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7	NUTRIENT DYNAMICS IN A PEATLAND FOREST RIPARIAN BUFFER ZONE
8	AND IMPLICATIONS FOR THE ESTABLISHMENT OF PLANTED SAPLINGS
9	
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20	
21	ABSTRACT
22	
23	Forestry on peatland throughout the world is now focused on minimising destructive effects
24	to the surrounding environment, especially during harvesting. These effects may be mitigated
25	through the use of well-developed riparian buffers zones (RBZs). However, much of the
26	commercial forestry planted in Ireland and the UK in the mid 20 th century was planted
27	without adequate RBZs. The creation of new RBZs prior to clearfelling may be a possible
28	mitigation measure in these circumstances. The aim of this paper was to assess the nutrient

29 content and phosphorus (P) adsorption capacity of the soil, and survival of planted saplings in

a RBZ, positioned downslope from a standing forest and partly covered with brash mats, five 30 years after its establishment. Dissolved reactive phosphorus (DRP) concentrations were 31 significantly higher under the brash mats in the RBZ when compared to all other areas. The 32 standing forest had the highest concentrations of ammonium nitrogen (NH₄–N), while total 33 oxidised nitrogen (TON) was similar for all areas. Water extractable phosphorus and 34 desorption-adsorption testing also confirmed the high concentrations of P under the brash 35 mats, but P did not leach through the peat to the stream. The overall survival rate of the 36 saplings was relatively high, with over half of *Quercus robur* (oak) (57 %), Sorbus aucuparia 37 (rowan) (57 %) and Betula pendula (birch) (51 %) surviving. Salix cinerea (willow) (22 %), 38 Alnus glutinosa (alder) (25 %) and Ilex aquifolium (holly) (44 %) did not survive as 39 successfully. The RBZ was capable of providing nutrients for the survival of planted saplings, 40 fertilizing the peat with degrading brash material and preventing elevated levels of nutrients 41 42 entering the adjacent aquatic ecosystem.

43

44 *Keywords:* Phosphorus, forestry, brash mats, riparian buffer zones, vegetation

45 **1.** Introduction

46

Peatlands are found in over 175 countries worldwide, are mostly present in moist 47 temperate climates in the northern hemisphere (Sjörs, 1980), and cover approximately 48 3 % of the total landmass in the world (4,000,000 km²) (Bain et al., 2011). These 49 ecosystems produce 10 % of the global freshwater supply and one-third of the world's 50 soil carbon content (Joosten and Clarke, 2002). Approximately 150,000 km² of this 51 52 landmass has been drained for commercial forestry, while the area not commercially drained, but forested, is unknown (Joosten and Clarke, 2002). Ireland's forest cover 53 stands at 10.15 %, or 700,000 ha, of the total surface area of the island (National Forest 54 55 Inventory, 2007). The Irish State, under the management of the Forest Service, carried out the majority of the afforestation in the mid 20th century. This was mainly 56 coniferous plantation on non-productive agricultural land (Bacon, 2003). It is 57 estimated that 59.6 % (417,200 ha) of forestry in Ireland is on peat (National Forest 58 Inventory, 2007) and approximately 300,000 ha of afforestation is on upland peat areas 59 60 (EEA, 2004; Rodgers et al., 2010). Harvesting of forestry on peat can be challenging due to high soil water contents (gravimetric water contents usually exceed 800 % 61 (Long and Jennings, 2006)), low ground bearing capacities of between 10 and 60 kPa 62 63 (Owende et al., 2002) and the vulnerable nature of the ecosystem (Forest Research, 2009). In Ireland, forestry harvesting practice (including thinning) minimises soil 64 disturbance by adopting appropriate mitigation measures such as: (1) the use of low 65 66 ground pressure machines and (2) the laying of brash mats, consisting of small branches and logs under all paths used by the felling and extraction machinery. The 67 scale of soil disturbance to a clearfell site is dependant on a combination of factors, 68

including the number of passes by machinery, soil water content and the effective useof brash mats (Gerasimov and Katarov, 2010).

71

Forestry on peatland throughout the world is now moving towards a 'progressive 72 management approach' (Joosten and Clarke, 2002), which incorporates sustainable 73 74 timber production alongside multiple uses such as habitat restoration, ecological regeneration and the minimisation of any potentially negative effects to the 75 76 surrounding environment. These negative effects may include eutrophication (an increase in nutrient levels in a watercourse causing excessive flora growth (Sharpley et 77 al., 2003)), sedimentation (an increase in suspended sediment (SS) release to a 78 79 watercourse causing damage to water ecology (Rodgers et al., 2011)) and biodiversity loss (a change of species, genetic and ecosystem diversity (Walker, 1992)). Coillte, the 80 Irish State's current forest management company, is certified under the Forest 81 Stewardship Council (FSC) to enforce strict environmental, economic and social 82 criteria for sustainable forest management (Coillte, 2012). This progressive and 83 84 sustainable management approach includes more effective planning to provide protection to water-courses from drainage, fertilisation and afforestation, final harvest 85 and regeneration (Owende et al., 2002). Some of this protection may be provided by 86 87 riparian buffer zones (RBZs).

88

The standard forestry practice in Ireland and the UK at the time of afforestation (in the 1950s) led to trees being planted in areas adjacent to water-courses with no allowance for a RBZ (Broadmeadow and Nisbet, 2004; Ryder et al., 2011). This lack of a buffer may result in elevated nutrient and SS release into water-courses during clearfelling

93 (Carling et al., 2001). Other negative effects in the absence of RBZs are the excessive quantity of shade to the stream provided by the overhanging mature conifer 94 plantations, which leads to a death of the riparian vegetation and leaves the bank sides 95 susceptible to erosion (Broadmeadow and Nisbet, 2004). The presence of commercial 96 conifers close to the edge of a stream is also likely to affect the emergence of 97 invertebrates and the biodiversity in comparison to deciduous trees (Broadmeadow and 98 Nisbet, 2004; Kominoski et al., 2012). Much of the commercial coniferous forestry 99 100 planted in the 1950s is now at harvesting age and the adoption of current forest practice which creates RBZs will minimise the risk of negative impacts on receiving 101 102 waters for successive rotation.

103

Riparian buffer zones are used in forestry worldwide in areas such as Fennoscandia 104 (Syversen and Borch, 2005; Väänänen et al., 2008), the USA and Canada (Aust and 105 Blinn, 2004; Luke et al., 2007), and in New Zealand (Parkyn et al., 2005), to 106 ameliorate the negative impacts of forestry on adjacent water-courses. In the UK, 107 108 forestry planning since the 1990s has allowed for RBZs of native hardwoods to provide shade and shelter for wildlife and the stream inhabitants, and for existing 109 conifer streamside plantations to be felled and restored (Farmer and Nisbet, 2004). 110 111 Current forest practice in Ireland incorporates the use of buffer zones along waterways, with widths of between 10 m and 25 m depending on slope and soil erodibility (Forest 112 113 Service, 2000). However, RBZs need to be created in old forest stands on peat soil in 114 the most sustainable method possible.

115

116 A RBZ can be created in two ways: (1) by leaving an intact strip of forest adjacent to 117 the stream and clearfelling the main coupe of trees behind it, or (2) by harvesting the

trees from a strip beside the stream a number of years prior to clearfelling the main 118 coupe and allowing the area to revegetate, either naturally or artificially (Ryder et al., 119 2011). Forest buffer zones (option one, with trees left in buffer zone) in the UK have 120 been shown to be successful at allowing sedimentation to occur within the buffer 121 122 because of a slowing down of the surface runoff due to the well-structured and normally drier character of forest soils (Broadmeadow and Nisbet, 2004) and the 123 increased macroposity from tree roots and soil fauna (Goudie, 2006). This is coupled 124 125 with the damming effect created by falling debris and protruding roots in the forest buffer, which form sediment traps (Broadmeadow and Nisbet, 2004). However, this 126 option may not be practical in the west of Ireland due to thin soil depths, exposed sites 127 128 and high winds, leading to the increased chance of wind throw close to the watercourse, resulting in a higher risk of sedimentation and nutrient runoff. The second 129 RBZ creation option has potential to be adopted in Ireland, as it increases the primary 130 production in the stream, provides adequate shade and leaf litter, promotes greater 131 132 biodiversity and taxon richness, and increases sunlight to the watercourse (Ryder et al., 133 2011). Ground vegetation is also an important method of slowing down flow and 134 trapping sediment (Broadmeadow and Nisbet, 2004). It has been noted, however, that there can be a significant time delay in establishing ground vegetation on sites on 135 136 which the logging residues have been left (Broadmeadow and Nisbet, 2004). Ormerod et al. (1993) conducted a study on 11 upland streams in forestry catchments that had 137 been clearfelled from one to seven years prior to their study and noted that the streams 138 139 had retained some of the characteristics of a forestry catchment stream, even after 7 years of recovery. Ryder et al. (2011) found that the creation of RBZs resulted in 140 increased water discharge and significantly higher SS loads to receiving waters, an 141

elevated stream temperature, and minor changes in the average abundances and taxon
richness of macroinvertebrate communities. These effects were consistent with the
short-term negative impacts of felling at the time of creation of the RBZs.
Nevertheless, the creation of RBZs in this way was not felt to have catastrophic effects
on the receiving water course and its inhabitants, and any impacts were short-lived
(Ryder et al, 2011).

148

149 Coillte's District Strategic Plan 2011 – 2015 specifies a 20 m unplanted strip followed by 10 - 20 m of broadleaf plantation between a permanent water-course and conifer 150 151 forest (Coillte, 2011). This would result in the production of scrub broadleaf cover 152 with a protective function only (Coillte, 2011). The tree species planted in a RBZ are generally recommended to be the native variety and species choice will have an impact 153 on the efficiency of the buffer (Broadmeadow and Nisbet, 2004). Factors such as shade 154 and canopy density need to be taken into consideration, as RBZs are seen to function 155 more efficiently when there is a high level of ground covering plants (Broadmeadow 156 157 and Nisbet, 2004). Dense planting of species with larger leaf areas, like Alnus (alder) 158 or *Quercus* (oak), may provide too much shade for the successful growth of the lower ground covering plants and it is recommended that they are not planted in large groups, 159 160 but rather dispersed throughout the RBZ with species with lower canopy density such as Salix (willow), Betula (birch) and Sorbus (rowan) (Broadmeadow and Nisbet, 161 2004). Alder is also suspected of adding to stream acidification due to its ability to fix 162 163 nitrogen (N) from the atmosphere and, therefore, should be limited in RBZ regeneration projects (Broadmeadow and Nisbet, 2004). It is relatively unknown which 164

(if any) native deciduous species are likely to survive, if planted in upland peatsfollowing clearfelling of coniferous forest.

167

Due to the upland nature of these areas, many of these catchments include headwater 168 169 streams, which are important salmonid habitats and need to be protected from nutrient enrichment. The phosphorus (P) retention capacity of a soil is partly dependent on its 170 abundance of aluminium (Al) and iron (Fe) compounds (Giesler et al., 2005; Väänänen 171 172 et al., 2006). Aluminium and Fe are readily available in mineral soil, but are lacking in peat. However, as the mineral layers, where they occur, in riparian peatland buffers aid 173 in retaining higher quantities of P than peat further back from the riparian zone 174 175 (Väänänen et al., 2006), one option to mitigate P loss from peat forests to receiving waters is to create RBZs in existing forest stands prior to clearfelling the main coupe 176 behind the buffer zone (Ryder et al., 2011). Desorption-adsorption isotherms can 177 indicate the amount of P retained in the soil and show the adsorption properties of the 178 soil, while water extractable phosphorus (WEP) testing measures the readily available 179 180 fraction of the soil P and is used as an indicator of the amount of P that may be carried from a soil by surface runoff in storm events. Current recommended buffer widths in 181 Ireland of 10 - 25 m may not be capable of removing all nutrients from the runoff 182 183 during high storm events when the majority of the P is transported, as the retention time may be too short for uptake of soluble P by vegetation (Rodgers et al., 2010). It 184 185 has been shown that elevated levels of nutrients and sediment are frequently associated 186 with clearfelling operations for up to 4 years (Cummins and Farrell, 2003; Rodgers et al., 2010; Rodgers et al., 2011). Although P can become fixed in the soil and only a 187 small amount may be leached to water-courses (Haygarth et al., 1998), even small 188

concentrations (> 35 μ g L⁻¹ molydbate reactive phosphorus (MRP)) can have a 189 negative impact on water quality (Bowman, 2009), leading to restrictions of use for 190 fisheries, recreation, industry and drinking water (Elrashidi, 2011; Sharpley et al., 191 192 2003). Phosphorus can be found in both dissolved and sediment-bound (minerals and organic matter) forms. Dissolved P is bio-available and is therefore the main cause of 193 eutrophication in freshwater (Elrashidi., 2011; Regan et al., 2010; Sharpley et al., 194 195 2003; Väänänen et al., 2006). In Ireland, P is the limiting nutrient for eutrophication (Hutton et al., 2008) and is therefore the nutrient of greatest interest. The limit for 196 MRP, which is similar to dissolved reactive phosphorus (DRP) (Haygarth et al., 1997), 197 concentrations in Irish rivers to maintain 'good ecological status' is 35 μ g L⁻¹ and for 198 'high ecological status' is 25 μ g L⁻¹ (Bowman, 2009). A conservative value of 30 μ g L⁻ 199 ¹ has been statistically linked with lower biological O ratings (biological quality 200 ratings) (EPA, 2005), phytoplankton production (Daniel et al., 1998) and increased 201 algal growth in freshwaters (Haygarth et al., 2005). 202

203

The aim of this study was to examine the characteristics of an uncultivated RBZ, in an 204 upland peat area in the west of Ireland. The RBZ was clearfelled 5 yr previous to the 205 206 present study and restocked 1 yr later with group planted broadleaf species. Specifically, the following characteristics were examined in the 5 yr old RBZ: (1) the 207 deciduous species of trees which were able to survive and thrive (2) the soil and 208 surface water nutrient content, and (3) the P adsorbing capacity of the soil in the 209 regenerated zone and in the standing forest. This allowed for an assessment of the 210 function and performance of RBZs to supply nutrients to various native species of 211

212 growing saplings within peatland forestry, and to provide some protection against 213 nutrient export into receiving waters.

214

- 215 2. Materials and Methods
- 216
- 217 2.1. Study Site Description
- 218

219 The study site was located in the Altaconey (also known as Altahoney) forest in the Burrishoole catchment in Co. Mayo, Ireland (ITM reference 495380, 809170) (Figure 220 1). This catchment is situated in the Nephin Beg range at an approximate elevation of 221 222 135 m above sea level. The study stream is a third-order stream (Strahler, 1957) and is located within a subcatchment area of 416.2 ha, of which 176.4 ha is fully forested 223 (Ryder et al., 2011). The site has a north-westerly aspect, while the study stream, 224 which is one of the main tributaries to the Altaconey River, flows in a southwest-to-225 northeast direction to the north of the site before turning south to join the Altaconey 226 227 River. There is a moderate climate, which is heavily influenced by the proximity of the Atlantic Ocean, with average air temperatures of 13 °C in summer and 4 °C in winter. 228 The site is subjected to approximately 2400 mm of rainfall every year, with 289 rain 229 230 days between May 2010 and April 2011. As a result, the area is characterised by upland spate streams and gorged drains. The Altaconey river responds quickly to 231 rainfall events, and discharge frequency curves are characterised by steep amplitudes 232 233 and extremely fast falling crests, with 75 % of the total runoff in the Altaconey river originating from direct runoff (Muller, 2000). Upland spate streams are very 234 characteristic of peat catchments in the west of Ireland, particularly within the 235

236 Burrishoole catchment (Allott et al., 2005). The average slope across the buffer zone is 5 % and this increases to 35 % within 10 m of the stream, while the slope down the 237 stream bed is approximately 2.5 %. The stream bed consists of boulders and gravel, 238 while mineral-rich peat is evident along the banks and slopes adjacent to the 239 watercourse. Blanket peat of varying depth down to 2 m covers the site, which 240 241 overlays a sand and gravel layer on top of the Cullydoo formation of Srahmore quartzite and schist bedrock (McConnell and Gatley, 2006). This blanket peat is an in-242 243 situ blanket mire with an average gravimetric water content of greater than 85 %, dry bulk density of approximately 0.1 g cm⁻³ and a mineral content of approximately 3 %. 244 Bedrock does not protrude the surface of peat and the minimum peat depth is 0.3 m. 245 246 Closer to the stream, the mineral-rich peat is at a shallower depth of less than 1 m, has an average gravimetric water content of 35 %, a dry bulk density of approximately 1 g 247 cm⁻³, and a mineral content of approximately 95 %. During the course of the study, the 248 RBZ had a yearly average water table depth of 0.17 m, while the average water table 249 depth in the standing forest was 0.42 m. 250

251

252 The site was planted in 1966 with Sitka Spruce (*Picea sitchensis*) and Lodgepole Pine (Pinus contorta). In May 2006, an area of 2.49 ha 30 m north, 50 m south and 300 m 253 254 along the stream was clearfelled to create the RBZ (Ryder et al., 2011) (Figure 1). This is wider than the current buffer width recommendation of 10 - 25 m. In line with best 255 management practice (BMP), brash mats were used to prevent soil damage by the 256 257 heavy logging machinery. These mats were created by the harvester, which laid the logging residues of branches and un-merchantable logs in front of the harvester in 258 continuous, slope-dependant strips on which it travelled as it felled the trees. These 259

were left *in situ* on completion of clearfelling. Typical forest practice would normally be to windrow these brash mats into regular rows away from the watercourse when preparing the site for replanting. The direction and position of the brash mats on the southern side of the RBZ are shown in Figure 1. No rutting due to brash mat use was noted on site.

265

In April 2007, one year after felling, the area was replanted with native broadleaved 266 tree species from Coillte nurseries, including Ilex aquifolium (holly), Sorbus aucuparia 267 (rowan), Alnus glutinosa (common alder), Salix cinerea (grey willow), Betula pendula 268 (common birch) and Quercus robur (oak pedunculate). These saplings were all 269 270 containerised and of varying height ranges: (1) 0.4 - 0.8 m (birch, rowan and willow) (2) 0.3 - 0.5 m (oak and alder) (3) 0.1 - 0.2 m (holly). All saplings were 2 yr old, 271 except the birch, which was 3 yr old. No fertilizer was applied and the area was not 272 cultivated, but the saplings were pre-treated by dipping in Dimethoate (pyrethroid 273 insecticide) to protect them against the pine weevil (Hylobus abietis) (Ryder et al., 274 275 2011). This planting was not intended to be productive commercial forestry (expected survival rates of > 90 % after 4 yr), but aimed to examine which species of trees had 276 the potential to establish and survive in a hostile peatland environment. The perimeter 277 278 of the created buffer zone was then fenced off to protect it from grazing by sheep and wild animals, not including deer, as a sufficiently high (exceeding 2.1 m) fence was 279 280 not installed.

281

282 **2.2.** Vegetation

A detailed description of the location and composition of the sapling planting regime 284 in April 2007, post clearfelling, was conducted by Ryder et al. (2011) (Table 1). 285 Thirty-three plots in total, 20 on the southern side and 13 on the northern side of the 286 stream, were planted in a 2 x 2 m block pattern with a red stake placed in the centre of 287 288 the plot for identification (Figure 2). Nine trees per plot were planted, totalling 297 saplings of various tree species across the site (birch, alder, rowan, willow, holly and 289 oak). No planting took place within 5 m of the stream. In August 2011, as part of the 290 291 present study, a survey was carried out to determine the percentage survival and 292 increase in height of the surviving saplings. An increase in height was measured as the percentage change from the average original height (obtained from Coillte Nurseries, 293 294 pers. comm.) to the measured height on site in August 2011. For example, no change in height was denoted as a 0 % change, while an increase in height from 0.4 m to 1 m 295 (a change in height of 0.6 m) was given a 150 % increase. 296

297

298 2.3. Water Analysis

299

300 Subsurface and surface water samples were collected throughout the site and upstream and downstream of the buffer (Figure 1), mainly during high peak or storm events 301 302 from April 2010 to April 2011 (n=5 dates) to examine the movement and concentration of nutrients in the peat and surface runoff. Sampling was focused on the 303 304 RBZ, but also included the adjacent mature standing forest to allow comparison with 305 the original condition of the buffer prior to clearfelling in 2006. All samples were grouped under four specific locations: (1) 1 m from the stream (within the RBZ) (2) 306 under brash mats (within the RBZ) (3) under the vegetated areas (within the RBZ but 307

not under brash mats) and (4) the standing forest. The standing forest to the left of the RBZ (in Figure 1) is at the same topographical location as the RBZ, has a similar slope and peat depth, and has similar mineral-rich peat near the stream. The direction of groundwater flow on site was perpendicular to the stream and the brash mats. Therefore, any vegetated areas within the RBZ, which had no brash directly on them, were still influenced by the decaying brash material.

314

315 Standpipes were installed on site for subsurface water quality measurement and their locations are illustrated in Figure 1. Each sampling location comprised a cluster of 3 316 sampling tubes positioned at 20 cm, 50 cm, and 100 cm depths below the soil surface. 317 318 Each standpipe consisted of a qualpex pipe with an internal diameter of 1.1 cm. Holes were drilled in the lower 10 cm of the pipe and this was covered with gauze. A steel 319 rod was inserted into the pipe for support, as it was hand-pushed into the peat. The top 320 of the standpipes were covered to prevent the ingress of rain water. Any water lodged 321 in the bottom of the standpipe was removed under suction the day before water 322 323 sampling and the standpipe was allowed to fill overnight. Once extracted from the 324 pipe, water samples were filtered on site using 0.45 µm filters.

325

All water samples were returned to the laboratory and tested the following day or frozen for testing at a later date. The water quality parameters measured were: (1) DRP (2) ammonium-N (NH₄-N) (3) nitrate-N (NO₃-N) and (4) total oxidised nitrogen (TON; NO₃-N + nitrite-N (NO₂-N)). All water samples were tested in accordance with standard methods (APHA, 1998) using a nutrient analyser (Konelab 20; Thermo Clinical Labsystems, Finland). Nutrient data were log₁₀ transformed and analysed with ANOVA (analysis of variance) in Datadesk (Data Description Inc., USA), to ascertain the main sources of variation. Date, depth of soil where the sample was taken and the location of the sample site were included as explanatory variables.

335

336 Inverse distance weighted (IDW) analysis was carried out on the study area using ArcGIS (Release Version 9.3, Environmental Systems Research Institute (ERSI), 337 California, USA) to show the concentrations of nutrients under the decaying brash 338 339 mats. Inverse distance weighted analysis is a geospatial analytical tool which interpolates between sampling points, giving a greater weight to values closest to the 340 cell value being interpolated. A 'halo' effect on individual standpipes can be caused 341 342 where very high concentrations are in close proximity to lower concentrations, giving a shorter distance for interpolation between the points. 343

344

345 **2.4.** Soil Analysis

346

347 Water extractable phosphorus and desorption-adsorption isotherm testing were carried 348 out on samples of the soil from the RBZ and the adjacent mature standing forest. For both tests, a series of sampling points were selected in three transects parallel to the 349 350 stream in the RBZ at the following locations: (1) 1 m from the stream (n=10) (2) under the brash mat approximately 35 m from the stream (n=20), and (3) under a vegetated 351 352 area in-between brash mats approximately 45 m from the stream (n=20). Soil samples 353 (n=10) were also collected from the mature standing forest to represent the 354 contributing area. To select the sampling locations, a grid was laid out on the standing forest, and soil samples were extracted at random locations on the grid. Samples were 355

extracted with a 30 mm-diameter gouge auger after clearing of the Oi horizon, litter layer, which was mainly composed of degrading moss and needles. Väänänen et al. (2007) found that this layer had the lowest P retention capacity and it was therefore omitted from testing in the present study. Samples were then placed in sealed bags on site and were homogenized by hand in the laboratory.

361

For WEP tests, samples were collected in spring 2011 at two depths, 0 - 0.1 m and 0.1 - 0.5 m, along each transect. Sub-samples of peat (n=5 from each depth), equivalent to 1 g dry weight, were mixed with 30 ml of deionized water and shaken for 30 min at 225 rpm using a rotary shaker after Rodgers et al. (2010). The filtered supernatant water (filtered with 0.45 µm filters) was tested using a nutrient analyser (Konelab 20; Thermo Clinical Labsystems, Finland). The remaining soil sample was used to determine the gravimetric water contents.

369

For desorption-adsorption isotherm testing, the soil samples were collected at depth 370 increments of 0 - 0.15 m and 0.15 - 0.30 m below the soil surface. Phosphorus 371 solutions were made up to concentrations of 0, 0.2, 0.5, 1, 2, 3.5 and 10 mg P L⁻¹. Sub-372 samples of peat (n=3 for each depth and each concentration), equivalent to 1 g dry 373 weight, were mixed with 40 ml of the P solution and shaken for 1 hr at 180 rpm using 374 a rotary shaker. The 10 mg P L^{-1} solution was only used for the samples collected 1 m 375 from the stream due to the high mineral content. The solutions were then allowed to 376 377 stand for 23 hr before being placed in the shaker again for 5 min at 120 rpm after Väänänen et al. (2008). The filtered (0.45 µm) supernatant water was tested using a 378 nutrient analyser (Konelab 20; Thermo Clinical Labsystems, Finland). The remaining 379

soil sample was used to determine the gravimetric water contents and the mineral
 content, which was determined by loss on ignition (LOI) at 550 °C (BSI, 1990).

382

- 383 **3. Results and Discussion**
- 384

385 3.1. Vegetation

386

387 The overall survival rate of the planted saplings by 2011 was relatively high, given that the site was not cultivated, no fertiliser was applied and broadleaves were planted in an 388 environment hostile for their survival. Over half of oak (57 %), rowan (57 %) and 389 390 birch (51 %) saplings survived, suggesting that adequate nutrients were available in the RBZ. However, the survival of willow (22 %), alder (25 %) and holly (44 %) was not 391 as successful, but evidence of surviving saplings was found in some plots. For saplings 392 of an original height and nature similar to that of this study, some degree of protection 393 and care should be afforded to ensure growth (M. Sheehy Skeffington, pers. comm.) 394 395 and vegetation control is vital for a plant to thrive (Renou-Wilson et al., 2008). However, maintenance and grass removal is generally not performed on saplings 396 planted in peat areas. The study area was fenced off to protect the saplings from 397 398 grazing (except deer who could possibly jump the fence), but grass and other shading species were not removed from around the saplings. Sphagnum spp., Erica spp. and 399 Calluna spp had naturally regenerated in the RBZ, and were likely to be competing 400 401 aggressively with the planted saplings for both nutrients and light. It is not known if naturally regenerated ground vegetation alone would suffice for excessive nutrient 402 uptake if the native saplings were not planted in the RBZ. Further research should be 403

404 carried out to quantify the need for broadleaf plantation on clearfelled RBZs for405 nutrient uptake.

406

Figure 3 shows the percentage increase in the height of the surviving saplings from the 407 various tree species. Even though 57 % of oak survived after 5 yr on site, there was 408 very little growth in the saplings (26 %). In comparison, the 51 % of birch that 409 survived had a percentage increase in height of 70 %. Similarly, Renou-Willson (2008) 410 411 found that oak seedlings only grew 13.9 cm in 3 yr where mounding was employed on a cutaway peatland in the Irish midlands, whereas native birch was reported to grow up 412 to 50 cm per year in the same location (Renou et al., 2007). In the present study, 413 414 *Calluna vulgaris* was very evident on the site and was close to the oak plots; this may have negatively impacted on the survival and growth of oak. Frost et al. (1997) noted 415 that competition from grass turf led to a significant increase in the seedling mortality 416 of oak species such as Quercus robur and observed that C. vulgaris had a negative 417 impact on the growth of seedlings of *Q. petraea* due to the hindering of the mycorrhiza 418 419 development (the mutually beneficial relationship between the fungus and the roots of 420 the plant). Rowan had the greatest increase in height over all other species, with a growth of 73 % in surviving saplings. The willow that survived experienced no growth 421 422 over the study period (0 %) with the majority of the plants barely progressing beyond seedling stage. Of the 12 alder plants that were originally planted, 3 survived, and only 423 424 one of these 3 surviving plants experienced growth during the 5 yr study period. Holly, 425 at approximately 0.15 m, was the smallest in size to be originally planted and the surviving holly saplings (44 %) saw an overall growth of 22 %. 426

In the west of Ireland, natural broadleaf regeneration is rare and is largely limited to 428 river banks of higher mineral content than the surrounding infertile peatland 429 (Conaghan, 2007, unpublished report). No planting took place within 5 m of the 430 stream, but it was noted that there was a number of large trees (>2 m high) of various 431 species (oak, rowan and holly) on the banks of the stream, which were not planted 432 433 during the saplings' planting regime in 2007. Conaghan (2007, unpublished report) observed that growth of broadleaved trees is more successful in previously forested 434 435 areas with a peat depth of less than 1 m, and also noted that sites with better drainage and shelter fostered a better environment for the growth and survival of transplants. 436 The exposed nature of the Altaconey site and the depth of peat may have adversely 437 438 affected the growth rate of the willow, alder and holly species. Conaghan (2007, unpublished report) also observed that the survival of willow cuttings placed directly 439 into the peat was low, but larger willow transplants, which were grown for a time prior 440 to transplanting in more fertile soil, did thrive. In the present study, the height of the 441 willow saplings planted in April 2007 was approximately 60 cm, but this did not 442 443 appear to survive (22 %) or grow (0 %) very well. Overall, the survival rate of the planted saplings was relatively high, taking into consideration the lack of cultivation, 444 artificial fertilisation and maintenance, possibly grazing by deer and late planting of 445 446 the saplings. A greater growth rate may have been obtained if any of these management techniques had been employed in the early stages of establishment. 447

448

449 **3.2.** Water Analysis

450

451 Date and depth were not significant sources of variation for any of the nutrient data, while the location of the sampling site was significant for both DRP and NH₄-N 452 (ANOVA, p < 0.05). Dissolved reactive phosphorus was significantly higher under 453 brash in the RBZ and was significantly lower close to the river (p<0.05, LSD post-hoc 454 test) (Figure 8). Ammonium-nitrogen in the standing forest was significantly higher 455 than that recorded under brash or in the vegetated parts of the RBZ (p<0.05, LSD post-456 hoc test). Levels of TON were generally similar across all locations sampled (Figure 457 458 8). Surface and subsurface concentrations of NO₃-N were all low and were, in many cases, below the limits of detection with a maximum concentration of 20 μ g L⁻¹ 459 (results not shown). 460

461

462 Inverse Distance Weighted images, generated from the subsurface DRP concentrations, show the comparison of the RBZ with the standing forest (Figure 4). 463 464 This illustrates the higher nutrient concentration under the decaying brash mats in the 465 RBZ, which were left on site 5 yr before the present study. The DRP concentration reduced close to the stream edge due to the adsorption capacity of the mineral-rich peat 466 near the stream (discussed in Section 4.3). The high concentrations of DRP in the 467 subsurface water under the brash mats and surrounding areas did not leach to the 468 stream, as frequent analysis of stream water upstream and downstream of the buffer 469 showed that it remained at between $4 - 10 \ \mu g \ L^{-1}$ (Figure 5). These values represent no 470 change from buffer creation (May 2006 - January 2007) (Ryder et al., unpublished 471 report), when MRP concentrations were approximately 5 μ g L⁻¹ in the stream. This is 472 similar to the concentration in the rain water in the area, which was approximately 6 473

474 μ g L⁻¹ (data not shown; figure based on 5 random rain samples analysed by the authors 475 over the study period).

476

Brash mats were created on site during clearfelling to protect the peat from 477 consolidation due to heavy machinery. Since creation of the RBZ in May 2006, 5 yr 478 prior to the present study, the peat was fertilised by these brash mats, as seen in Figure 479 480 4, and may easily have been removed from site for commercial purposes (Forest Research, 2009). However, peat is considered highly vulnerable to a loss in fertility 481 and the removal of brash material from site can deplete the amount of base cations and 482 reduce available nutrients for the future growth of trees (Forest Research, 2009). The 483 potential loss of nutrients may be minimised through careful timing of brash removal 484 485 after the needles have fallen. Needles contain half-to-two thirds of total nutrients of the brash material and the needle drop time period may occur anywhere from 3 to 9 mo 486 487 following clearfelling, depending on local climate and season (Forest Research, 2009). 488 Hyvönen et al. (2000) showed that after 6 - 8 yr of decomposition, needles and twigs provided more nutrients for future tree growth as opposed to larger branches, and the 489 decomposition rate (and therefore nutrient addition) decreased with increasing branch 490 491 diameter. It was noted by Hyvönen et al. (2000), however, that 16 yr after clearfelling, the decomposing branches increased the carbon content of the forest floor by up to 50 492 - 100 % and woody logging residues provided more N and P release than needles. 493 Nutrient release from decaying brash may enter sensitive receiving waters (Stevens et 494 al., 1995), but this did not occur at the site of the present study. However, if brash was 495 496 to be removed from peatland sites following fertilisation from needle drop time period,

497 other factors such as sediment release and economic value of degraded brash would498 need to be considered.

499

500 **3.3.** Soil Analysis

501

The WEP was highest in the vegetated areas and under the brash mats in the RBZ 502 (Figure 6) due to the leaching of P from the decaying brash mat into the soil in the 5 yr 503 504 since the creation of the buffer zone. Similar results were obtained by Rodgers et al. (2010), who found that WEP under windrows of brash was significantly higher than 505 WEP in a windrow/brash-free area. The impact of the brash on WEP is a function of 506 507 the length of time it is left on site and the time taken for regeneration of vegetation to occur (Macrea et al., 2005). The role of vegetation in nutrient uptake was investigated 508 by O' Driscoll et al. (2011), who measured WEP concentrations of 6–9 mg P kg⁻¹ dry 509 soil from a seeded plot in contrast to 27 mg P kg⁻¹ dry soil from an unplanted plot 510 positioned on a recently harvested site. As the brash mats run perpendicular to the flow 511 512 of water in the present study, any vegetated areas down-slope from the brash mats, but not directly overlain by brash mats, were also affected. Water extractable phosphorus 513 decreased closer to the stream, but this reduction was due to the presence of a mineral-514 rich peat along the bank of the stream, which protected the water-course from 515 increases in nutrient concentration. As there is a strong correlation between WEP 516 measured in peat and DRP concentration in surface runoff (O' Driscoll et al., 2011), 517 518 the potential for high concentrations of DRP in surface runoff from under the brash mats is high. 519

The desorption-adsorption isotherms of P adsorption by weight (mg g⁻¹ dry material) 521 showed that, while the P adsorption capacity was of the same magnitude in all areas 522 for the 0 - 0.15 m depth examined, more P adsorption took place at a distance of 1 m 523 from the stream at the 0.15 - 0.3 m depth (Figure 7). This was due to the mineral-rich 524 peat at this location. At both depths, the peat directly underneath the brash mat 525 appeared to be at P saturation and had little remaining adsorption capacity (reflecting 526 the high DRP concentrations at these points; Figure 4). As is typical for soils with a 527 528 low P retention capacity, the P adsorbed to the peat continued to rise with higher P solutions and a maximum adsorption value was not reached (Väänänen et al., 2007). 529 Desorption of P from the peat in all areas and at both depths occurred when it was 530 overlain with water with a P concentration of 0 mg L^{-1} (Figure 7). This was greatest 531 under the brash mats and under the vegetated areas, especially at the 0 - 0.15 m depth. 532

533

When the results were expressed per volume of dry material (mg cm^{-3}) and the bulk 534 densities of the mineral-rich peat soil 1 m from the stream (approximately 1 g cm⁻³) 535 and the peat further up the buffer $(35 - 45 \text{ m from the stream}; approximately 0.1 \text{ g cm}^{-1})$ 536 ³) were considered, the differences in the adsorption capacity of the soils was more 537 pronounced: the P adsorption capacity of the mineral-rich peat 1 m from the stream 538 539 were much higher than the peat layers further up the buffer. Loss on ignition analysis showed that there was 90 - 95 % mineral content in the samples 1 m from the stream, 540 while the samples further back from the stream (35 - 45 m) had a 98 - 100 % organic 541 542 content. This trend was similar to what was found by Väänänen et al. (2006) in their study on peat and mineral soils in Finland. 543

545 **4.** Conclusions

546

The created RBZ was capable of providing nutrients to planted saplings,
 fertilizing the peat with degrading brash material and preventing elevated levels
 of nutrients entering the adjacent water-course. This indicates that a created
 RBZ is a realistic management option in peatland forests.

- The overall survival rate of the planted saplings in the RBZ was relatively high,
 with over half of oak, rowan and birch saplings surviving after 5 yr. The
 survival of willow, alder and holly was not as successful, possibly due to a
 number of factors including the exposed nature of the site, peat depth,
 maintenance, cultivation and fertilization.
- 3. Dissolved reactive phosphorus concentrations were significantly higher under 556 the brash mats in the RBZ compared to all other areas. These high 557 concentrations of DRP were due to the degrading brash mats left on site 558 following clearfelling. However, this did not leach to the stream as the 559 560 concentration of DRP upstream and downstream of the buffer remained low throughout the study. The standing forest had the highest concentrations of 561 NH_4-N , while TON was similar for all areas. It is recommended to leave brash 562 mats on site following clearfelling to fertilise the site and to reduce disturbance 563 to the vulnerable peat sites. 564
- 4. Water extractable phosphorus and desorption-adsorption testing also confirmed
 the high concentrations of P under the brash mats. Water extractable
 phosphorus was highest in the vegetated areas and under the brash mats in the

RBZ. Desorption of P was highest under the brash mats and adsorption wasgreatest in the mineral-rich peat soil adjacent to the stream.

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- Figure 1. Location of Altaconey Riparian Buffer Zone (RBZ) with all standpipes (20,
- 50 and 100 cm depths), stream sampling locations upstream and downstream of buffer,
- and rain gauge.









Figure 2. Sapling plot planting locations



Figure 3. Percentage average increase in height of surviving saplings on site from
April 2007 to August 2011 per tree species. Error bars indicate standard error.

Figure 4. Average dissolved reactive phosphorus (DRP) concentration from 20 cm, 50 cm and 100 cm depths below the ground surface measured over a 12 month period (April 2010 – April 2011) and expressed as μ g L⁻¹





Figure 5. Dissolved reactive phosphorus (DRP) concentration measured over a 12 month period (April 2010 – April 2011) and expressed as $\mu g L^{-1}$ in stream water upstream and downstream of the RBZ.



Figure 6. Water extractable Phosphorus (WEP) concentration (mg kg⁻¹ dry soil) in riparian buffer zone (1 m from the stream, under brash and vegetated area) and forest at 0 - 0.1 m and 0.1 - 0.5 m depths. Error bars indicate standard deviation.



Figure 7: Phosphorus (P) adsorption isotherms in riparian buffer zone and forest by 830 weight (mg g⁻¹) on left and by volume (mg cm⁻³) on right at 0 - 0.15 m (top) and 0.15-831 0.30 m (bottom) depths. Log scale on X axis for clarity. 832



Phosphorus in equilibrium solution (mg L⁻¹)



Figure 8: Box Plots of dissolved reactive phosphorus (DRP) (top), ammonium-N (NH₄-N) (middle) and total oxidized nitrogen (TON) (bottom) for regenerated buffer area (1 m from the stream, under brash mats and under the vegetated area) and standing forest at 20 cm, 50 cm and 100 cm depths from April 2010 – April 2011. All units are μ g L⁻¹.



845





	April 2007							August 2011					
Plot No.	Birch	Oak	Rowan	Willow	Holly	Alder	Birch	Oak	Rowan	Willow	Holly	Alder	
1	9	-	-	-	-	-	7	-	-	-	-	-	
2	-	9	-	-	-	-	-	8	-	-	-	-	
3	-	9	-	-	-	-	-	5	-	-	-	-	
4	9	-	-	-	-	-	6	-	-	-	-	-	
5	-	-	9	-	-	-	-	-	3	-	-	-	
6	-	9	-	-	-	-	-	0	-	-	-	-	
7	-	9	-	-	-	-	-	8	-	-	-	-	
8	9	-	-	-	-	-	2	-	-	-	-	-	
9	-	9	-	-	-	-	-	2	-	-	-	-	
10	-	9	-	-	-	-	-	4	-	-	-	-	
11	9	-	-	-	-	-	9	-	-	-	-	-	
12	-	9	-	-	-	-	-	9	-	-	-	-	
13	6	-	3	-	-	-	3	-	1	-	-	-	
14	9	-	-	-	-	-	3	-	-	-	-	-	
15	6	-	3	-	-	-	6	-	1	-	-	-	
16	6	-	3	-	-	-	2	-	2	-	-	-	
17	-	-	9	-	-	-		-	4	-	-	-	
18	9	-	-	-	-	-	9	-	-	-	-	-	
19	6	-	3	-	-	-	4	-	2	-	-	-	
20	6	-	3	-	-	-	4	-	3	-	-	-	
21	9	-	-	-	-	-	3	-	-	-	-	-	
22	6	-	-	-	-	3	3	-	-	-	-	1	
23	6	-	-	-	-	3	1	-	-	-	-	1	
24	-	-	-	9	-	-	-	-	-	2	-	-	
25	9	-	-	-	-	-	6	-	-	-	-	-	
26	-	-	9	-	-	-	-	-	2	-	-	-	
27	6	-	-	-	-	3	2	-	-	-	-	1	
28	6	-	-	-	-	3	2	-	-	-	-	-	
29	6	-	3	-	-	-	-	-	1	-	-	-	
30	-	-	6	-	3	-	-	-	5	-	1	-	
31	-	-	6	-	3	-	-	-	6	-	2	-	
32	-	-	6	-	3	-	-	-	6	-	1	-	
33	9	-	-	-	-	-	0	-	-	-	-	-	
Total	141	63	63	9	9	12	72	36	36	2	4	3	
					% Sı	urvival	51%	57%	57%	22%	44%	25%	

Table 1: Description of the location and composition of the sapling planting regime in
April 2007, post clearfelling and surviving trees in August 2011.