}$, the average P concentrations in the receiving water of the main river were 7 ± 5
114 $\mu\text{g TRP l}^{-1}$ – about 10m upstream of the confluence of the study stream with the main river
115 (USC), and $9 \pm 8 \mu\text{g TRP l}^{-1}$ - about 30 m downstream of this confluence (DSC). In a storm
116 event, when the TRP in the study stream increased from about $3 \mu\text{g TRP l}^{-1}$ to $292 \mu\text{g TRP l}^{-1}$,
117 the TRP concentrations at the DSC in the main river increased from about $5 \mu\text{g TRP l}^{-1}$ to about
118 $11 \mu\text{g TRP l}^{-1}$, which was much lower than the critical value of $30 \mu\text{g TRP l}^{-1}$. Phased felling is
119 being used widely in Ireland. However, this management strategy does not reduce the total P load
120 leaving the harvested catchment, which could be bound to the bed sediment of the receiving
121 waters. If the P concentration in the river bed or lake sediment increases above the saturation
122 point, it could be released and become available to phytoplankton (EPA 2004).

123

124 **A possible novel practice – grass seeding**

125
126 The increase of P release is due to the disruption of the P cycle after harvesting, which reduces
127 the catchment's P conservation capacity. The conservation of nutrients is dependent on a
128 functional balance within the intra-system cycle of the ecosystem and critical to this balance is
129 the uptake of water and nutrients by plants. Previous studies have indicated that vegetation can
130 retain the available P *in situ* and reduce P release from forest activities. In Finland, Silvan et al.
131 (2004) demonstrated that plants are effective in retaining P in peatlands. In China and Australia
132 vetiver grass in buffer zones and wetlands has shown a huge potential for removing P from
133 wastewater and polluted water (Wagner et al. 2003). Loach (1968) found that *Molinia caerulea*
134 could uptake 3.4 kg TP/ha in the wet-heath soils. Sheaffer *et al.* (2008) reported a P uptake of 30
135 kg/ha by *Phalaris arundinacea* in their wastewater treatment sites. However, recovery of blanket
136 peat vegetation following forest harvesting usually takes several years. Connaghan (2007) found
137 that *Juncus effusus* could develop in riparian areas within three years of clearfelling, whereas
138 further away from the river where peat depth increased and soil fertility decreased vegetation
139 took six to ten years to recover.

140
141 It appears that natural re-vegetation arising from the seed bank is likely to be too slow to
142 significantly mitigate against the P from felling, which mainly occurs in the first three years after
143 harvesting (Rodgers et al. 2010; Cummins & Farrell 2003). In order to minimise the release of
144 nutrients to receiving waters after harvesting, a rational approach is to maximise the ground
145 vegetative growth over the first year after harvesting. This can be achieved by seeding the
146 clearfelled area with fast-growing suitable native vegetation. Sowing herbaceous species to
147 reduce soil erosion has been widely used during the first year after forest fire (Ruby 1989).
148 However, no study has been done on the possibility of sowing grass immediately after harvesting
149 to mitigate nutrient release. In this study, we examined if seeding grasses immediately after
150 harvesting would have potential as a new forestry best management practice (BMP). It is
151 hypothesized that by sowing the appropriate grass species in the blanket peat forest area
152 immediately after harvesting, significant amounts of P will be quickly taken up and conserved *in*
153 *situ*, which will result in reduced P release. To test this hypothesis, a trial experiment was first
154 carried out to identify the successful germination grass species in the blanket peatland. The grass

155 species were then sown in three harvested blanket peat forest plots. The biomass and P content of
156 the above ground vegetation were tested one year after grass seeding. In order to compare P up
157 take by vegetation in seeded versus natural re-vegetated areas, vegetation surveys were also
158 carried out in nine blanket peat forest sites which were harvested 1-5 years ago in the west of
159 Ireland.

160

161 **MATERIAL AND METHODS**

162

163 **Site description**

164

165 The study was carried out in nine sites in County Mayo in the west of Ireland (Figure 1; Table 2).
166 A total of nine sites were surveyed for natural re-vegetation in the blanket peat area after
167 harvesting. All the sites have similar soil type and hydrological conditions. They are covered
168 with blanket peat and overlie mainly quartzite and schist bedrock receiving an average
169 precipitation of over 2,000 mm per year. During the harvesting operation, boles were removed,
170 and tree residues (i.e. needles, twigs and branches) were collected together to form the brash
171 material mats and windrows. A second rotation of *Pinus contorta* was planted in all sites within 6
172 months after harvesting, except in the Glennamong and Teevaloughan. No fertilizer was applied
173 in the replanting operation.

174

175 **Trial and plot-scale experiment**

176

177 Ten widespread native Irish grass species, which were considered to be suitable for the purpose
178 of this study, were chosen for the trial experiment. They included: (1) *Agrostis capillaris*, (2)
179 *Epilobium angustifolium*, (3) *Eriophorum vaginatum*, (4) *Festuca rubra*, (5) *Holcus lanatus*, (6)
180 *Juncus effusus*, (7) *Lolium perenne*, (8) *Molinia caerulea*, (9) *Phalaris arudinacea* and (10)
181 *Phragmites australis*. Grass seeds were purchased from Emorsgate Seeds, Norfolk, UK.

182

183 Previous to the field trial test, a sample of seeds was tested for viability using a controlled
184 laboratory germination test (Rao et al. 2006). For each species, 25 seeds were placed in a petri-
185 dish on 42 mm diameter Whatman filter paper, with 8 replicates. 3 ml of distilled water was

186 added and the dishes were arranged in cultivation chambers with fluorescent tubes of white light
187 and a light/ darkness timer, at 15 - 25°C. Dishes were sampled daily during three weeks. A seed
188 was considered germinated when the radicle emerged. Distilled water was added whenever
189 moisture loss was detected.

190
191 In the field trial test, a total of thirty three plots with an area of 900 cm² each were defined in the
192 brash free area in Teevaloughan site (Site 7 in Figure 1 and Table 2). 300 seeds of each of the ten
193 candidate species were scattered on three replicate plots (10 x 3 plots). Three replicate control
194 plots were also included. The plots were surveyed weekly for four months. Percent seedling
195 emergence was calculated as the number of visible seedlings divided by the total number of seeds
196 scattered on each plot.

197
198 In the Glennamong site (Site 8 in Figure 1 and Table 2), an area of about 1 ha was clearfelled in
199 August 2009 and three plots of 100 m² (plot 1), 360 m² (plot 2) and 660 m² (plot 3) were
200 identified for the grass seeding plot-scale study. Each plot received the same sowing treatment,
201 which comprised of a 50:50 ratio of *Holcus lanatus* and *Agrostis capillaris*. The ground was
202 undisturbed and the seed was distributed evenly by hand at an initial rate of 36 kg ha⁻¹ on top of
203 the old forest residue layer in October 2009. December 2009 and January 2010 were
204 exceptionally cold months and a layer of snow measuring 30 cm in depth was recorded above the
205 seeded area. To eliminate the risk of seed establishment failure the plots were seeded again in
206 February 2010 at the same rate of 36 kg ha⁻¹. The area which was not seeded was used as control.

207
208 **Above ground vegetation biomass and P content measurement**

209
210 To estimate the aboveground vegetation biomass in nine study sites, thirty two 0.25 m x 0.25 m
211 quadrats were randomly sampled (Moore and Chapman 1986) in each site in August 2010. All
212 vegetation lying within the quadrat was harvested to within 1 cm and dried at 80 °C in the
213 laboratory on the day of collection for 48 hours. Samples were then weighed and the biomass
214 was calculated by using Equation 1. Total phosphorus (TP) content of the vegetation was
215 measured in accordance with Ryan et al. (2001). About 1 g of dry matter from each sample was
216 weighed, ground and put into a furnace at a temperature of 550°C overnight, then 5 ml of 2 N

217 HCl was added to extract the P and subsequently diluted to 50 ml with deionised water. P in the
218 solution was analyzed using a Konelab 20 Analyser (Konelab Ltd.).

219

$$220 \quad B_p = \frac{W_t}{S_t} \times 10000 \quad \text{Equation 1}$$

221 Where B_p is the biomass production (kg/ha); W_t is the total dry weight of the samples (kg) and
222 S_t is the total area (m²).

223

224 **Soil water extractable phosphorus (WEP) measurement**

225

226 100-mm-deep soil cores consisting of the humic and upper peat layers were collected using a 30-
227 mm-diameter gouge auger in the Glennamong site. 4, 8 and 14 soil samples were taken from plot
228 1, 2 and 3, respectively. Soil samples were analyzed for gravimetric water content and water
229 extractable P (WEP). The core samples were placed in bags, hand mixed until visually
230 homogenized, and subsamples of approximately 0.5 g (dry weight) were removed and extracted
231 in 30 ml of deionised water, and measured for P using a Konelab 20 Analyser. The remaining
232 core samples were dried to determine their gravimetric moisture contents (Macrae et al. 2005).

233

234 **Data analysis**

235

236 In order to investigate the effects of grass seeding on total above ground biomass production,
237 grass phosphorus uptake and soil water extractable phosphorus, data collected in the sown and
238 control plots were compared by using t-tests. All statistical analyses were conducted using the
239 SPSS statistical package for windows.

240

241 **RESULTS**

242

243 **Biomass and P content of natural re-vegetation in blanket peat forests after harvesting**

244

245 Figure 2 shows the biomass and P content of natural re-vegetation in 9 study sites. The biomass
246 of the above ground vegetation has a strong linear relationship with years after harvesting (Figure

247 2a). Vegetation appears to begin recolonising about one and half years after harvesting. 5 years
248 later the above ground vegetation linearly increased to about 6000 kg biomass ha⁻¹. P content in
249 the above ground vegetation also linearly increased and reached 3.5 kg TP ha⁻¹ five years after
250 harvesting (Figure 2b).

251

252 **Successful germination grass species**

253

254 Figure 3 shows the germination rates of ten grass species examined in laboratory conditions.
255 Most species germinated successfully within three weeks. *Agrostis capillaris*, *Phalaris*
256 *arudinacea*, *Phragmites australis* and *Holcus lanatus* have the highest viable rates of 99%,
257 68.5%, 64% and 60.5%, respectively. *Molinia caerulea* has the lowest rate of only 2%. Low
258 *Molinia caerulea* germination rates of 3% and 9% were also reported by other researchers
259 (Grime *et al.* 1981; Grime *et al.* 1988; Brys *et al.* 2005). In their study, Grime *et al.* (1981)
260 believed that the low germination percentage could be due to the low temperature.

261

262 During the 16 week field trial study in Teevaloughan, no grass growth was observed in the
263 control plots. In the study plots, 7 out of 10 grass species successfully germinated. At the end of
264 the study, *Holcus lanatus*, *Agrostis capillaris*, *Festuca rubra*, *Phragmites australis*, *Phalaris*
265 *arudinacea*, *Lolium perenne* and *Epilobium angustifolium* had the germination rates of 44%,
266 41%, 57%, 8%, 11%, 18% and 3%, respectively (Figure 4). *Holcus lanatus*, *Agrostis capillaris*
267 and *Festuca rubra* had the highest germination rates. However, *Festuca rubra* was observed to
268 be discoloured towards the end of the study period, as was noted by O'Toole *et al.* (1964), which
269 could be due to poor nutrients concentrations in the soil. Similar phenomena were also found in
270 *Phragmites australis* and *Lolium perenne*, which died back after week 7 and week 9,
271 respectively. Only 2 species –*Holcus lanatus* and *Agrostis capillaris* - germinated successfully in
272 the forested peatland habitat, and continued to grow and thrive up to 13 weeks after seeding and
273 are considered to be suitable for the purpose of this study.

274

275 **Impact of grass seeding on the biomass and P content of above ground vegetation**

276

277 Figure 5 shows the above ground biomass and P content in the sown and control plots. Seeding

278 of *Holcus lanatus* and *Agrostis capillaris* increased the above ground vegetation biomass and P
279 content one year after grass seeding. While there was very little vegetation growth in the control
280 plots (22 kg biomass ha⁻¹ with P content of 0.02kg TP ha⁻¹), vegetation biomass of 2753 kg ha⁻¹,
281 723 kg ha⁻¹ and 2050 kg ha⁻¹ were observed in the three study plots, giving the TP content of 2.83
282 kg ha⁻¹, 0.65 kg ha⁻¹ and 3.07 kg ha⁻¹, respectively (Figure 5). The above ground biomass and P
283 content in the sown plots was significantly higher than in the control plots (t test, p < 0.01). The
284 vegetation collected for testing was cut to 1cm aboveground level so these estimates could in fact
285 be higher when taken below ground biomass production into account which has been estimated
286 at 30% of the total plant biomass (Scholes and Hall 1996). In the UK, Goodwin et al. (1998)
287 found that *Holcus lanatus* produced biomass of 3405 kg ha⁻¹ with P concentrations of 1.64 mg
288 TP (g biomass)⁻¹, giving the total P content of 5.58 kg P ha⁻¹.

289

290 **Impact of grass seeding on soil water extractable phosphorus**

291

292 Figure 6 shows the water extractable phosphorus (WEP) concentrations in the sown plots and the
293 control plots. The WEP in the three study plots were 9 mg P (kg dry soil)⁻¹, 12 mg P (kg dry soil)⁻¹
294 and 6 mg P (kg dry soil)⁻¹, respectively, which was significantly lower than the value of 27 mg
295 P (kg dry soil)⁻¹ in the control areas (Figure 6) (t-test, p < 0.01).

296

297 **DISCUSSION**

298

299 In this study, *Calluna vulgaris*, *Molinia caerulea* and *Juncus effusus* are the main species
300 presenting at the natural re-vegetation sites. Similar findings were reported by Connaghan (2007).
301 Recovery of blanket peat vegetation following forest harvesting usually takes several years
302 (Connaghan 2007). In this study, it took five years for the natural re-vegetation to have the above
303 ground biomass of 6000 kg ha⁻¹. In a study by Allison & Ausden (2006) where plots were
304 established on pine plantation heathland, which was recently clearfelled, it took four years for an
305 increase in percentage frequency of *Calluna vulgaris* - a native heathland species - to appear. In
306 the west of Ireland, Connaghan (2007) carried out grass surveys in 8 blanket peat sites and found
307 that bare soil could still account for 35% one year after harvesting. The slow vegetation recovery
308 of the harvested blanket peat forest sites could be due to (1) a significant reduction of the seed

309 bank, (2) the burial of the seed bank by a thick layer of needle litter and (3) the slow germination
310 characteristics of the seeds typically found at these sites (Pywell et al. 2002).

311
312 In a study to improve the peatland for the purpose of agriculture, O'Toole et al. (1964)
313 highlighted the difficulties involved in attempting to identify successful species to seed peatland
314 in Ireland. Grennan and Mulqueen (1964) sowed seed mixtures of Italian ryegrass (*Lolium*
315 *multiflorum* L.), perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata*), timothy
316 (*Phleum pratense*), late flowering red clover (*Trifolium pratense*) and white clover (*Trifolium*
317 *repens* L.) in the blanket peatland and found that when there were no phosphorus additions, all
318 sown species died off after germination. In this study, only 2 grass species - *Holcus lanatus* and
319 *Agrostis capillaris* – were found to germinate successfully and continue to grow in the harvested
320 blanket peat forest areas. After 10 years of study, O'Toole et al. (1964) found that *Holcus lanatus*
321 was one of the most suitable species for seeding blanket peatland. In a study on the effects of
322 sowing native herbaceous species on the post-fire recovery in a heathland, Fernández-Abascal et
323 al. (2004) found that *Festuca rubra* appears before *Agrostis capillaris* and dies back earlier also.
324 They deemed *Agrostis capillaris* a more suitable species than *Festuca rubra*. In a study
325 investigating spatial and temporal patterns of growth and nutrient uptake of five co-existing
326 grasses, Veresoglou and Fitter (1984) found that *Holcus lanatus* displays a maximum nutrient
327 uptake when soil moisture content and extractable P were high. In contrast, they found *Agrostis*
328 *capillaris* had a tendency to uptake peak P when the soil was drier. The use of these two
329 herbaceous species in this study may complement one another through increasing uptake
330 duration.

331
332 Piirainen et al. (2007) found that as ground vegetation develops, P uptake and recycling can be
333 expected to diminish leaching over time. In this study, the relatively low WEP in the study plots
334 is likely to be a result of P up-take by the seeded grasses. *Holcus lanatus* and *Agrostis capillaris*
335 have been reported to have high P uptake capacity. Veresoglou and Fitter (1984) carried out a
336 study on nutrient uptake in five co-existing grasses and found that *Holcus lanatus* and *Agrostis*
337 *capillaris* could uptake $16.9 \text{ mg TP (m}^2 \cdot \text{d)}^{-1}$ and $2.7 \text{ mg TP (m}^2 \cdot \text{d)}^{-1}$, respectively. As WEP has
338 strong linear relationship with TP concentrations in the runoff (Schindler et al. 2009) and has
339 been proved to be a useful indicator of soluble P concentrations in peat soil runoff water (Daly

340 and Styles 2005), it is expected that the reduction of WEP in the grass seeded plots could result
341 in reduction of P runoff release.

342

343 **FUTURE RESEARCH**

344

345 Future research on the potential of grass seeding as forestry BMP should measure stream
346 chemistry to assess the success of the practice at protection water quality. It is expected that the P
347 measured in the grass would render a corresponding reduction in the P exported by the stream
348 after harvesting. However this has not been addressed by this study.

349

350 Sowing grass immediately after harvesting may affect forest regeneration. The inter-specific
351 interactions between seeded grasses and the replanted seedlings can be positive and negative, and
352 require further studies (Goldberg 1990; Maestr et al. 2004; Niu and Wan 2008; Maestr et al.
353 2009). The seeded grasses store significant amount of P released from the peat and the logging
354 residues. When the canopy of the next forest crop gradually closes over, the vegetation decays
355 and releases the nutrients for uptake by the growing trees, which will facilitate forest
356 regeneration. In fact, these nutrients slowly released from grass could be critical for the
357 reforestation in peatlands, because of the poor nutrients of the soil and the low fertilisation rate
358 limited by forest Guidelines (Forest service 2000). In contrast, the sowing grasses may compete
359 for nutrients and lights with replanted seedlings in the first few years after seeding (Li et al.
360 2010). However, this negative impact can be diminished by choosing the right seeding rates and
361 seeding distance from the seedlings. Future research could be carried out on an appropriate
362 seeding rate, to ensure the nutrient release to the receiving water, the competition with the
363 replanted seedlings and the costs can be minimized.

364

365 **CONCLUSION**

366

367 The results of this study indicate that (1) *Holcus lanatus* and *Agrostis capillaris* can be quickly
368 established in blanket peat forest areas after harvesting and (2) sowing *Holcus lanatus* and
369 *Agrostis capillaris* immediately after harvesting has the potential to immobilize the P that would
370 otherwise be available for leaching. One year after sowing, the P contents in the above ground

371 vegetation biomass could be up to 3.07 kg P ha⁻¹. Further research into the feasibility of grass
372 seeding as a potential new BMP is clearly warranted. Sowing the right grass species at
373 appropriate rates should diminish the deleterious effects of forest harvesting on surface water
374 quality and facilitate the forest regeneration.

375

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Table list

Table 1 Performance of buffer zones on P removal

Soil	Total P removal	Dissolved reactive P removal	Vegetations	Width (m)	References
Clay	40%	0	Grass	10	Uusi-Kämpä (2005)
Clay	40%	-70%	Natural vegetation	10	Uusi-Kämpä (2005)
Silty loam	14%		Grass	5	Syversen and Borch (2005)
Silty loam	26%		Grass	10	Syversen and Borch (2005)
Silty loam	40%		Grass	15	Syversen and Borch(2005)
	70%	75%	Grass	113	Bhattarai <i>et al.</i> , (2009)
Silt, loam and sand	31%		Grass	2	Abu-Zreig <i>et al.</i> , (2003)
Silt, loam and sand	89%		Grass	15	Abu-Zreig <i>et al.</i> , (2003)
	61%		Grass	4.6	Dillaha <i>et al.</i> , (1989)
	79%		Grass	9.1	Dillaha <i>et al.</i> , (1989)
	18%		Grass	4.6	Magette <i>et al.</i> , (1989)
	46%		Grass	9.1	Magette <i>et al.</i> , (1989)
		66%		8	Vought <i>et al.</i> , (1994)
		95%		16	Vought <i>et al.</i> , (1994)
Peatland	67%		Forest		Marttila and Kløve. (2010)
Clay and sand		41%	Grass	4.1	Yates and Prasher (2009)
Silt loam	42.9%		Grass	8	Mankin <i>et al.</i> , (2007)
	67%			20	Mander <i>et al.</i> , (1997)
	81%			28	Mander <i>et al.</i> , (1997)
Silt loam	91.8%		Shrub	8	Mankin <i>et al.</i> , (2007)
Loamy sand		63%	Forest/grass	75	Lowrance <i>et al.</i> , (1984)

Table 2 Background information on the study sites

Site No.	Site name	Tree species before harvesting	Year of planting	Year of harvesting	Main vegetation type
1	Srahrevagh	<i>lodgepole pine</i>	1971	2005	<i>Calluna vulgaris</i> , <i>Molinia caerulea</i> , <i>Eriophorum angustifolium</i>
2	Glendahurk-1	<i>lodgepole pine</i>	1971	2006	<i>Molinia caerulea</i> , <i>Calluna vulgaris</i> , <i>Juncus bulbous</i>
3	Altahoney	<i>lodgepole pine</i>	1971	2006	<i>Calluna vulgaris</i> , <i>Juncus effusus</i>
4	Maumaratta	<i>lodgepole pine</i>	1971	2007	<i>Molinia caerulea</i>
5	Goulaun	<i>lodgepole pine</i>	1971	2008	<i>Calluna vulgaris</i> , <i>Juncus bulbous</i> , <i>Sphagnum sp.</i>
6	Glendahurk-2	<i>lodgepole pine</i>	1971	2008	<i>Molinia caerulea</i> , <i>Calluna vulgaris</i> ,
7	Teevaloughan	<i>lodgepole pine and Sitka spruce</i>	1971	2009	-
8	Glennamong	<i>lodgepole pine</i>	1971	2009	-
9	Tawynahulty	<i>lodgepole pine</i>	1971	2009	-

Figure 1 Locations of the study sites (Site 1: Srahrevagh; site 2: Glendahurk-2; site 3: Altahoney; site 4: Maumaratta; site 5: Goulaun; site 6: Glendahurk-1; site 7: Teevaloughan; site 8: Glennamong; site 9: Tawnynahulty).

Figure 2 Relationship between biomass and P content of the above ground vegetation and years after harvesting

Figure 3 Successful germination rates of ten grass species examined in laboratory conditions (Error bars indicate standard deviation)

Figure 4 Germination rates of ten grass species planted in the trial experimental

Figure 5 Biomass and P content of above ground vegetation in the study plots and control in the Glennamong (Plot 1: 100 m², Plot 2: 360 m², Plot 3: 660 m²; The bars indicate the standard deviation)

Figure 6 Water extractable phosphorus (WEP) in the study plots and control area in Glennamong (Plot 1: 100 m², Plot 2: 360 m², Plot 3: 660 m²; The bars indicate the standard deviation)

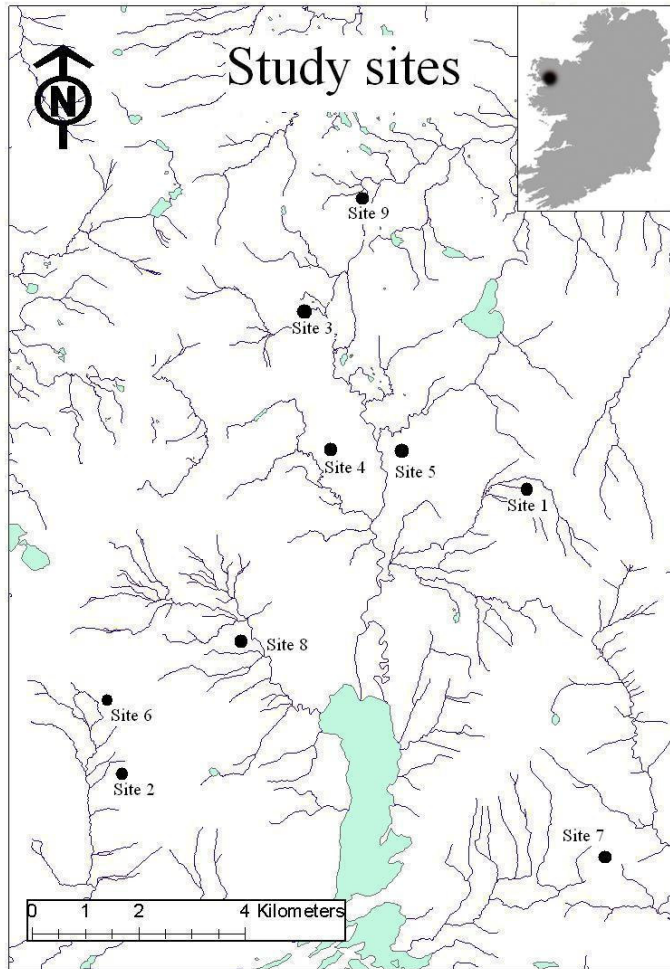


Figure 1

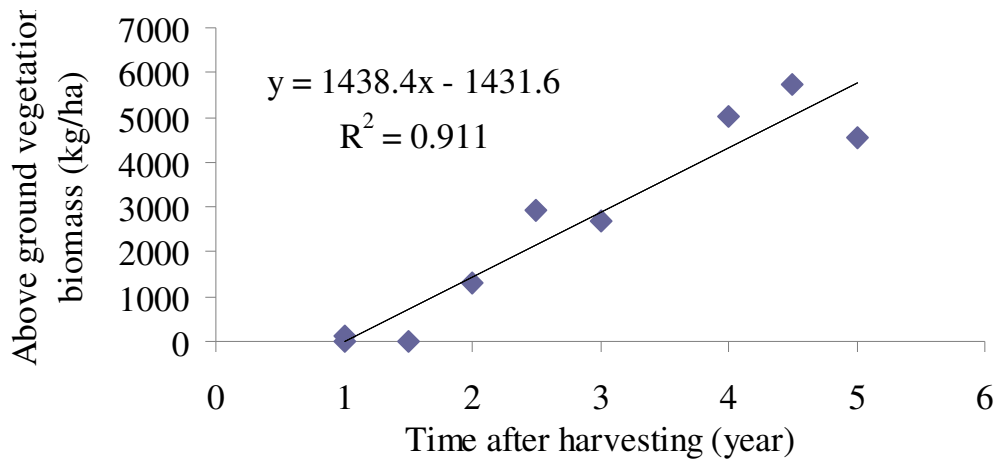


Figure 2a

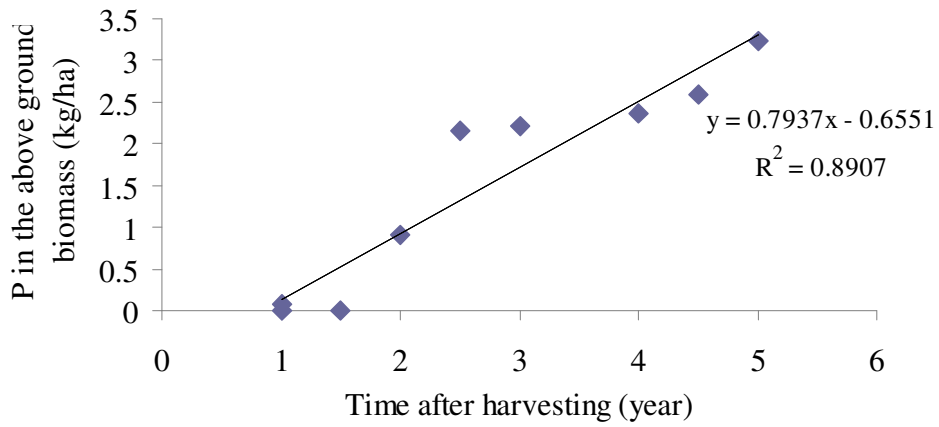


Figure 2b

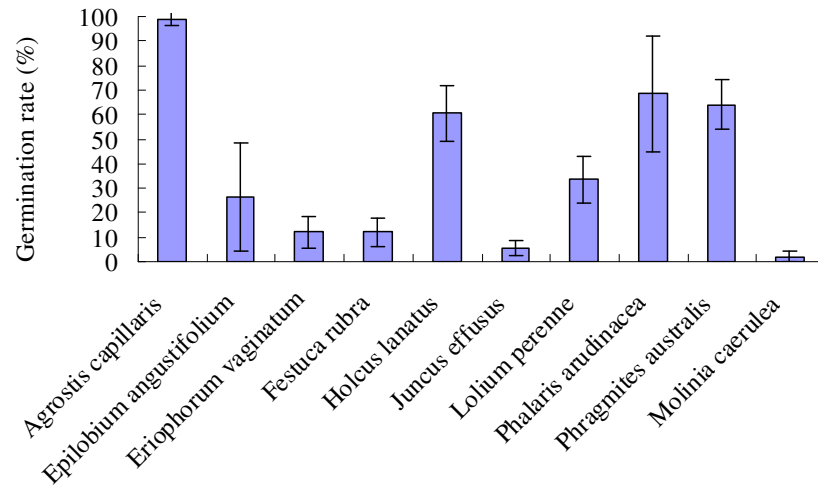


Figure 3

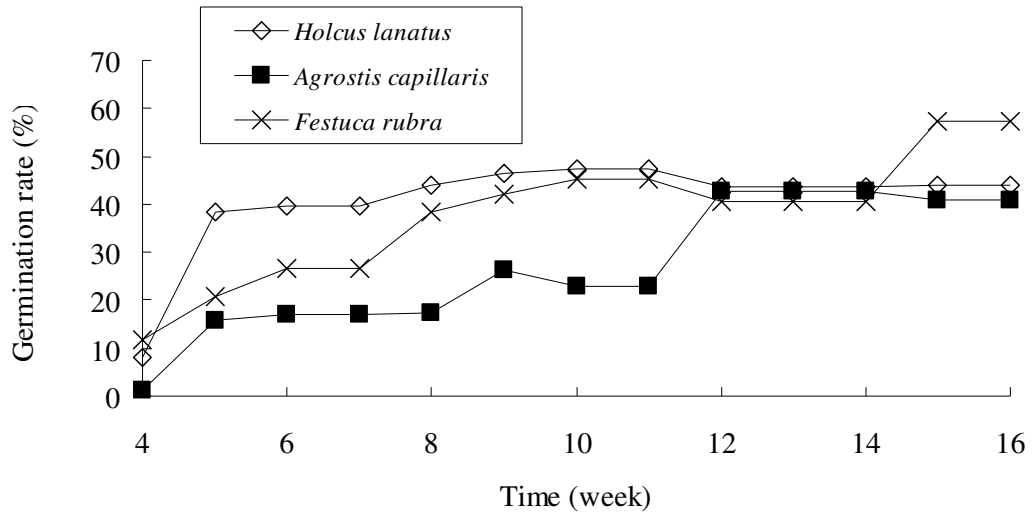


Figure 4a

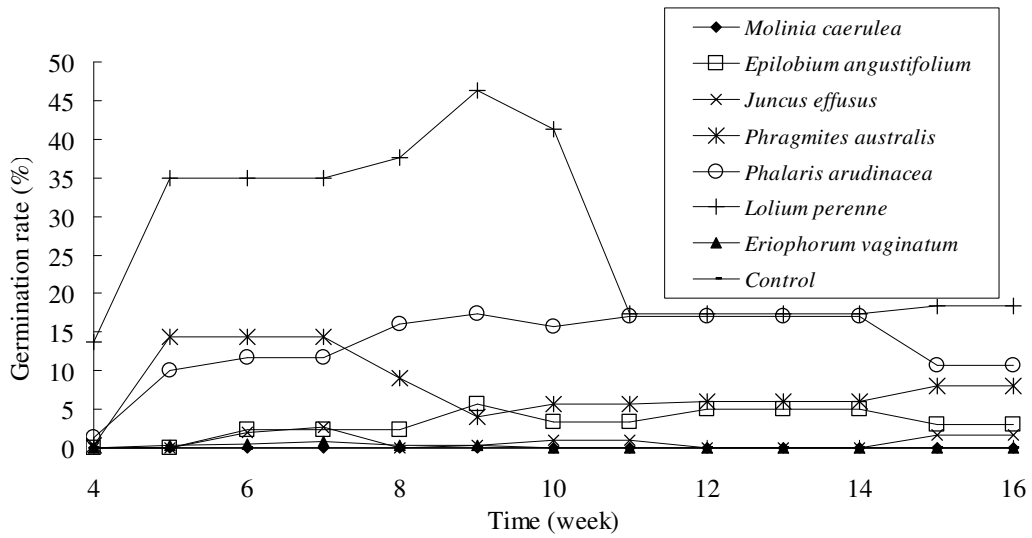


Figure 4b

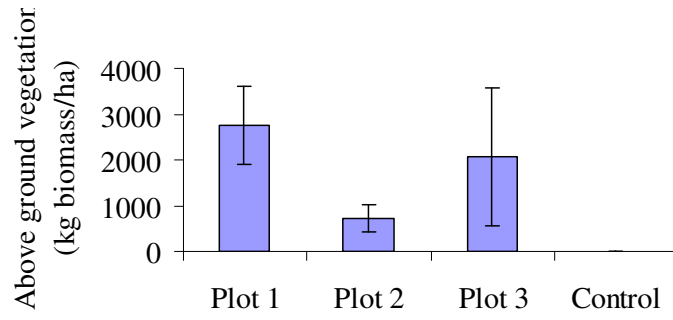


Figure 5a

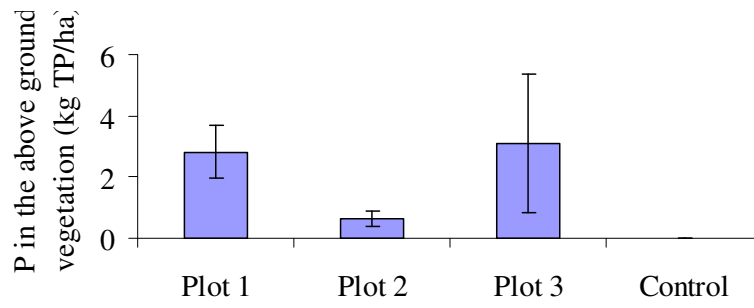


Figure 5b

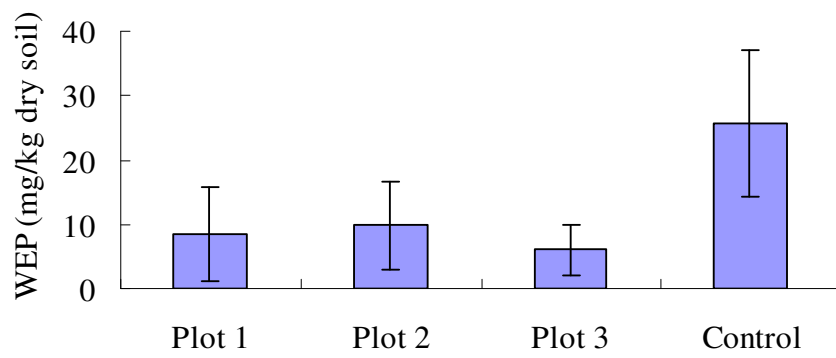


Figure 6