



## **Nutrient dynamics in a peatland forest riparian buffer zone and implications for the establishment of planted saplings**

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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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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<sup>th</sup> 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

30 a RBZ, positioned downslope from a standing forest and partly covered with brash mats, five  
31 years after its establishment. Dissolved reactive phosphorus (DRP) concentrations were  
32 significantly higher under the brash mats in the RBZ when compared to all other areas. The  
33 standing forest had the highest concentrations of ammonium nitrogen ( $\text{NH}_4\text{-N}$ ), while total  
34 oxidised nitrogen (TON) was similar for all areas. Water extractable phosphorus and  
35 desorption-adsorption testing also confirmed the high concentrations of P under the brash  
36 mats, but P did not leach through the peat to the stream. The overall survival rate of the  
37 saplings was relatively high, with over half of *Quercus robur* (oak) (57 %), *Sorbus aucuparia*  
38 (rowan) (57 %) and *Betula pendula* (birch) (51 %) surviving. *Salix cinerea* (willow) (22 %),  
39 *Alnus glutinosa* (alder) (25 %) and *Ilex aquifolium* (holly) (44 %) did not survive as  
40 successfully. The RBZ was capable of providing nutrients for the survival of planted saplings,  
41 fertilizing the peat with degrading brash material and preventing elevated levels of nutrients  
42 entering the adjacent aquatic ecosystem.

43

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

45 **1. Introduction**

46

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

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

71

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

88

89 The standard forestry practice in Ireland and the UK at the time of afforestation (in the  
90 1950s) led to trees being planted in areas adjacent to water-courses with no allowance  
91 for a RBZ (Broadmeadow and Nisbet, 2004; Ryder et al., 2011). This lack of a buffer  
92 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  
94 quantity of shade to the stream provided by the overhanging mature conifer  
95 plantations, which leads to a death of the riparian vegetation and leaves the bank sides  
96 susceptible to erosion (Broadmeadow and Nisbet, 2004). The presence of commercial  
97 conifers close to the edge of a stream is also likely to affect the emergence of  
98 invertebrates and the biodiversity in comparison to deciduous trees (Broadmeadow and  
99 Nisbet, 2004; Kominoski et al., 2012). Much of the commercial coniferous forestry  
100 planted in the 1950s is now at harvesting age and the adoption of current forest  
101 practice which creates RBZs will minimise the risk of negative impacts on receiving  
102 waters for successive rotation.

103

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

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

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

148

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

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

167

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

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

203

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

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

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

251

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

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

265

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

281

## 282 **2.2. Vegetation**

283

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

297

### 298 **2.3. Water Analysis**

299

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

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

314

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

326 All water samples were returned to the laboratory and tested the following day or  
327 frozen for testing at a later date. The water quality parameters measured were: (1) DRP  
328 (2) ammonium-N ( $\text{NH}_4\text{-N}$ ) (3) nitrate-N ( $\text{NO}_3\text{-N}$ ) and (4) total oxidised nitrogen  
329 (TON;  $\text{NO}_3\text{-N}$  + nitrite-N ( $\text{NO}_2\text{-N}$ )). All water samples were tested in accordance with  
330 standard methods (APHA, 1998) using a nutrient analyser (Konelab 20; Thermo  
331 Clinical LabSystems, Finland). Nutrient data were  $\log_{10}$  transformed and analysed with

332 ANOVA (analysis of variance) in Datadesk (Data Description Inc., USA), to ascertain  
333 the main sources of variation. Date, depth of soil where the sample was taken and the  
334 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  
337 ArcGIS (Release Version 9.3, Environmental Systems Research Institute (ERSI),  
338 California, USA) to show the concentrations of nutrients under the decaying brash  
339 mats. Inverse distance weighted analysis is a geospatial analytical tool which  
340 interpolates between sampling points, giving a greater weight to values closest to the  
341 cell value being interpolated. A 'halo' effect on individual standpipes can be caused  
342 where very high concentrations are in close proximity to lower concentrations, giving a  
343 shorter distance for interpolation between the points.

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  
349 both tests, a series of sampling points were selected in three transects parallel to the  
350 stream in the RBZ at the following locations: (1) 1 m from the stream (n=10) (2) under  
351 the brash mat approximately 35 m from the stream (n=20), and (3) under a vegetated  
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  
355 forest, and soil samples were extracted at random locations on the grid. Samples were

356 extracted with a 30 mm-diameter gouge auger after clearing of the Oi horizon, litter  
357 layer, which was mainly composed of degrading moss and needles. Väänänen et al.  
358 (2007) found that this layer had the lowest P retention capacity and it was therefore  
359 omitted from testing in the present study. Samples were then placed in sealed bags on  
360 site and were homogenized by hand in the laboratory.

361

362 For WEP tests, samples were collected in spring 2011 at two depths, 0 – 0.1 m and 0.1  
363 – 0.5 m, along each transect. Sub-samples of peat (n=5 from each depth), equivalent to  
364 1 g dry weight, were mixed with 30 ml of deionized water and shaken for 30 min at  
365 225 rpm using a rotary shaker after Rodgers et al. (2010). The filtered supernatant  
366 water (filtered with 0.45 µm filters) was tested using a nutrient analyser (Konelab 20;  
367 Thermo Clinical Labsystems, Finland). The remaining soil sample was used to  
368 determine the gravimetric water contents.

369

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

380 soil sample was used to determine the gravimetric water contents and the mineral  
381 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  
388 the site was not cultivated, no fertiliser was applied and broadleaves were planted in an  
389 environment hostile for their survival. Over half of oak (57 %), rowan (57 %) and  
390 birch (51 %) saplings survived, suggesting that adequate nutrients were available in the  
391 RBZ. However, the survival of willow (22 %), alder (25 %) and holly (44 %) was not  
392 as successful, but evidence of surviving saplings was found in some plots. For saplings  
393 of an original height and nature similar to that of this study, some degree of protection  
394 and care should be afforded to ensure growth (M. Sheehy Skeffington, pers. comm.)  
395 and vegetation control is vital for a plant to thrive (Renou-Wilson et al., 2008).  
396 However, maintenance and grass removal is generally not performed on saplings  
397 planted in peat areas. The study area was fenced off to protect the saplings from  
398 grazing (except deer who could possibly jump the fence), but grass and other shading  
399 species were not removed from around the saplings. *Sphagnum* spp., *Erica* spp. and  
400 *Calluna* spp had naturally regenerated in the RBZ, and were likely to be competing  
401 aggressively with the planted saplings for both nutrients and light. It is not known if  
402 naturally regenerated ground vegetation alone would suffice for excessive nutrient  
403 uptake if the native saplings were not planted in the RBZ. Further research should be

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

406

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

427

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

448

### 449 **3.2. Water Analysis**

450

451 Date and depth were not significant sources of variation for any of the nutrient data,  
452 while the location of the sampling site was significant for both DRP and NH<sub>4</sub>-N  
453 (ANOVA,  $p < 0.05$ ). Dissolved reactive phosphorus was significantly higher under  
454 brush in the RBZ and was significantly lower close to the river ( $p < 0.05$ , LSD post-hoc  
455 test) (Figure 8). Ammonium-nitrogen in the standing forest was significantly higher  
456 than that recorded under brush or in the vegetated parts of the RBZ ( $p < 0.05$ , LSD post-  
457 hoc test). Levels of TON were generally similar across all locations sampled (Figure  
458 8). Surface and subsurface concentrations of NO<sub>3</sub>-N were all low and were, in many  
459 cases, below the limits of detection with a maximum concentration of 20 µg L<sup>-1</sup>  
460 (results not shown).

461

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

474  $\mu\text{g L}^{-1}$  (data not shown; figure based on 5 random rain samples analysed by the authors  
475 over the study period).

476

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

499

### 500 **3.3. Soil Analysis**

501

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

520

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

533

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

544

545 **4. Conclusions**

546

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

551 2. The overall survival rate of the planted saplings in the RBZ was relatively high,  
552 with over half of oak, rowan and birch saplings surviving after 5 yr. The  
553 survival of willow, alder and holly was not as successful, possibly due to a  
554 number of factors including the exposed nature of the site, peat depth,  
555 maintenance, cultivation and fertilization.

556 3. Dissolved reactive phosphorus concentrations were significantly higher under  
557 the brush mats in the RBZ compared to all other areas. These high  
558 concentrations of DRP were due to the degrading brush mats left on site  
559 following clearfelling. However, this did not leach to the stream as the  
560 concentration of DRP upstream and downstream of the buffer remained low  
561 throughout the study. The standing forest had the highest concentrations of  
562  $\text{NH}_4\text{-N}$ , while TON was similar for all areas. It is recommended to leave brush  
563 mats on site following clearfelling to fertilise the site and to reduce disturbance  
564 to the vulnerable peat sites.

565 4. Water extractable phosphorus and desorption-adsorption testing also confirmed  
566 the high concentrations of P under the brush mats. Water extractable  
567 phosphorus was highest in the vegetated areas and under the brush mats in the

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

570

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572

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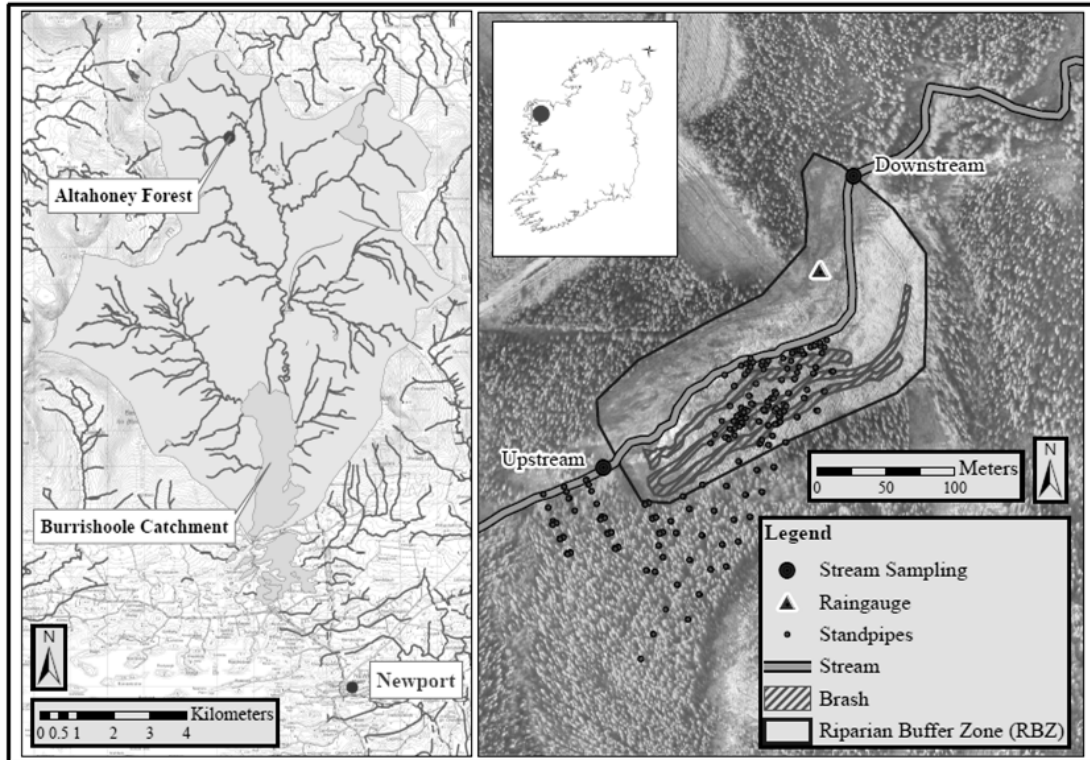
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740 **Figure 1.** Location of Altaconey Riparian Buffer Zone (RBZ) with all standpipes (20,  
741 50 and 100 cm depths), stream sampling locations upstream and downstream of buffer,  
742 and rain gauge.



754 **Figure 2.** Sapling plot planting locations



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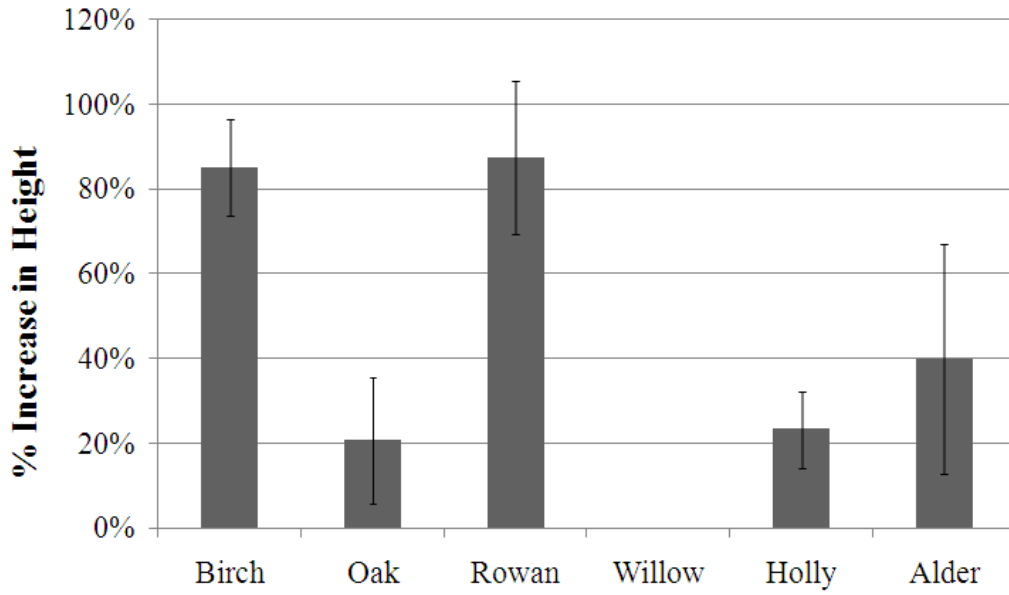
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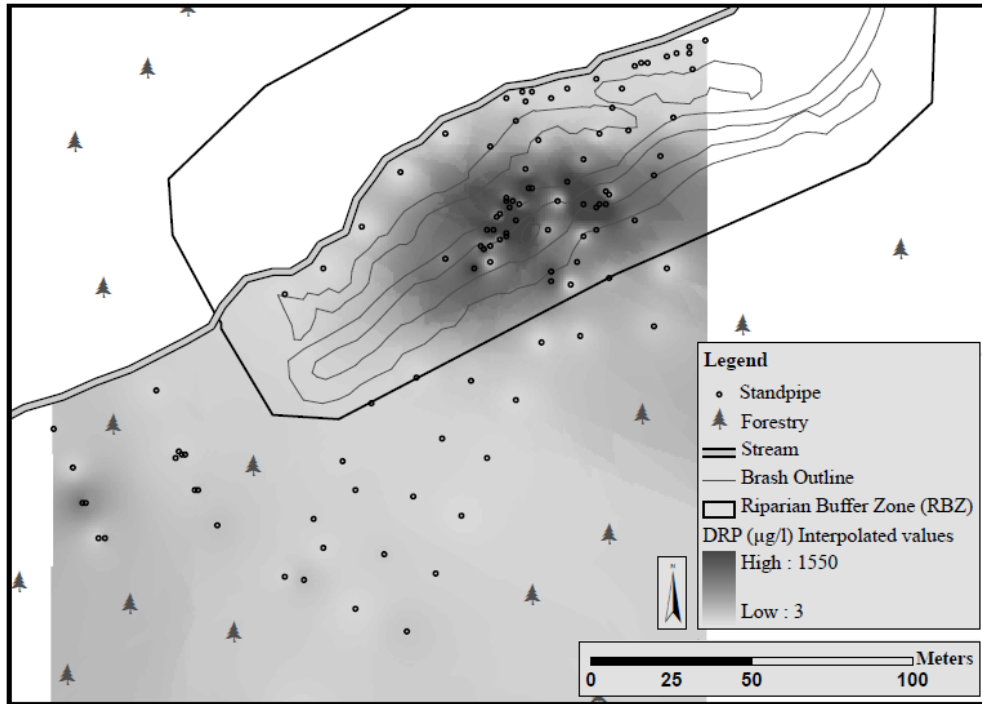
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768 **Figure 3.** Percentage average increase in height of surviving saplings on site from  
769 April 2007 to August 2011 per tree species. Error bars indicate standard error.



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783 **Figure 4.** Average dissolved reactive phosphorus (DRP) concentration from 20 cm, 50  
784 cm and 100 cm depths below the ground surface measured over a 12 month period  
785 (April 2010 – April 2011) and expressed as  $\mu\text{g L}^{-1}$



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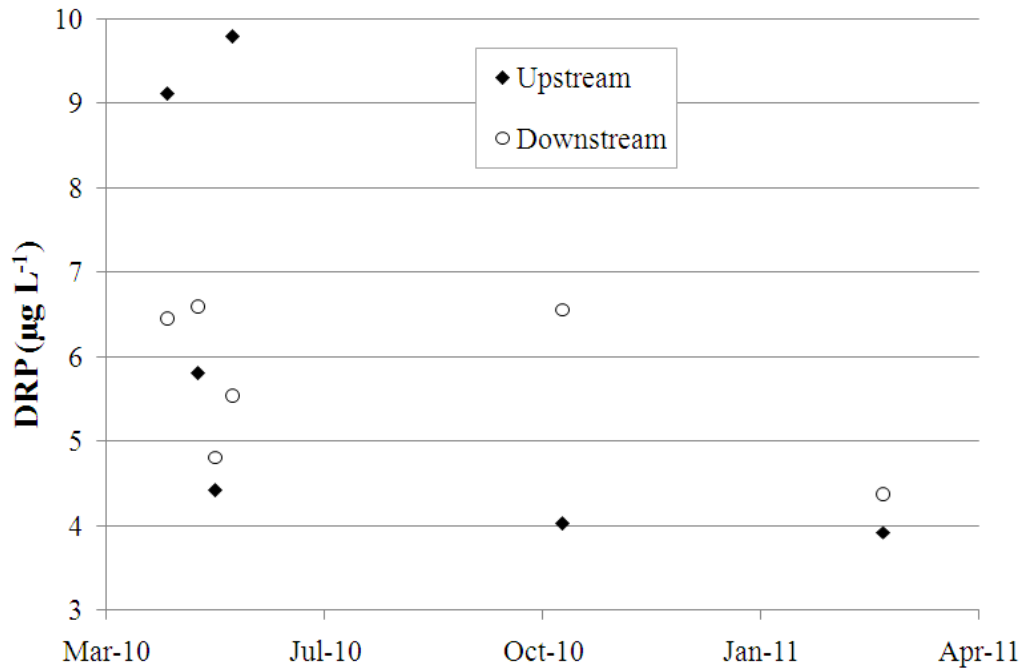
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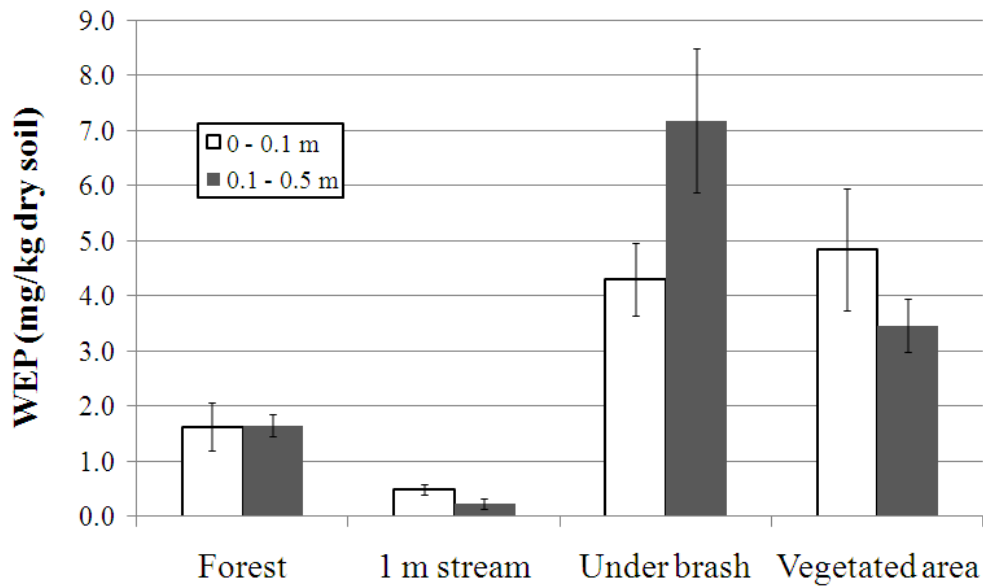
797 **Figure 5.** Dissolved reactive phosphorus (DRP) concentration measured over a 12  
798 month period (April 2010 – April 2011) and expressed as  $\mu\text{g L}^{-1}$  in stream water  
799 upstream and downstream of the RBZ.



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813 **Figure 6.** Water extractable Phosphorus (WEP) concentration ( $\text{mg kg}^{-1}$  dry soil) in  
814 riparian buffer zone (1 m from the stream, under brush and vegetated area) and forest  
815 at 0 – 0.1 m and 0.1 – 0.5 m depths. Error bars indicate standard deviation.

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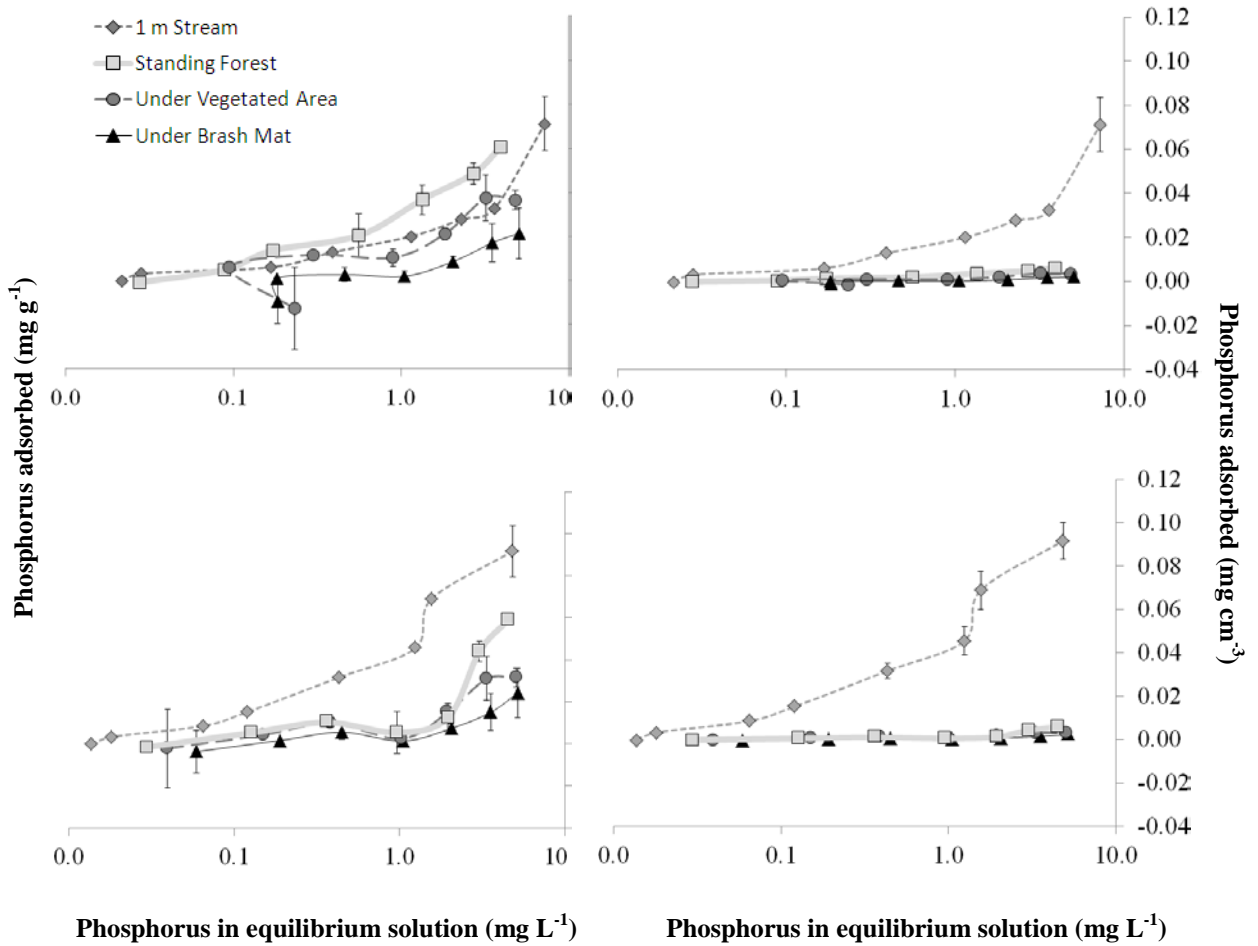
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830 **Figure 7:** Phosphorus (P) adsorption isotherms in riparian buffer zone and forest by  
 831 weight ( $\text{mg g}^{-1}$ ) on left and by volume ( $\text{mg cm}^{-3}$ ) on right at 0 – 0.15 m (top) and 0.15-  
 832 0.30 m (bottom) depths. Log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



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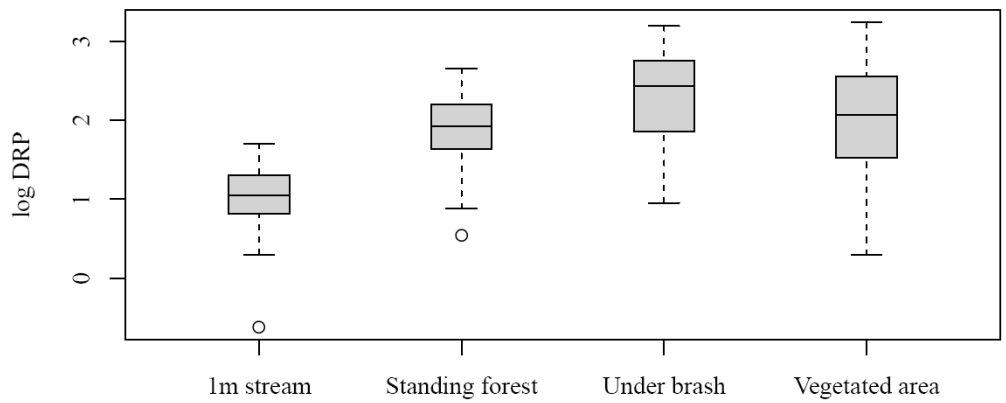
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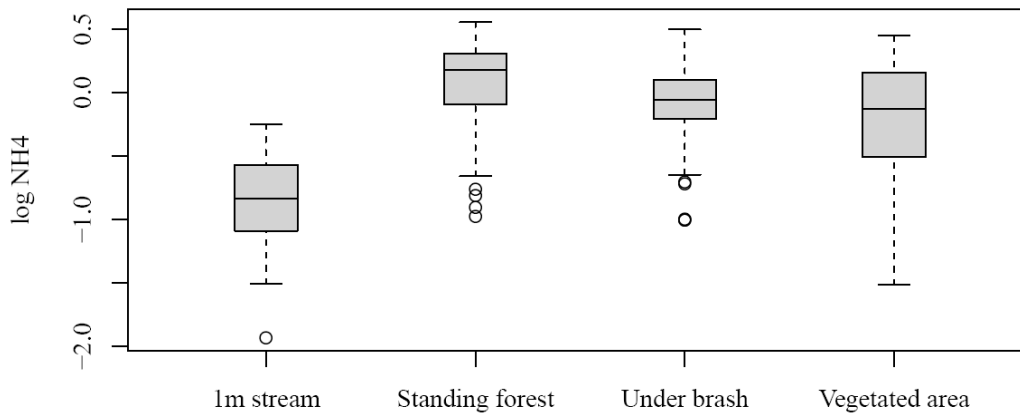
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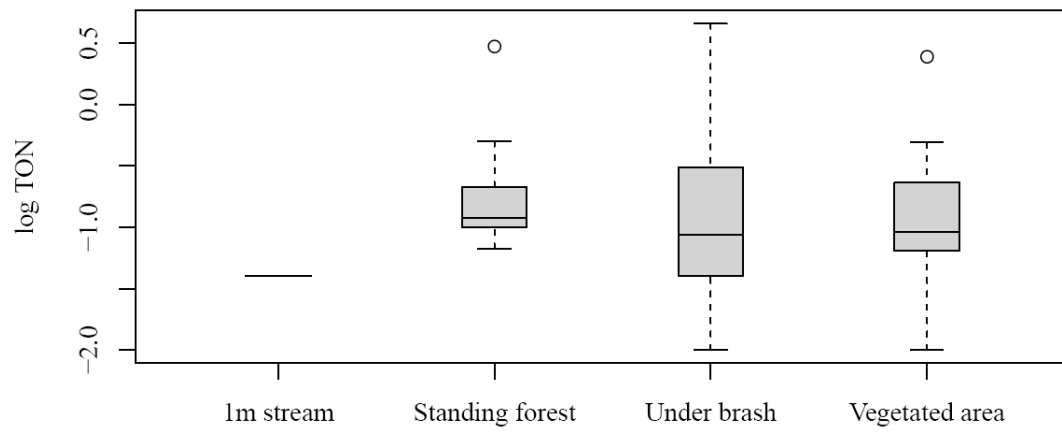
840 **Figure 8:** Box Plots of dissolved reactive phosphorus (DRP) (top), ammonium-N  
841 ( $\text{NH}_4\text{-N}$ ) (middle) and total oxidized nitrogen (TON) (bottom) for regenerated buffer  
842 area (1 m from the stream, under brush mats and under the vegetated area) and  
843 standing forest at 20 cm, 50 cm and 100 cm depths from April 2010 – April 2011. All  
844 units are  $\mu\text{g L}^{-1}$ .



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

Plot No.	April 2007						August 2011						
	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	-	-	-	-	-	
<b>Total</b>	<b>141</b>	<b>63</b>	<b>63</b>	<b>9</b>	<b>9</b>	<b>12</b>	<b>72</b>	<b>36</b>	<b>36</b>	<b>2</b>	<b>4</b>	<b>3</b>	
							<b>% Survival</b>	<b>51%</b>	<b>57%</b>	<b>57%</b>	<b>22%</b>	<b>44%</b>	<b>25%</b>

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