



## Implications of applied best management practice for peatland forest harvesting

Title	Implications of applied best management practice for peatland forest harvesting
Author(s)	Finnegan, Joanne;Regan, John T.;Healy, Mark G.
Publication Date	2013-12-20
Publisher	Elsevier (ScienceDirect)
Repository DOI	<a href="https://doi.org/10.1016/j.ecoleng.2013.12.003">10.1016/j.ecoleng.2013.12.003</a>

5  
6 **Implications of applied best management practice for peatland forest harvesting**

7 J. Finnegan<sup>a</sup>, J.T. Regan<sup>a</sup>, M. O'Connor<sup>a,b</sup>, P. Wilson<sup>c</sup>, and M.G. Healy\*<sup>a</sup>

8 <sup>a</sup>*Civil Engineering, National University of Ireland, Galway, Ireland*

9 <sup>b</sup>*Marine Institute, Newport, County Mayo, Ireland*

10 <sup>c</sup>*Dept. of Mathematics and Computer Science, Faculty of Science and Engineering,*  
11 *University of Wolverhampton, UK.*

12  
13 \* Tel +353 91 495364 fax +353 91 494507, email [mark.healy@nuigalway.ie](mailto:mark.healy@nuigalway.ie)  
14

15 **ABSTRACT**

16 Elevated levels of nutrients and suspended sediment (SS), and changes to other  
17 environmental parameters, are frequently associated with forestry harvesting (clearfelling)  
18 operations, and are indicative of the potentially complex changing environment associated  
19 with clearfelling. Current and future recommended best management practices (BMPs) for  
20 forestry clearfelling on upland peat catchments must provide for a healthy soil and good  
21 water quality. The aim of this study was to quantify the effects of implementation, or  
22 violation, of BMPs in the clearfelling of an upland peat conifer forest. Over periods of 12  
23 months prior to clearfelling and 15 months after clearfelling, two peatland forests, comprising  
24 a study control (no clearfelling) and a study site (clearfelling), were monitored for the release  
25 of phosphorus (P) and nitrogen (N) species (dissolved reactive phosphorus (DRP), total  
26 phosphorus (TP), total oxidised nitrogen (TON) and ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N)), SS,  
27 dissolved oxygen (DO), electrical conductivity (EC), pH and stream water temperature.  
28 Clearfelling was conducted during poor weather conditions and a watercourse, which drained  
29 the study site, was not protected. The maximum recorded concentration exported from the  
30 study site after clearfelling was 471 µg L<sup>-1</sup> for DRP, 611 µg L<sup>-1</sup> for TP, 1336 µg L<sup>-1</sup> for NH<sub>4</sub><sup>+</sup>-  
31 N, and 194 µg L<sup>-1</sup> for TON. Concentrations of SS exiting the study site increased in one of  
32 the two samples taken during clearfelling (maximum release of 481 mg L<sup>-1</sup>, with 68% of this  
33 organic) and returned to pre-clearfelling levels, or below, within 6 months of the  
34 commencement of clearfelling. Exports of TP and DRP from the study site were 0.9 and 0.4

35 kg ha<sup>-1</sup> yr<sup>-1</sup>, which were greater than the study control (0.6 and 0.2 kg ha<sup>-1</sup> yr<sup>-1</sup>, respectively).

36 This indicated that the mitigation practices employed on site were not effective in phosphorus  
37 retention.

38

39 **Keywords:** nutrients, forestry, brash mats, peat, clearfelling, harvesting

40 **1. Introduction**

41

42 Ireland's forest cover stands at 10% (698,000 ha) of the total surface area of the island  
43 and 59.6% of total afforestation is on peat (National Forest Inventory, 2007). Most of this  
44 forestry is now at harvestable age (Renou-Wilson et al., 2011) and peatland forests are  
45 particularly sensitive to soil erosion from clearfelling (the harvesting of all marketable  
46 trees in a stand at the end of a rotation) (Forest Service, 2000a). Clearfelling of this forest  
47 may cause elevated levels of nutrients (Cummins and Farrell, 2003a; Rodgers et al.,  
48 2010; Finnegan et al., 2012) and suspended sediment (SS) (Rodgers et al., 2011) in  
49 adjacent waterways for up to 4 years after harvest (Adamson and Hornung, 1990; Neal et  
50 al., 1999), which may have an impact on the ecosystem of the recipient watercourse and  
51 soil quality in the forest (Vasconcellos et al., 2013). Therefore, current and future  
52 recommended best management practices (BMPs) for forestry clearfelling on upland peat  
53 catchments must consider soil and water quality (Collins et al., 2000).

54

55 Forestry operations on peatland throughout the world are now moving towards a  
56 'progressive management approach' (Joosten and Clarke, 2002), which aims to reduce  
57 the potentially negative effects to the surrounding environment. Coillte, the Irish State's  
58 current forest management company, is certified under the Forest Stewardship Council  
59 (FSC) to enforce environmental, economic and social criteria for sustainable forest  
60 management (Coillte, 2012). These criteria include detailed planning (prior to the  
61 commencement of clearfelling) to provide protection to watercourses from drainage,  
62 fertilisation and afforestation, final harvest and regeneration (Owende et al., 2002). The  
63 'Code of Best Forest Practice – Ireland' (Collins et al., 2000), and the associated  
64 guidance documents (Forest Service, 2000a,b,c,d,e,f), which are based on the principles  
65 of Sustainable Forest Management (SFM), contain BMPs for all forestry operations,  
66 including nursery practices, planting, thinning and transport of materials (Collins et al.,  
67 2000). Under present BMPs, management of final harvest needs to include consideration  
68 of felling coupe (an area of woodland that has been clearfelled or is planned for clear  
69 felling; Coillte, 2013) size and shape, road construction, soil type and sensitivities, local  
70 watercourses, extraction routes (the areas, overlain by brash material, on which harvested  
71 trees are transported from site) and landing areas (Collins et al., 2000) (Table 1). In  
72 particular, the practice of clearfelling in dry weather, the use of brash mats (logging

73 residues used for machinery traffic) and ancillary structures such as silt traps, are  
74 recommended (Forest Service, 2000a). Harvest site restoration guidelines include  
75 provisions for drain and road repair, and water management on extraction routes (Forest  
76 Service, 2000a) in order to prevent, or reduce, excessive loss of nutrients and sediment to  
77 receiving watercourses.

78

79 Best management practices in Irish forestry are not based on quantifiable scientific data,  
80 but are based on empirical data arising from local knowledge as well as BMPs in  
81 existence elsewhere. They do, however, provide a conceptual framework, to which the  
82 adherence or non-adherence to BMPs may be compared. In fact, some evidence suggests  
83 that the implementation of BMPs may not be effective in reducing phosphorus (P), for  
84 example, as the major cause for enhanced P export may be P release from harvest  
85 residues (Palviainen et al., 2004; Kaila et al., 2012). Similarly, BMPs concerning the  
86 time of year and the weather during which felling is conducted, may not impact the  
87 export of nutrients from a harvested area (Rodgers et al., 2010). Although BMPs are of  
88 questionable merit, they do govern forestry practices in Ireland and elsewhere. Therefore,  
89 the hypothesis of this study is that adherence to BMPs means that export of nutrients and  
90 suspended solids (SS), arising from clearfelling of forested blanket peat, will be  
91 mitigated.

92

93 Nutrients such as nitrogen (N) and P are often applied to land at the afforestation stage to  
94 enhance and promote growth of selected species within ombrotrophic blanket peats  
95 (peats which have low nutrient concentrations and poor adsorption capacities) in the west  
96 of Ireland (Farrell and Boyle, 1990; Renou and Farrell, 2005). This, combined with N  
97 deposition from the atmosphere and ammonification within the peat layers, has led to N  
98 saturation, primarily present as ammonium ( $\text{NH}_4^+$ ), in some upland peat catchments in  
99 the UK (Daniels et al., 2012). Ammonium can leach from the peat and be converted to  
100 nitrate ( $\text{NO}_3^-$ ) by nitrification within streams (Daniels et al., 2012), leading to toxic  
101 environments for aquatic life forms (Stark and Richards, 2008). Similarly, concentrations  
102 of P ( $> 35 \mu\text{g L}^{-1}$  molybdate reactive phosphorus (MRP)) can have a negative impact on  
103 water quality (Bowman, 2009), leading to restrictions for fisheries, recreation, industry  
104 and drinking water (Sharpley, 2003; Elrashidi, 2011). Blanket peat has a poor P

105 adsorption capacity (O'Driscoll et al., 2011) and during the forest operations of drainage,  
106 fertilisation and clearfelling, hydrological losses of P can increase (Cummins and Farrell,  
107 2003a; Nieminen, 2003; Väänänen et al., 2008). Phosphorus release in the clearfelled  
108 area in the first 3 years after clearfelling of a mixed boreal forest was shown by  
109 Palviainen et al. (2004) to be mainly due to decomposition of foliage, which accounted  
110 for 70% of total P release from logging residues. Furthermore, Kaila et al. (2012) showed  
111 that P is easily released from harvest residue needles in clearfelled areas and concluded  
112 that this easy P release may be a cause for the reported high P losses from peat soils soon  
113 after clearfelling. Rodgers et al. (2010) reported high P losses from a clearfelled peat site  
114 and showed that more than 80% of P export occurred during storm events. However, they  
115 also showed that P levels in streams draining clearfelled areas can return to pre-clearfell  
116 levels within 4 years of clearfelling. Peat soils are also susceptible to damage by  
117 clearfelling, machinery traffic and subsequent rutting and compaction (Collins et al.,  
118 2000). After clearfelling, SS levels in receiving waters can increase due to soil  
119 disturbance, bank erosion and increased flow from the harvested areas, but these impacts  
120 are generally not long-term (Rodgers et al., 2011).

121

122 Other environmental parameters, such as dissolved oxygen (DO) (Ensign and Mallin,  
123 2001), electrical conductivity (EC) (Cummins and Farrell, 2003b), pH (Neal et al., 1992)  
124 and stream water temperature (Stott and Marks, 2000), may be impacted by clearfelling,  
125 and are indicative of the potentially complex changing environment associated with  
126 forestry harvesting (Rodgers et al., 2008). An increase in biochemical oxygen demand  
127 (BOD) from increased organic material and algal blooms can decrease the DO levels in  
128 waterbodies downstream of clearfelled areas (Ensign and Mallin, 2001). By comparing  
129 lakes in catchments with different land uses, Drinan et al. (2012) were able to show that  
130 DO concentrations were lower in lakes located in catchments with clearfelling or mature  
131 plantations, than lakes located in catchments where only unplanted blanket bog was  
132 present.

133

134 Stream water temperature is seen as one of the best indicators of stream vitality, and can  
135 be affected by forestry operations such as afforestation and deforestation (Stott and  
136 Marks, 2000; Quinn and Wright-Stow, 2008). Studies in the UK have shown that a  
137 decrease in stream water temperature occurs after afforestation (Weatherley and

138 Ormerod, 1990), while an increase occurs after deforestation (Neal et al., 1992). A  
139 reduction in water temperature in spring and summer due to tree coverage of streams can  
140 lead to lower rates of development of invertebrates and fish (Weatherley and Ormerod,  
141 1990). However, the impact of deforestation on ecology and the recovery of ecology are  
142 less clear, with either increases in invertebrates (Kirby et al., 1991) or no change in  
143 biological status being reported (Gee and Smith, 1997).

144

145 The upland peat catchments of the west of Ireland are classified as acid sensitive with the  
146 main pressures (such as acidification and nutrient and sediment addition) on rivers  
147 coming from forestry operations and peat degradation (O' Driscoll et al., 2012). The  
148 typical low pH values (approximately 4) of these catchment streams is assumed to result  
149 from the high runoff from low permeability, acidic soils, with little interaction with  
150 groundwater to neutralise the acidity, as seen in similar sites in the UK (Neal et al.,  
151 2004). Forests may exacerbate the existing acid conditions both indirectly, through  
152 canopy interception of atmospheric pollutants, and directly, by the uptake of base cations  
153 and nutrients during biomass growth and subsequent removal from site during  
154 clearfelling (Johnson et al., 2008). The net loss of base cations that accompanies the  
155 harvesting of stem wood, or any other form of biomass extraction, may affect the vitality  
156 and stability of the forest ecosystem (Hüttl and Schneider, 1998). Base cations are  
157 important for buffering against changes in soil and water acidity (Lucas et al., 2013). As  
158 the number of base cations decreases, there is an increase in the percentage of aluminium  
159 ( $Al^{3+}$ ) and hydrogen ( $H^+$ ) ions relative to base cations and therefore a reduction in soil  
160 pH. Little is known about the impact of clearfelling on stream water pH in upland peat  
161 forestry in Ireland.

162

163 To date, there are little published data on the effects of forest clearfelling on receiving  
164 waterbodies in Ireland (Rodgers et al., 2011). There is a need to quantify the effects of  
165 implementation of BMPs (or deviation from BMPs), in peatland forestry clearfelling  
166 operations, on nutrient and sediment release (Coillte, 2008). Therefore, the aim of the  
167 present study was to examine, in a paired catchment study including a study control (no  
168 clearfelling) and a study site (clearfelling), the impact of clearfelling of an upland peat  
169 conifer forest on the release of P, N and SS, expressed as concentrations and loads

170 released, and the changes in DO, EC, pH and stream water temperature, after the  
171 implementation of BMPs.

172

## 173 **2. Materials and Methods**

174

### 175 **2.1. Study Site Description**

176

177 The study area was located in the Glennamong forest in the Burrishoole catchment in Co.  
178 Mayo, Ireland (ITM reference 494252, 803180) (Figure 1). Two adjacent sub-catchments  
179 were studied: (1) a control catchment (CC), in which no clearfelling or forestry  
180 operations took place and (2) a study catchment (SC), in which clearfelling of the  
181 catchment took place (identified as ‘Control’ and ‘Study’ in Figure 1). The CC and SC  
182 are each approximately 10 ha in area, and each is drained by a small ephemeral stream  
183 instrumented with sampling equipment (identified as ‘Steams’ and ‘Sampling’ in Figure  
184 1). These streams flow into the Glennamong River, which is a fourth-order river at the  
185 point of entry of the streams (Strahler, 1964). The study area is situated at an  
186 approximate elevation of 95 m above ordnance datum (AOD) and there is a moderate  
187 climate, which is heavily influenced by the proximity of the Atlantic Ocean. The average  
188 air temperature is 13 °C in summer and 4 °C in winter, while the mean annual rainfall for  
189 the catchment is 2000 mm (Rodgers et al., 2011). The catchment has a low buffering  
190 capacity and has been classified as acid oligotrophic (O’Driscoll et al., 2012). Blanket  
191 peat of varying depth down to 1 m covers the site, which overlays an Anaffrin formation  
192 of quartzite and schist bedrock (McConnell and Gatley, 2006). The blanket peat is an *in*  
193 *situ* blanket mire with an average gravimetric water content of 85% and a dry bulk  
194 density of approximately 0.1 g cm<sup>-3</sup>. The organic matter content is greater than 91%, and  
195 the P, iron (Fe) and Al content of the peat layers down to a depth of 40 cm below the  
196 surface varies between 0.19 and 0.35, 0.94 – 1.31 and 1.34 – 1.67 g kg<sup>-1</sup> dry peat,  
197 respectively (Asam et al., 2012). The threshold phosphorus concentration (EPCo) above  
198 which net sorption occurs, was estimated by Asam et al. (2012) to be 28 µg L<sup>-1</sup> in the  
199 humus layer (0 – 5 cm depth below the surface).

200

201 The site was planted with lodgepole pine (*Pinus contorta*) in 1972. The CC is at the same  
202 topographical location as the SC, and has a similar slope and peat depth. Clearfelling of

203 the SC commenced on February 8, 2011. Bole-only clearfelling, which involves the  
204 removal of only the merchantable timber from site, leaving the branches and logging  
205 residue (brush material) to degrade on site, was carried out with a harvester (Timberjack  
206 1470D) and a forwarder (8-wheeled, Timberjack 1110). A total of 14.8 ha of forest was  
207 clearfelled, of which 9.4 ha drained into the small stream in the SC. This stream has a  
208 mineral bed, no buffer strip due to its size, occasionally goes underground and is not  
209 identified on ordinance survey (OS) maps. Therefore, very little care was afforded to the  
210 stream during clearfelling, and occasionally brush mats were laid over the stream and  
211 parallel to the path of the stream. Operations continued during heavy rainfall and resulted  
212 in deep rutting (up to 1.5 m) on the main extraction routes. Timber was removed from the  
213 site *via* extraction racks running parallel to the slope of the site, and was deposited at a  
214 timber landing area adjacent to the road. Harvesting finished at the end of March 2011  
215 and forwarding continued until the middle of April 2011. Temporary silt traps were  
216 installed on completion of forwarding and extra brush was placed on the rutted extraction  
217 routes for water management control. Three permanent silt traps, preceded upslope by  
218 settling ponds, were constructed with filter stone and geotextile at the end of April 2011.  
219 No drain cleaning took place on site and, to date, no maintenance of silt traps has been  
220 conducted. Windrowing (arranging the brush mats into piles) and replanting took place  
221 on the site in late 2013.

222

## 223 **2.2. Best management practice**

224

225 A comparison of the actual clearfelling practice at the study site, in comparison to BMPs  
226 (Forest Service, 2000a, b), is shown in Table 1. As far as practicable, clearfelling at the  
227 study site was carried out in accordance with BMPs, with harvesting plans, coupe size,  
228 timber landing areas, use of brush mats, site restoration and machine servicing being  
229 conducted. Road planning and construction was not necessary due to the existing road on  
230 site. A number of deviations in the implementation of BMPs were encountered due to the  
231 specific site conditions, which included lack of dry weather and avoidance of  
232 watercourses. The study site received a total rainfall of 5250 mm distributed over 625  
233 rain days during the duration of the present study (February 2010 to May 2012; 821 days  
234 in total). As such, there were only 196 days (24% of study duration) on which  
235 clearfelling could take place in the absence of rainfall. In 2011 alone, the rainfall

236 recorded in the SC was 3037 mm. During the clearfelling operations, which lasted  
237 approximately 80 days, there were 59 days of rainfall (387 mm in total), of which 44  
238 were classed as wet days (measured rainfall greater than 1 mm). Due to time constraints  
239 and availability of the machines, clearfelling was conducted during poor weather  
240 conditions.

241

242 The forestry and water quality guidelines (Forest Service, 2000b) and the Code of Best  
243 Forest Practice – Ireland (Collins et al., 2000) stipulate the establishment of buffer zones  
244 along all aquatic zones, within which ground preparation and other forest operations are  
245 curtailed. They define an aquatic zone ‘as a permanent or seasonal river, stream, or lake  
246 shown on an Ordnance Survey 6 inch map’. The stream draining the SC was not on the  
247 Ordnance Survey 6 inch map, as it was little more than a drainage channel and  
248 occasionally went underground. Therefore, a buffer zone was not established adjacent to  
249 the SC stream prior to planting. Upland spate streams are very characteristic of peat  
250 catchments in the west of Ireland, particularly within the Burrishoole catchment (Allott et  
251 al., 2005) and during periods of high rainfall, the SC stream carried large volumes of  
252 water (relative to the normal flow within the SC stream) from the catchment to the  
253 receiving river. Due to the sensitive nature of peatland sites, these small streams, despite  
254 their lack of order number, should be protected during clearfelling operations. In the  
255 present study, temporary silt traps were installed at the end of clearfelling, but this may  
256 have been too late to prevent SS export during the clearfelling process (Section 3.1.3).

257

### 258 **2.3. Measurement and Analysis**

259

260 Installation of H-flumes (or open channel flow nozzles) and water level recorders for  
261 flow measurement (OTT SE200, Germany), data sondes (Hydrolab, USA) for continuous  
262 measurement (every 5 minutes) of environmental parameters (DO, EC, pH and  
263 temperature) and ISCO samplers (Teledyne ISCO, USA) for stream water collection in  
264 the two streams in the CC and SC (identified as ‘Sampling’ in Figure 1) began in  
265 February 2010. The ISCO samplers were set to collect samples every hour, but  
266 occasionally it was set to take samples every two hours. The upper flow limit of the H-  
267 flumes was  $148 \text{ L s}^{-1}$ . The sondes were removed for calibration every 8-10 weeks. For  
268 analysis, the SC was divided into pre-clearfell (pre-CF) and post-clearfell (post-CF)

269 periods. Pre-CF data collection took place from February 2010 to February 2011 (12  
270 months pre-CF data) and post-CF data collection took place from February 2011 to May  
271 2012 (15 months post-CF data). The nutrient and sediment release during a total of 18  
272 storm events (n=8 pre-CF, n=2 during CF and n=8 post-CF; and n=24 samples within  
273 each storm event), over 24- or 48-hour time periods, were monitored using the ISCO  
274 samplers in the CC and SC streams (Figure 2). A weather station (Vantage Pro 2, Davis,  
275 USA) was positioned at the study site.

276

277 After collection, all water samples were returned to the laboratory and SS and nutrient  
278 analysis was carried out within 24 hr. Occasionally, some water samples were frozen at -  
279 20°C and analysed for nutrients within 2 to 3 days of collection. The water quality  
280 parameters measured were: (1) dissolved reactive phosphorus (DRP) (2) total phosphorus  
281 (TP) (3)  $\text{NH}_4^+$ -N (4) total oxidised nitrogen (TON =  $\text{NO}_3^-$  + nitrate ( $\text{NO}_2^-$ )) and (5) SS.  
282 The SS component was further classified into organic suspended sediment (OSS) and  
283 mineral suspended sediment (MSS). All water samples were tested in accordance with  
284 standard methods (APHA, 2005) using a nutrient analyser (Konelab 20; Thermo Clinical  
285 Labsystems, Finland). Suspended sediment testing was carried out by passing a known  
286 volume of water through a pre-dried and weighed 1.2  $\mu\text{m}$  GF/C filter disc (Whatman,  
287 England) under suction. The filter and retained sediment were then dried at 105 °C for 24  
288 hr and reweighed to give the total SS (APHA, 2005). The MSS was determined by loss  
289 on ignition (LOI) at 550 °C (BSI, 1990). The OSS was calculated as the difference  
290 between total SS and MSS.

291

292 In order to determine the flow-weighted mean concentration (FWMC) of each nutrient  
293 for each storm event, it was first necessary to calculate the mass of nutrient lost during  
294 each sampling period. This was done by multiplying the concentration ( $\text{mg L}^{-1}$ ) of  
295 nutrient in a sample by the total flow volume (L) measured in the stream over the  
296 sampling period. The sum of the mass release over the 24 samples (collected during the  
297 storm) was then divided by the sum of the flow in the stream over the sampling duration  
298 to give the FWMC. This allowed for comparisons, independent of flow, between the SC  
299 and CC to be conducted.

300

301 Storm events in the control and study catchments were monitored for discharge, sediment  
302 and nutrient concentrations. A storm event was defined as the time when the flow begins  
303 to increase on the rising limb of an event to the time when flow on the falling limb  
304 intercepts the base flow with a slope of  $0.0055 \text{ L s}^{-1} \text{ ha}^{-1} \text{ hr}^{-1}$  (Yusop et al., 2006). Yields  
305 of TP, SS and DRP were related to cumulative water discharge during these events by  
306 (Rodgers et al., 2010):

307

$$308 \quad Y = \alpha Q + \beta \quad [1]$$

309

310 where Y represents the total yield of a parameter of interest (g; measured using  
311 autosamplers), Q is the cumulative discharge of a storm event (L; measured in the H-  
312 flumes of the streams in the control and study catchments), and  $\alpha$  ( $\text{g L}^{-1}$ ) and  $\beta$  ( $\text{g L}^{-1}$ ) are  
313 obtained by the least squares method. Using Eq. [1], the sediment and nutrient loads in  
314 kg per harvested/control areas were estimated over the study duration. During base flow  
315 conditions, the discharge and parameter concentrations were low, so these were omitted  
316 from the analyses. This assumption was reasonable, as Rodgers et al. (2010) found that  
317 over 80% of total reactive phosphorus (TRP) was released during storm events over a 4-  
318 year period.

319

320 With the exception of TON, which was found to better conform with the pre-requisites of  
321 the analysis if not transformed, the data were log transformed (when being used as a  
322 response variable) and analysed in R (version 3.0, 32 bit). (Note that where the size of an  
323 effect is quoted, the values have been converted back to the raw values, i.e. they are not  
324 on the log scale). Date (i.e. pre or post clear-felling), location of the sample site, SS, DRP  
325 and  $\text{NH}_4^+\text{-N}$  were included as explanatory variables. A general linear model was used to  
326 analyse the data. This method of analysis may be regarded as an extension of ANOVA  
327 and ANCOVA; it permits that significance and the extent of the effect of the various  
328 dependent variables on the response variable to be assessed independently. Of particular  
329 interest to this study, is that it allows the effects of clear-felling itself to be assessed,  
330 eliminating possible effects due to measurements being taken pre- or post the clear-  
331 felling date.

332

333 **3. Results and Discussion**

334

### 335 **3.1. Nutrient and SS concentration**

336

337 Throughout the entire study period, there was no significant difference between the pre-  
338 CF and post-CF nutrient concentrations in the CC, and prior to clear-felling, there was no  
339 significant difference between the CC and SC for any of the nutrient concentrations  
340 measured, with the exception of  $\text{NH}_4^+\text{-N}$ , which was higher in the study than the control  
341 site ( $p < 0.001$ ), and was higher post the clear felling date than before that date (after the  
342 effect of clear-felling has been accounted for) ( $p = 0.011$ ), and in TON, which was higher  
343 post the clear felling date than before that date (after the effects of clear-felling have been  
344 accounted for) ( $p = 0.014$ ). A summary of nutrient concentrations post-CF is shown in  
345 Table 2 and a summary of the nutrient and SS loads exported from the CC and SS post-  
346 CF (as  $\text{kg ha}^{-1} \text{ yr}^{-1}$ ) is shown in Table 3.

347

#### 348 *3.1.1 Dissolved Reactive Phosphorus and Total Phosphorus*

349

350 The DRP (Figure 3) was significantly higher ( $p < 0.005$ ) in the SC than the CC due to  
351 clearfelling. Total phosphorus was not recorded prior to clearfelling, but was higher in  
352 the SC than the CC after clearfelling (Figure 4;  $p < 0.005$ ). The limit for MRP, which is  
353 similar to DRP (Haygarth et al., 1997), for good status of surface water bodies is  $\leq 35 \mu\text{g}$   
354  $\text{L}^{-1}$  (S.I. No. 272 of 2009). The FWMCs and peak concentrations of DRP pre-CF were  
355 well below this limit for both sites. Although the FWMC concentration from the post-CF  
356 SC only exceeded this limit on one of the ten sampling dates ( $39 \mu\text{g L}^{-1} \text{ P}$  on October 31,  
357 2011), seven of the eight sampling times post-CF had peak DRP concentrations in excess  
358 of  $35 \mu\text{g L}^{-1}$  (peak DRP concentrations, usually only attained for an hour, ranged from  $42$   
359  $\mu\text{g L}^{-1}$  to  $471 \mu\text{g L}^{-1}$ ). Flow-weighted and peak concentrations of TP measured in the SC  
360 and CC streams in the period prior to the start of clearfelling in the SC were below the  
361 EPA critical threshold limit for TP of  $62 \mu\text{g L}^{-1}$  (Coillte, 2008). During and after  
362 clearfelling of the SC, the flow-weighted and peak concentrations of TP exceeded this  
363 limit on six of the ten sampling dates, but returned below the critical limit for the final  
364 two sampling dates. Similar P concentrations were released from a similar sized  
365 catchment (20 ha) during the restoration (clearfelling of conifers followed by drain  
366 blocking) of a blanket bog in the southwest of Ireland (Coillte, 2008). Increases in DRP

367 and TP of greater magnitude than the present study were measured after clearfelling of a  
368 1-km<sup>2</sup> and a 1-ha peat catchment in the west of Ireland by Cummins and Farrell (2003a).  
369 They found that maximum (non-flow-weighted) concentrations of MRP increased from 9  
370  $\mu\text{g L}^{-1}$  (1 km<sup>2</sup> catchment) and 93  $\mu\text{g L}^{-1}$  (1 ha catchment) to 256  $\mu\text{g L}^{-1}$  and 3530  $\mu\text{g L}^{-1}$ ,  
371 respectively, within a few weeks of clearfelling, and the median values obtained were  
372 just over 100  $\mu\text{g L}^{-1}$  (1 km<sup>2</sup> catchment) and 1000  $\mu\text{g L}^{-1}$  (1 ha catchment). However,  
373 unlike the present study, which has mineral content in its stream bed, the stream and  
374 drain beds of the Cummins and Farrell (2003a) study consisted of purely peat-based  
375 matter and the flowing water had no interaction with mineral material, therefore giving  
376 little opportunity for adsorption of P to mineral layers. Rodgers et al. (2010) measured  
377 average FWMC of  $14 \pm 10 \mu\text{g TP L}^{-1}$  in the receiving waters, prior to the clearfelling of a  
378 peatland study site, using BMPs. A peak in the FWMC of TP of 201  $\mu\text{g L}^{-1}$  was reached  
379 5 weeks after the end of clearfelling, but this concentration had reduced back to pre-  
380 clearfelling concentrations 10 weeks after felling. The concentrations of P in the  
381 receiving waters can return to pre-clearfelling levels within 4 years of harvesting  
382 (Rodgers et al., 2010).

383

384 Exports of DRP, estimated using measured data and Eqn. [1], indicated that the DRP  
385 export from the study catchment was 0.4 kg ha<sup>-1</sup> yr<sup>-1</sup> versus 0.2 kg ha<sup>-1</sup> yr<sup>-1</sup> for the control  
386 catchment one year following clearfelling (Table 3). Similarly, TP exports were greater  
387 for the study catchment than the control catchment. The main mechanism of P release  
388 was not erosion (exports of SS were similar for both catchments were similar; Table 3),  
389 but was most likely P release from harvested residues. The poor P adsorption capacity of  
390 the peat meant that most of it was transported off site. The only other study to date that  
391 has quantified the export of P from forested blanket peat was Rodgers et al. (2010), who  
392 measured a total export load of approximately 5 kg total reactive phosphorus (TRP) kg  
393 ha<sup>-1</sup> over a 4-year study period (Table 3) and attributed it to decomposing logging  
394 residues and poor P sorption capacity of the peat. No study has previously quantified  
395 export loads of DRP or TP from forested blanket peat sites.

396

397 The water extractable phosphorus (WEP) concentration, indicating the potential of a soil  
398 source to release P into runoff water, may be high under brash material (Finnegan et al.,  
399 2012), and is a function of the length of time brash is left on site and the time taken for

400 regeneration of vegetation to occur (Macrae et al., 2005). The export of P post-CF is  
401 therefore linked to the amount and management of brash material on site. This P export is  
402 due to the poor adsorption capacity of peat (O'Driscoll et al., 2011) and fast (within one  
403 year after felling) and extensive (over 30% of P in brash material) mineralisation of P  
404 from the logging residues (Stevens et al., 1995). Phosphorus export from logging  
405 residues, spread evenly throughout the site, was also noted on a clearfell site in Finland,  
406 where the P leaching was as much as 17 times greater after clearfelling than before  
407 clearfelling (Piiirainen et al., 2004). It is also common practice in Ireland to leave the  
408 brash mats across the site post-CF and arrange it into windrows once machinery is on site  
409 for reforestation, 1 ½ to 2 years after clearfelling (Collins et al., 2000). It was expected  
410 that the degradation of the extra brash placed on the rutted extraction routes for water  
411 management control would increase the dissolved P concentration in the stream post-CF  
412 in the SC, but this has not occurred to date.

413

#### 414 *3.1.2 Ammonium-Nitrogen and Total Oxidised Nitrogen*

415

416 Whilst the  $\text{NH}_4^+\text{-N}$  (Figure 5) was significantly higher ( $p<0.005$ ) in the SC than the CC  
417 after clear-felling, there is no evidence that this was due to the clear-felling itself  
418 ( $p>0.05$ ), and may have been due to variation in levels between study and control sites,  
419 and variations pre and post the clear-felling date (see Section 3.1). There is, however,  
420 significant evidence of a mean increase in TON levels due to clear-felling ( $p<0.005$ ) and  
421 further significant evidence of an increase in TON levels due to being post the clear-  
422 felling date ( $p=0.0148$ ). The FWMC of  $\text{NH}_4^+\text{-N}$  and TON (Figure 6) in the CC and SC  
423 before clearfelling was below  $0.1 \text{ mg L}^{-1}$ . Peak concentrations of  $\text{NH}_4^+\text{-N}$  in the CC and  
424 SC, attained for a maximum of one hour and only on one sampling date pre-CF, were  
425  $0.18$  and  $0.26 \text{ mg L}^{-1}$ . Post-CF, the FWMC of  $\text{NH}_4^+\text{-N}$  and TON rose to a maximum of  
426  $0.17$  and  $0.18 \text{ mg L}^{-1}$ , respectively, and peak concentrations for  $\text{NH}_4^+\text{-N}$  and TON were  
427  $1.36$  and  $0.19 \text{ mg L}^{-1}$ .

428

429 There are no critical limits for  $\text{NH}_4^+\text{-N}$  for river water bodies in Ireland. As a proxy value  
430 for  $\text{NH}_4^+\text{-N}$ , the critical limit for total ammonia (ionic- $\text{NH}_4$  + un-ionic  $\text{NH}_3$ ) is used,  
431 which has a mean value of  $0.065 \text{ mg L}^{-1}$ , or  $0.14 \text{ mg L}^{-1}$  95% of the time, for good status  
432 of river water bodies (S.I. No. 272 of 2009). The flow-weighted and peak concentrations

433 of  $\text{NH}_4^+$ -N in the SC post-CF exceeded this value. The maximum threshold for  $\text{NH}_4^+$ -N  
434 in groundwater is  $0.175 \text{ mg L}^{-1}$  (S.I. No. 9 of 2010). Although the maximum FWMC of  
435  $\text{NH}_4^+$ -N in the SC post-CF was below this threshold, peak concentrations exceeded this  
436 threshold on five of the eight sampling periods after clearfelling had finished.

437

438 Elevated levels of N are generally associated with forestry clearfelling (Nieminen, 1998;  
439 Cummins and Farrell, 2003b), but these increases normally do not occur until 1 year after  
440 clearfelling and may continue for up to 3 years (Cummins and Farrell, 2003b). Unlike P,  
441 initial high concentrations of N do not come from the degradation of brash material  
442 (Stevens et al., 1995). The delay in the release of N concentrations is due to the initial  
443 high N immobilization of the brash material, which has a high carbon (C):N ratio  
444 (Nieminen, 1998). The increase in N after clearfelling is a combination of the subsequent  
445 biological mineralisation of organic matter and the reduced uptake from biomass  
446 following the removal of the trees (Nieminen, 1998; Cummins and Farrell, 2003b).

447

448 Neal et al. (1999) noted that elevated levels of N post-CF on forestry sites across Britain  
449 was on a minority of sites, and leaching depended on local conditions. This was also  
450 noted by Kreuzweiser et al. (2008) in their review of logging impacts in Boreal regions.  
451 Ammonium-N has a high adsorption capacity to exchange sites, which retains it on site,  
452 therefore N release post-CF is generally in the form of  $\text{NO}_3^-$ -N (Nieminen, 1998). The  
453 production of  $\text{NO}_3^-$ -N is largely due to nitrification, which requires an aerobic zone, and  
454 is generally limited in peatland sites due to shallow watertables (Von Arnold et al.,  
455 2005). Consequently, N leaching is higher from nutrient-rich, well drained minerotrophic  
456 peatlands (Nieminen, 1998) than from the ombrotrophic peats found on the present study  
457 site. This could be a possible reason for the lower N export from the Glennamong  
458 catchments.

459

### 460 *3.1.3 Suspended Sediment*

461

462 Flow-weighted mean concentrations of SS in the SC increased only once in samples  
463 taken during clearfelling and returned to pre-CF levels, or below pre-CF levels, within 6  
464 months of the commencement of clearfelling (Figure 7). This rise during clearfelling was  
465 not significant for SS, and there was no significant difference in date or location of

466 sampling for OSS (Figure 8) or MSS (Figure 9). The total amount of SS exported from  
467 both sites were similar (approximately 200 kg ha<sup>-1</sup> yr<sup>-1</sup>; Table 3) over the year following  
468 clearfelling, which indicated that the majority of SS was exported soon after clearfelling  
469 began and there was no longer any material for subsequent transportation.

470

471 Large increases in SS were only noted during one storm, which occurred during the end  
472 of the clearfelling period in early April 2011 (Figure 10). Over a period of 12 hours, 18.4  
473 mm of rain fell, producing an average flow in the stream of 21.3 L s<sup>-1</sup> with an associated  
474 median SS concentration of 35.4 mg L<sup>-1</sup> (the maximum release at the peak of the storm  
475 was 481 mg L<sup>-1</sup> SS of which 68% was organic in nature). During this storm, the highest  
476 concentrations of SS and TP were measured during the increasing limb of the  
477 hydrograph, with lower concentrations been measured during the decreasing limb of the  
478 hydrograph. The highly mobile DRP appeared to be less dependent on increasing or  
479 decreasing limbs of the hydrograph. The recommended level of SS in salmonid waters is  
480 25 mg L<sup>-1</sup> (European Community, 1988), therefore the release at peak storm levels was  
481 over 19 times greater than the recommended level. Following installation of silt traps and  
482 extra brush placement on rutted extraction routes at the end of clearfelling, the FWMCs  
483 of SS returned to pre-CF levels or below pre-CF levels. However, peak concentrations of  
484 SS post-CF in the SS exceeded this threshold on six of the eight sampling occasions,  
485 when a maximum SS concentration of 63 mg L<sup>-1</sup> was measured. Peak SS concentrations  
486 in the CC also exceeded the threshold limits on two of the sampling occasions post-CF,  
487 when a maximum concentration of 52 mg L<sup>-1</sup> was measured. Similar patterns in SS  
488 concentrations were noted by Nieminen (2003) on a peatland clearfell site in southern  
489 Finland, with the only significant increase in SS coming from the most productive,  
490 highly fertile mire which was ditch-mounded in such a way that the ditches reached  
491 down into the fine textured mineral soil below the peat layer. Rodgers et al. (2011) also  
492 found that clearfelling, in line with BMPs, on a peat catchment did not result in a  
493 significant SS concentration increase after clearfelling although higher daily peak SS  
494 concentrations were observed. Furthermore, no adverse impacts on the receiving waters  
495 were noted in their study.

496

497 Increased sediment export after clearfelling, following implementation of BMPs, has  
498 been reported by other studies (Kirby et al., 1991; Ensign and Mallin, 2001; Aust and

499 Blinn, 2004; McBroom et al., 2008; Ryder et al., 2011). Variations in results can relate to  
500 different site slopes, weather conditions and the rate of vegetation growth post-CF  
501 (Rodgers et al., 2011). Higher rates of sediment loss are associated with steeper slopes  
502 (McBroom et al., 2008) and the rapid regeneration of vegetation within clearfelled areas  
503 can reduce SS export (Aust and Blinn, 2004). However, establishing ground vegetation  
504 can be slow on sites where brush material has not been removed (Broadmeadow and  
505 Nisbet, 2004).

506

### 507 **3.2. Water parameters: DO, EC, pH and temperature**

508

#### 509 *3.2.1 Dissolved Oxygen*

510

511 Prior to clearfelling, DO levels at both sites were significantly different from each other  
512 ( $p<0.05$ ), with the CC having significantly higher values (Figure 11). During clearfelling,  
513 the DO dropped to zero in the SC, and continued to fluctuate for up to one month after  
514 the end of felling. During this time the DO saturation was below the Irish EPA range for  
515 acceptable DO saturation (between 80% and 120% saturation; Bowman, 2009). The  
516 higher concentrations of OSS measured during clearfelling may also have affected the  
517 DO concentration within the receiving waters due to the organic component being  
518 biologically active and thus utilising oxygen during decomposition (Rodgers et al.,  
519 2011). Extra light to the stream, provided by the removal of the tree canopy, may also  
520 have enhanced algal blooms in the stream of the SC. A similar pattern was noted by  
521 Ensign and Mallin (2001) on a wetland clearfell site in the eastern US, which they  
522 attributed to an increased BOD load from logging residues and algal blooms.

523

#### 524 *3.2.2 Electrical Conductivity*

525

526 There was no significant difference in the EC of both streams pre-CF, and the EC of the  
527 SC was generally above, or the same as, that of the CC. During periods of low flow or  
528 dry weather, the EC dropped to zero due to the sonde being exposed to the atmosphere  
529 (these values have been removed from the graphs for clarity). During clearfelling, the EC  
530 dropped in the SC and stayed below that of the CC for the remainder of the study (Figure  
531 12;  $p<0.05$ ). An identical pattern was found in the restoration of a blanket bog in the

532 southwest of Ireland (Coillte, 2008), and Cummins and Farrell (2003a) found, on a  
533 clearfelled peatland site, that values of EC reduced after clearfelling.

534

### 535 *3.2.3 pH*

536

537 The pH was consistently higher in the CC than the SC pre-CF. By the end of clearfelling,  
538 this pattern swapped, with the SC having a higher pH (Figure 13). The pH measured in a  
539 stream during restoration (clearfelling of conifers followed by drain blocking) of a  
540 blanket bog in the southwest of Ireland (Coillte, 2008) varied from 7.5 during low flow  
541 to approximately 4.3 during peak storm events, which is characteristic of acid sensitive  
542 blanket bogs. Similarly, in the present study, the initial high pH (seen at the end of  
543 October 2010) and the observed peaks in April 2011 followed dry periods when the pH  
544 was elevated due to more interaction with the bedrock in the stream. Rodgers et al.  
545 (2008) attributed the higher values of pH during low flow to a greater residence time  
546 within their study site, and interaction with an aquifer located above their sampling point.

547

548 There are few other long-term data in Ireland on changes in pH levels following  
549 harvesting (Johnson et al., 2008). Long-term studies in the UK (Neal et al., 1992) all  
550 show a slight decrease, or no change, in the pH after clearfelling. Dissimilar to these  
551 studies, Cummins and Farrell (2003b) observed an elevated pH immediately after  
552 clearfelling on a peatland site, and attributed this to the road side location of the sampling  
553 point which may have allowed dust, caused by road works or increased traffic, to enter  
554 water samples. However, elevated pH levels have been reported by other researchers  
555 (Ryder et al., 2011) on peatland sites which were not attributable to the roadside location  
556 of the sampling point. The increase in pH post-CF could be due to the decomposition of  
557 brash material on site (Staaf and Olsson, 1991), which allowed the return of base cations  
558 to the soil (Thiffault et al., 2011).

559

### 560 *3.2.4 Temperature*

561

562 The temperature of the stream water on both sites pre-CF was not significantly different  
563 from each other, and both sites responded well to the air temperature changes. Post-CF  
564 saw a significant rise in the stream water temperature in the SC and was likely due to the

565 removal of the tree canopy, and more light and solar radiation entering the stream  
566 (Rodgers et al., 2008) (Figure 14). However, this rise in temperature was not significant  
567 ( $p=0.0725$ ). A rise in stream water temperature was also noted by Stott and Marks (2000)  
568 in a forest clearfell study of a similar size (20 ha) on a peaty gley catchment in mid-  
569 Wales, and by Rodgers et al. (2008) in a clearfell study in Ireland. Changes to stream  
570 water temperature impacts most on the aquatic fauna of a waterbody (Mellina et al.,  
571 2002), and studies have shown results ranging from little recovery of invertebrates after  
572 clearfelling (Gee and Smith, 1997) to an increase in the number of mayflies (Kirby et al.,  
573 1991). The influence of the increase in stream temperature on the aquatic fauna of the  
574 Glennamong catchment was not investigated in the current study.

575

### 576 **3.3. Outlook for implementation of best management practices**

577

578 Best management practices in clearfelling operations, as recommended by the forest  
579 management organisation in Ireland (Coillte) and the Forest Service guidelines (Forest  
580 Service, 2000a,b,c,d,e,f), were generally followed in this study. The results of this study  
581 indicated that BMPs were not effective in reducing P loads from the clearfelled site. The  
582 release of TP and DRP from the clearfelled site was not mitigated by any BMPs  
583 employed, and was most likely released from decaying forest residues and poor soil P  
584 adsorption. Although the implementation of BMPs in forestry clearfelling has been  
585 shown to be effective at decreasing non-point source pollution to receiving watercourses  
586 (Ensign and Mallin, 2001; Wallbrink and Croke, 2002; Aust and Blinn, 2004; Johnston et  
587 al., 2008), none of these studies have attempted to estimate the export of nutrients or SS  
588 off site in terms of  $\text{kg ha}^{-1}$ . Suspended solids concentrations increased during clearfelling,  
589 but quickly reduced. This may have been more to do with the lack of easily erodible  
590 material than the efficacy of BMPs employed.

591

592 Whole tree harvesting (WTH) may reduce the export of nutrients from harvested sites,  
593 but this technique leads to the removal of base cations and may have consequences for  
594 future rotations (Nisbet et al., 1997). In addition, WTH may further compound the  
595 acidification of peatland forested catchments (Ågren and Löfgren, 2012) and, therefore,  
596 is inadvisable in the acid sensitive catchments of the west of Ireland. The leaching of  
597 cations from degrading foliage may reverse the effect of acidification in low N-releasing

598 sites (Neal et al., 1999). Nutrient export from nutrient-poor peat, similar to that in the  
599 current study, is less likely than from highly productive mires (Nieminen, 2003).

600

#### 601 **4. Conclusions**

602

603 The hypothesis of this study was that BMPs are effective in mitigating the transport of  
604 nutrients and sediment off site in clearfelled forested peatlands. Following clearfelling,  
605 DRP and TP concentrations rose in the clearfelled site and loads released were greater  
606 than the control (unharvested) site. This indicated that BMPs may not have been effective  
607 in reducing P releases from the clearfelled site. Most of the SS was released soon after  
608 clearfelling began and any reductions measured may not necessarily have been due to  
609 BMPs than the lack of easily erodible material on site. Site-specific parameters, such as  
610 the depth of peat or the slope of a site, and other potential confounding factors, such as  
611 the time of felling and weather conditions at the time of felling, may impact on nutrient  
612 and sediment release rates, and cognisance should be taken of these factors when drafting  
613 a harvest plan.

614

615 As recommended in the BMPs, a site should be thoroughly inspected prior to  
616 clearfelling. However, this should take place during, or immediately after, a period of  
617 prolonged rainfall. In the present study, a stream draining the study site, not identified on  
618 an Ordinance Survey 6-inch map and not visible during a site inspection which took  
619 place in dry weather, carried large volumes of water from the catchment to the receiving  
620 waterbody during adverse weather conditions.

621

#### 622 **5. Acknowledgements**

623

624 This work was funded by the Department of Agriculture, Fisheries and the Marine  
625 (DAFM) and the Environmental Protection Agency (EPA) under the STRIVE program  
626 2007 – 2013. The authors wish to acknowledge the input of Coillte in allowing access to  
627 state forestry for this project, and for providing logistical support and advice. A special  
628 thanks to Dr. Michael Rodgers, Dr. Zaki-ul-Zaman Asam and the Marine Institute for  
629 their help throughout this project and for supplying the orthophotography.

630 **References**

- 631 Ågren, A., Löfgren, S., 2012. pH sensitivity of Swedish forest streams related to  
632 catchment characteristics and geographical location – implications for forest  
633 bioenergy harvest and ash return. *Forest Ecol. Manag.* 276, 10-23.
- 634 Allott, N., McGinnity, P., O'Hea, B., 2005. Factors influencing the downstream transport  
635 of sediment in the Lough Feeagh catchment, Burrishoole, Co. Mayo, Ireland.  
636 *Freshwater Forum*, pp. 126-138.
- 637 APHA, 2005. Standard methods for the examination of water and wastewater. American  
638 Public Health Association, Washington.
- 639 Asam, Z., Kaila, A., Nieminen, M., Sarkkola, S., O' Driscoll, C., O' Connor, M., Sana,  
640 A., Rodgers, M., Xiao, L., 2012. Assessment of phosphorus retention efficiency  
641 of blanket peat buffer areas using a laboratory flume approach. *Ecol. Eng.*, 49,  
642 160 – 169.
- 643 Aust, W.M., Blinn, C.R., 2004. Forestry best management practices for timber harvesting  
644 and site preparation in the eastern United States: An overview of water quality  
645 and productivity research during the past 20 years (1982–2002). *Wat. Air Soil*  
646 *Poll.* 4, 5-36.
- 647 Bowman, J., 2009. New water framework directive environmental quality standards and  
648 biological and hydromorphological classification systems for surface waters in  
649 Ireland. *Biol. and Environ.* 109B, 247-260.
- 650 Broadmeadow, S., Nisbet, T.R., 2004. The effects of riparian forest management on the  
651 freshwater environment: A literature review of best management practice. *Hydrol.*  
652 *Earth Syst. Sc.* 8, 286-305.
- 653 BSI, 1990. Determination by mass-loss on ignition. British standard methods of test for  
654 soils for civil engineering purposes. Chemical and electro-chemical tests. BSI.,  
655 London.
- 656 Coillte, 2008. Technical final report for restoring active blanket bog in Ireland (LIFE02  
657 NAT/IRL/8490). Coillte, Mullingar, <http://www.irishbogrestorationproject.ie>  
658 (assessed 13 August 2013).
- 659 Coillte, 2012.  
660 [http://www.coillte.ie/coillteforest/responsible\\_forest\\_management\\_and\\_certificati](http://www.coillte.ie/coillteforest/responsible_forest_management_and_certificati)  
661 [on/certification\\_introduction/](http://www.coillte.ie/coillteforest/responsible_forest_management_and_certificati) (assessed 13 August 2013).

- 662 Coillte, 2013. Glossary.  
663 [http://www.coillte.ie/coillteforest/plans/forest\\_management\\_plans/glossary/](http://www.coillte.ie/coillteforest/plans/forest_management_plans/glossary/)  
664 (assessed 13 August 2013).
- 665 Collins, K.D., Gallagher, G., Gardiner, J.J., Hendrick, E., McAree, A., 2000. Code of  
666 best forest practice - Ireland. Forest Service, Dublin.  
667 <http://www.agriculture.gov.ie/media/migration/forestry/publications/codeofbestforestrypractice/Code%20of%20Best%20Forest%20Prac%20Part%201.pdf> (assessed  
668 13 August 2013).
- 669
- 670 Cummins, T., Farrell, E.P., 2003a. Biogeochemical impacts of clearfelling and  
671 reforestation on blanket peatland streams I. phosphorus. *Forest Ecol. Manag.* 180,  
672 545-555.
- 673 Cummins, T., Farrell, E.P., 2003b. Biogeochemical impacts of clearfelling and  
674 reforestation on blanket-peatland streams II. Major ions and dissolved organic  
675 carbon. *Forest Ecol. Manag.* 180, 557-570.
- 676 Daniels, S.M., Evans, M.G., Agnew, C.T., Allott, T.E.H., 2012. Ammonium release from  
677 a blanket peatland into headwater stream systems. *Environ. Pollut.* 163, 261-272.
- 678 Drinan, T., Graham, C., O'Halloran, J., Harrison, S., 2012. The impact of conifer  
679 plantation forestry on the Chydoridae (Cladocera) communities of peatland lakes.  
680 *Hydrobiologia*, 1-17.
- 681 Elrashidi, M.A., 2011. Selection of an appropriate phosphorus test for soils,  
682 [ftp://ftpfc.sc.egov.usda.gov/NSSC/Analytical\\_Soils/phosphor.pdf](ftp://ftpfc.sc.egov.usda.gov/NSSC/Analytical_Soils/phosphor.pdf). (assessed 13  
683 August 2013).
- 684 Ensign, S.H., Mallin, M.A., 2001. Stream water quality changes following timber harvest  
685 in a coastal plain swamp forest. *Wat. Res.* 35, 3381-3390.
- 686 European Community, 1988. EEC of the European Parliament and of the Council of 18  
687 July 1978, on the quality of Salmonid Waters Regulation (the quality of fresh  
688 waters needing protection or improvement in order to support fish life). In:  
689 Official Journal of the European Communities (Ed.), Directive 78/659/, EEC.
- 690 Farrell, E.P., Boyle, G., 1990. Peatland forestry in the 1990s. 1. Low-level blanket bog.  
691 *Ir. Forest.* 47, 69-78.
- 692 Finnegan, J., Regan, J.T., De Eyto, E., Ryder, E., Tiernan, D., Healy, M.G., 2012.  
693 Nutrient dynamics in a peatland forest riparian buffer zone and implications for  
694 the establishment of planted saplings. *Ecol. Eng.* 47, 155– 164.

- 695 Forest Service, 2000a. Forest harvesting and the environment guidelines. Department of  
696 the Marine and Natural Resources, Dublin.  
697 [http://www.agriculture.gov.ie/media/migration/forestry/publications/harvesting.p](http://www.agriculture.gov.ie/media/migration/forestry/publications/harvesting.pdf)  
698 [df](http://www.agriculture.gov.ie/media/migration/forestry/publications/harvesting.pdf) (assessed 13 August 2013).
- 699 Forest Service, 2000b. Forest and Water Quality Guidelines. Department of the Marine  
700 and Natural Resources, Dublin.  
701 [http://www.agriculture.gov.ie/media/migration/forestry/publications/water\\_qualit](http://www.agriculture.gov.ie/media/migration/forestry/publications/water_quality.pdf)  
702 [y.pdf](http://www.agriculture.gov.ie/media/migration/forestry/publications/water_quality.pdf) (assessed 13 August 2013).
- 703 Forest Service, 2000c. Forest biodiversity guidelines. Department of the Marine and  
704 Natural Resources, Dublin.  
705 [http://www.agriculture.gov.ie/media/migration/forestry/publications/biodiversity.](http://www.agriculture.gov.ie/media/migration/forestry/publications/biodiversity.pdf)  
706 [pdf](http://www.agriculture.gov.ie/media/migration/forestry/publications/biodiversity.pdf) (assessed 13 August 2013).
- 707 Forest Service, 2000d. Forest protection guidelines. Department of the Marine and  
708 Natural Resources, Dublin.  
709 <http://www.agriculture.gov.ie/media/migration/forestry/publications/fsFPG.pdf>  
710 (assessed 13 August 2013).
- 711 Forest Service, 2000e. Forestry and archaeology guidelines. Department of the Marine  
712 and Natural Resources, Dublin.  
713 [http://www.agriculture.gov.ie/media/migration/forestry/publications/archaeology.](http://www.agriculture.gov.ie/media/migration/forestry/publications/archaeology.pdf)  
714 [pdf](http://www.agriculture.gov.ie/media/migration/forestry/publications/archaeology.pdf) (assessed 13 August 2013).
- 715 Forest Service, 2000f. Forestry and the landscape guidelines. Department of the Marine  
716 and Natural Resources, Dublin.  
717 [http://www.agriculture.gov.ie/media/migration/forestry/publications/landscape.pd](http://www.agriculture.gov.ie/media/migration/forestry/publications/landscape.pdf)  
718 [f](http://www.agriculture.gov.ie/media/migration/forestry/publications/landscape.pdf) (assessed 13 August 2013).
- 719 Haygarth, P.M., Warwick, M.S., House, W.A., 1997. Size distribution of colloidal  
720 molybdate reactive phosphorus in river waters and soil solution. *Wat. Res.* 31,  
721 439-448.
- 722 Hüttl, R. F., B.U. Schneider, 1998. Forest ecosystem degradation and rehabilitation.  
723 *Ecol. Eng.* 10, 19–31.
- 724 Kaila, A., Asam, Asam, Z., Sarkkola, S., Xiao, L., Laurén, A., Vasander, H., Nieminen,  
725 M. 2012. Decomposition of harvest residue needles on peatlands drained for  
726 forestry – Implications for nutrient and heavy metal dynamics. *For. Ecol.*  
727 *Manage.* 277, 141 – 149.

728 Johnson, J., Farrell, E.P., Barrs, J.-R., Cruikshanks, R., Matson, R., Kelly Quinn, M.,  
729 2008. Forests and surface waters acidification literature review. In: Water  
730 Framework Directive, Water Framework Directive, Western River Basin District  
731 [http://www.wfdireland.ie/docs/22\\_ForestAndWater/Forests%20and%20Surface%  
732 20Water%20Acidification\\_literature%20Review.pdf](http://www.wfdireland.ie/docs/22_ForestAndWater/Forests%20and%20Surface%20Water%20Acidification_literature%20Review.pdf) (assessed 13 August 2013).

733 Joosten, H., Clarke, D., 2002. Wise use of mires and peatlands. A framework for  
734 decision-making. International Mire Conservation Group and International Peat  
735 Society.

736 Lucas, R.W., Sponseller, R. A., Laudon, H., 2013. Controls over base cation  
737 concentrations in stream and river waters : Along-term analysis on the role of  
738 deposition and climate. *Ecosystems* 16, 707-721.

739 Macrae, M.L., Redding, T.E., Creed, I.F., Bell, W.R., Devito, K.J., 2005. Soil, surface  
740 water and ground water phosphorus relationships in a partially harvested Boreal  
741 Plain aspen catchment. *Forest Ecol. Manag.* 206, 315-329.

742 McBroom, M.W., Beasley, R.S., Chang, M., Ice, G.G., 2008. Water quality effects of  
743 clearcut harvesting and forest fertilization with best management practices. *J.*  
744 *Environ. Qual.* 37, 114-124.

745 McConnell, B., Gatley, S., 2006. Bedrock Geology of Ireland. Derived from the  
746 Geological Survey of Ireland 1:100,000 Bedrock Map Series and the Geological  
747 Survey of Northern Ireland 1:250,000 Geological Map of Northern Ireland.

748 National Forest Inventory, 2007. National forest inventory Republic of Ireland - Results.  
749 Forest Service, Wexford.  
750 [http://www.agriculture.gov.ie/media/migration/forestry/nationalforestinventory/n  
751 ationalforestinventorypublications/4330NFIRResults.pdf](http://www.agriculture.gov.ie/media/migration/forestry/nationalforestinventory/nationalforestinventorypublications/4330NFIRResults.pdf) (assessed 13 August  
752 2013).

753 Neal, C., Reynolds, B., Neal, M., Wickham, H., Hill, L., Williams, B., 1999. The impact  
754 of conifer harvesting on stream water quality: the Afon Hafren, mid-Wales.  
755 *Hydrol. Earth Syst. Sci.* 8, 503-520.

756 Neal, C., Reynolds, B., Neal, M., Wickham, H., Hill, L., Williams, B., 2004. The water  
757 quality of streams draining a plantation forest on gley soils: The Nant Tanllwyth,  
758 Plynlimon mid-Wales. *Hydrol. Earth Syst. Sci.* 8, 485-502.

759 Neal, C., Smith, C.J., Hills, S., 1992. Forestry impact on upland water quality. Institute of  
760 Hydrology.

761 Nieminen, M., 1998. Changes in nitrogen cycling following the clearcutting of drained  
762 peatland forests in southern Finland. *Boreal Environ. Res.* 3, 9-21.

763 Nieminen, M., 2003. Effects of clear-cutting and site preparation on water quality from a  
764 drained Scots pine mire in southern Finland. *Boreal Environ. Res.* 8, 53-59.

765 Nisbet, T., Dutch, J., Moffat, A., 1997. Whole-tree harvesting - A guide to good practice.  
766 Forestry Commission, Edinburgh, UK.  
767 [http://www.forestry.gov.uk/pdf/wth.pdf/\\$file/wth.pdf](http://www.forestry.gov.uk/pdf/wth.pdf/$file/wth.pdf) (assessed 13 August 2013).

768 O'Driscoll, C., De Eyto, E., Rodgers, M., O'Connor, M., Asam, Z.U.Z., Xiao, L., 2012.  
769 Diatom assemblages and their associated environmental factors in upland peat  
770 forest rivers. *Ecol. Indic.* 18, 443-451.

771 O'Driscoll, C., Rodgers, M., O'Connor, M., Asam, Z.-u.-Z., de Eyto, E., Poole, R., Xiao,  
772 L., 2011. A potential solution to mitigate phosphorus release following  
773 clearfelling in peatland forest catchments. *Wat Air Soil. Poll.* 221, 1-11.

774 Owende, P.M.O., Lyons, J., Haarlaa, R., Peltola, A., Spinelli, R., Molano, J., Ward, S.M.,  
775 2002. Operations protocol for eco-efficient wood harvesting on sensitive sites. In.  
776 ECOWOOD Partnership. <http://www.ucd.ie/foresteng/> (assessed 13 August  
777 2013).

778 Palviainen, M., Finér, L., Kurka, A.-M., Mannerkoski, H., Piirainen, S., Starr, M., 2004.  
779 Decomposition and nutrient release from logging residues after clear-cutting of  
780 mixed boreal forest. *Plant and Soil* 263, 53-67.

781 Renou-Wilson, F., Bolger, T., Bullock, C., Convery, F., Curry, J., Ward, S., Wilson, D.,  
782 Müller, C., 2011. BOGLAND: Sustainable management of peatlands in Ireland.  
783 STRIVE 75. EPA, Co. Wexford, Ireland.  
784 <http://www.epa.ie/downloads/pubs/research/land/name.31495.en.html> (assessed  
785 13 August 2013).

786 Renou, F., Farrell, E.P., 2005. Reclaiming peatlands for forestry: the Irish Experience. In,  
787 Restoration of Boreal and Temperate Forests. CRC Press, Boca Raton.

788 Rodgers, M., O'Connor, M., Healy, M.G., O'Driscoll, C., Asam, Z.-u.-Z., Nieminen, M.,  
789 Poole, R., Müller, M., Xiao, L., 2010. Phosphorus release from forest harvesting  
790 on an upland blanket peat catchment. *Forest Ecol. Manag.* 260, 2241-2248.

791 Rodgers, M., O'Connor, M., Robinson, M., Muller, M., Poole, R., Xiao, L., 2011.  
792 Suspended solid yield from forest harvesting on upland blanket peat. *Hydrol.*  
793 *Process.* 25, 207-216.

794 Rodgers, M., Xiao, L., Müller, M., O'Connor, M., E., D.E., Poole, R., Robinson, M.,  
795 Healy, M.G., 2008. Quantification of erosion and phosphorus release from a peat  
796 soil forest catchment. STRIVE Report Series No. 8. EPA, Co. Wexford, Ireland.  
797 <http://www.epa.ie/downloads/pubs/research/land/name,25212,en.html> (assessed  
798 13 August 2013).

799 Ryder, L., de Eyto, E., Gormally, M., Sheehy Skeffington, M., Dillane, M., Poole, R.,  
800 2011. Riparian zone creation in established coniferous forests in Irish upland peat  
801 catchments: Physical, chemical and biological implications. *Biol. and Environ.*  
802 111.

803 S.I. No. 272 of 2009. European communities environmental objectives (surface waters)  
804 regulations.  
805 [http://www.environ.ie/en/Legislation/Environment/Water/FileDownload,20824,e](http://www.environ.ie/en/Legislation/Environment/Water/FileDownload,20824,en.pdf)  
806 [n.pdf](http://www.environ.ie/en/Legislation/Environment/Water/FileDownload,20824,en.pdf) (assessed 13 August 2013).

807 Stevens, P.A., Norris, D.A., Williams, T.G., Hughes, S., Durrant, D.W., Anderson, M.A.,  
808 Weatherley, N.S., Hornung, M., Woods, C., 1995. Nutrient losses after  
809 clearfelling in Beddgelert Forest: A comparison of the effects of conventional and  
810 whole-tree harvest on soil water chemistry. *Forestry* 68, 115-131.

811 Stott, T., Marks, S., 2000. Effects of plantation forest clearfelling on stream temperatures  
812 in the Plynlimon experimental catchments, mid-Wales. *Hydrol. Earth Syst. Sc.i* 4,  
813 95-104.

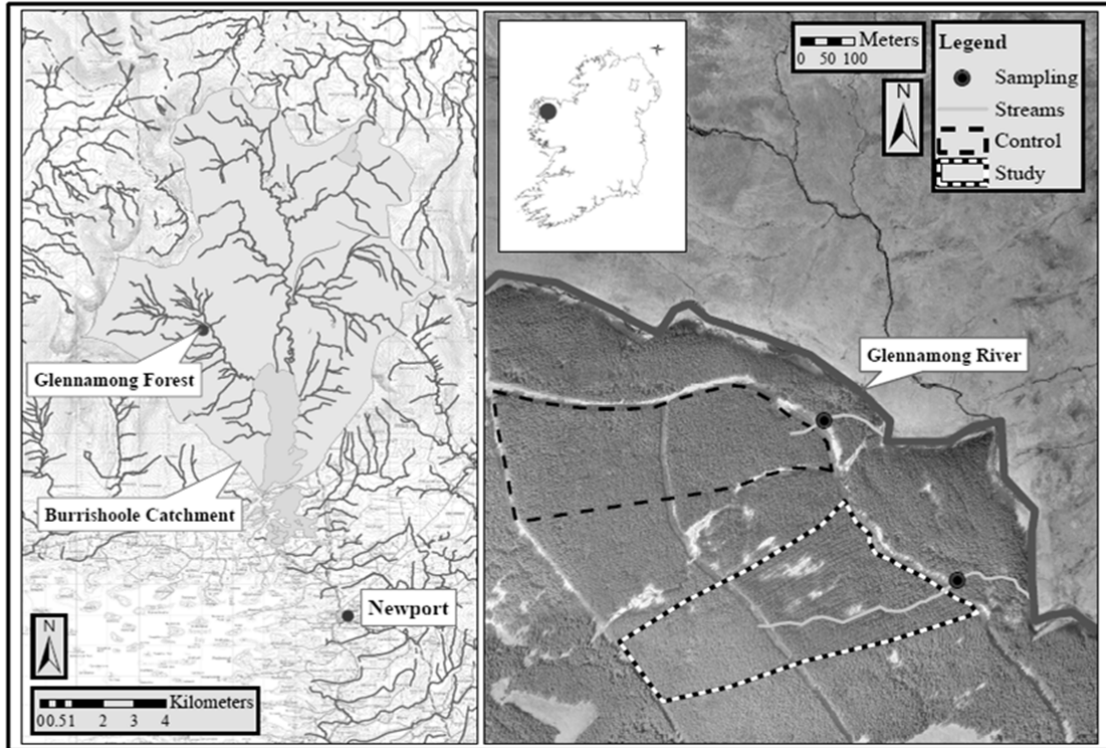
814 Strahler, A.N., 1964. Quantitative geomorphology of drainage basin and channel  
815 networks. *Handbook of Applied Hydrology*.

816 Väänänen, R., Nieminen, M., Vuollekoski, M., Nousiainen, H., Sallantausta, T., Tuittila,  
817 E.S., Ilvesniemi, H., 2008. Retention of phosphorus in peatland buffer zones at  
818 six forested catchments in southern Finland. *Silva Fennica* 42, 211-231.

819 Vasconcellos, R.L.F., Bonfim, J.A., Andreote, F.D., Mendes, L.W., Baretta, D., Cardoso,  
820 E.J.B.N., 2013. Microbiological indicators of soil quality in a riparian forest  
821 recovery gradient. *Ecol. Eng.* 53, 313 – 320.

822 Wallbrink, P., Croke, J., 2002. A combined rainfall simulator and tracer approach to  
823 assess the role of best management practices in minimising sediment  
824 redistribution and loss in forests after harvesting. *Forest Ecol. Manag.* 170, 217-  
825 232.

- 826 Weatherley, N.S., Ormerod, S.J., 1990. Forests and the temperature of upland streams in  
827 Wales: a modelling exploration of the biological effects. *Freshwat. Biol.* 24, 109-  
828 122.
- 829 Yusop, Z., Douglas, I., Nik, R.A., 2006. Export of dissolved and undissolved nutrients  
830 from forested catchments in Peninsular Malaysia. *Forest Ecol. Manage.* 224, 26 –  
831 44.
- 832



833

834

835 **Figure 1:** Location of the Glennamong Forest control catchment (CC) and study  
836 catchment (SC).

837

838

839

840

841

842

843

844

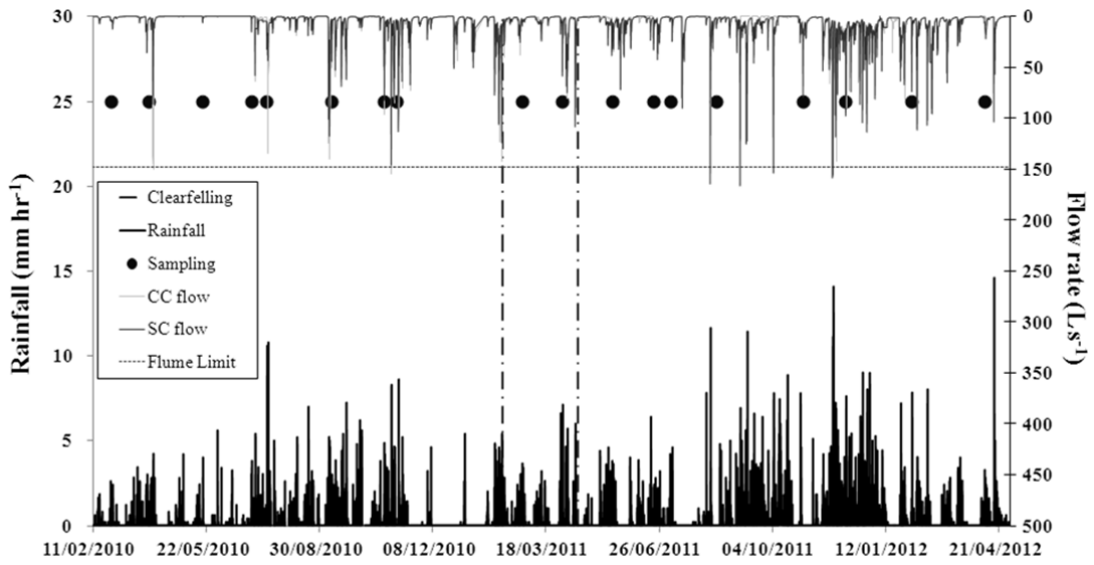
845

846

847

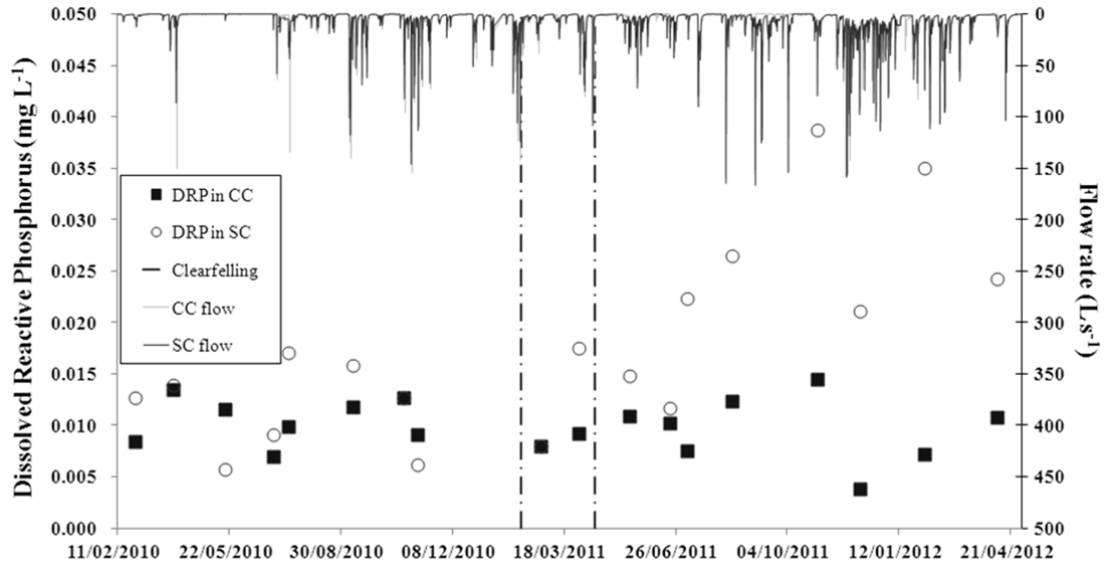
848

849



850  
 851  
 852  
 853  
 854  
 855  
 856  
 857  
 858  
 859  
 860  
 861

**Figure 2.** Rainfall ( $\text{mm hr}^{-1}$ ) from the Glennamong weather station and stream water sampling dates from February 2010 to May 2012. Flow rates ( $\text{L s}^{-1}$ ) from the control catchment (CC) and study catchment (SC) are on the inverted secondary axis.



862

863

864 **Figure 3.** Flow-weighted mean concentrations of dissolved reactive phosphorus (DRP)

865 (mg L<sup>-1</sup>) measured in the control catchment (CC) and the study catchment (SC) from

866 February 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

867

868

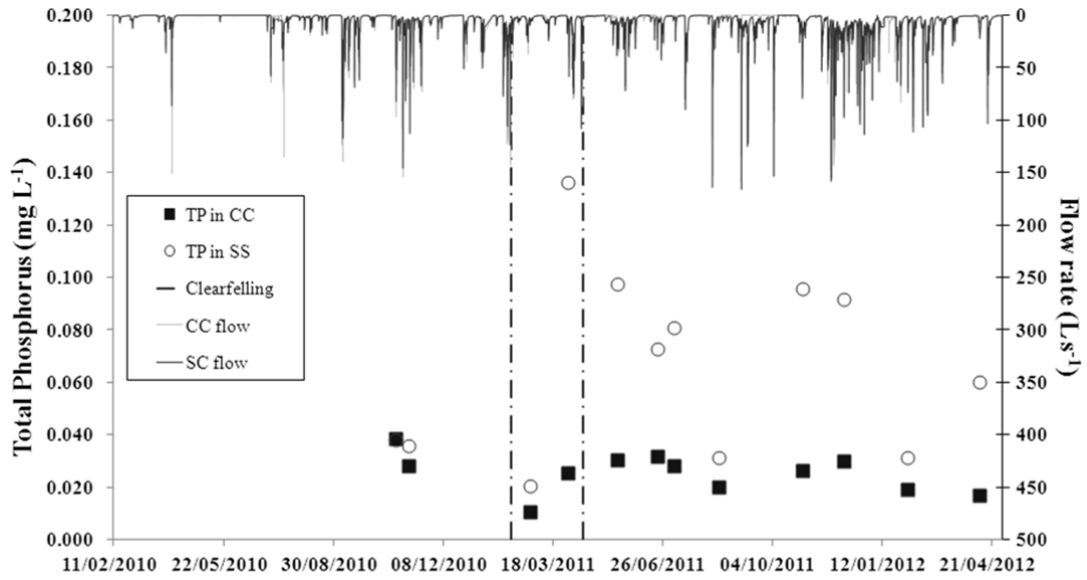
869

870

871

872

873



874

875

876 **Figure 4.** Flow-weighted mean concentrations of total phosphorus (TP) (mg L<sup>-1</sup>)  
 877 measured in the control catchment (CC) and the study catchment (SC) from February  
 878 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

879

880

881

882

883

884

885

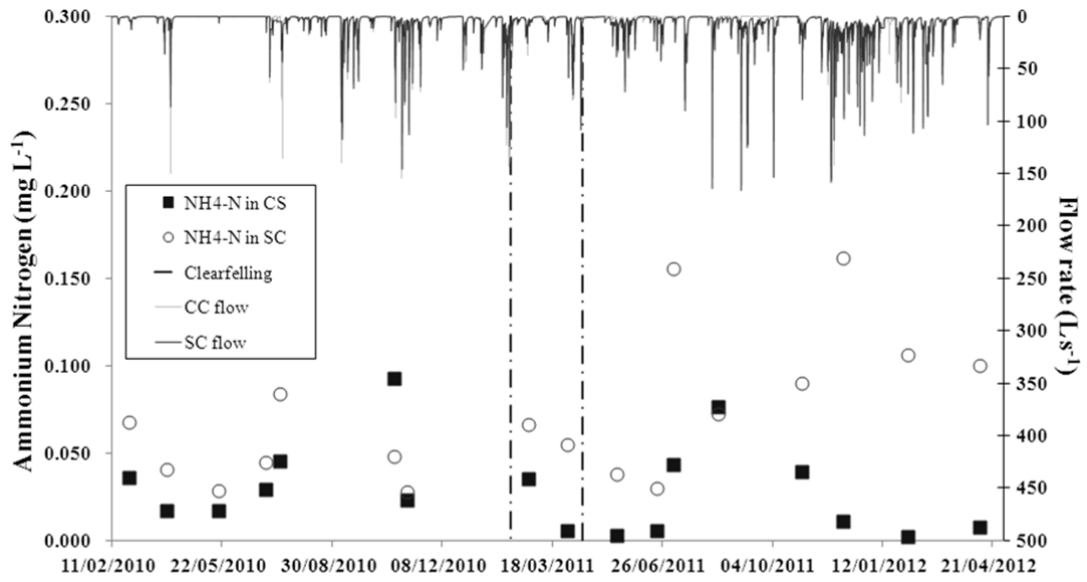
886

887

888

889

890



891

892

893 **Figure 5.** Flow-weighted mean concentrations of ammonium-nitrogen (NH<sub>4</sub><sup>+</sup>-N) (mg L<sup>-1</sup>)  
 894 <sup>1</sup>) measured in the control catchment (CC) and the study catchment (SC) from February  
 895 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

896

897

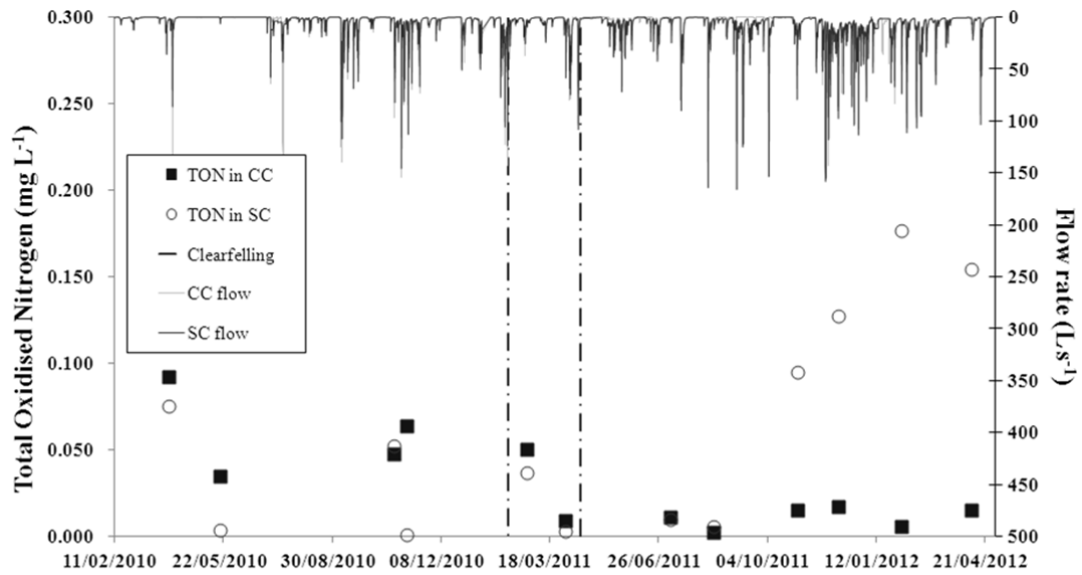
898

899

900

901

902



903

904

905 **Figure 6.** Flow-weighted mean concentrations of total oxidised nitrogen (TON) (mg L<sup>-1</sup>)

906 measured in the control catchment (CC) and the study catchment (SC) from February

907 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

908

909

910

911

912

913

914

915

916

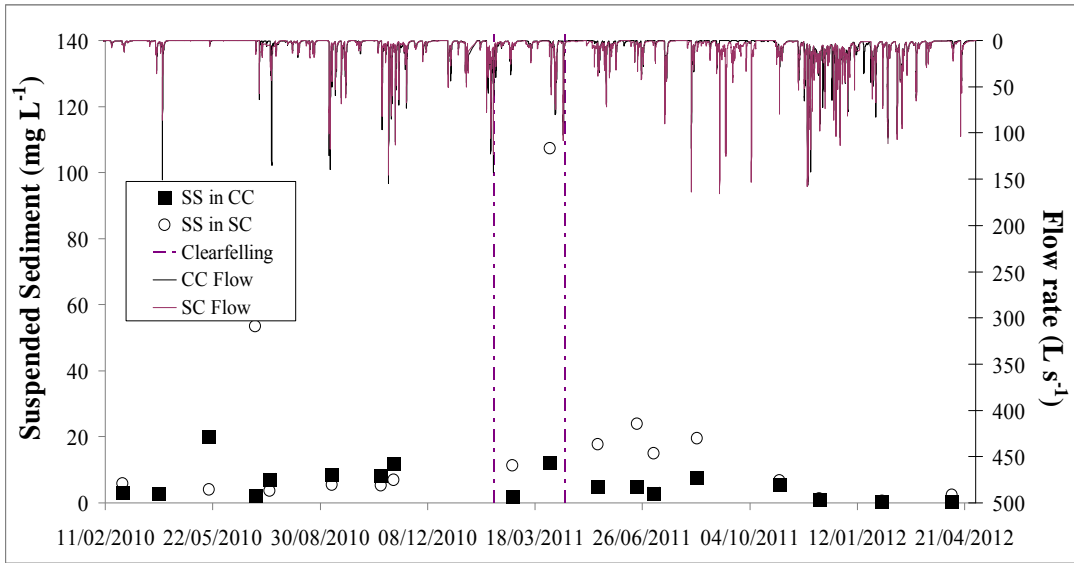
917

918

919

920

921



922

923

924 **Figure 7.** Flow-weighted mean concentrations of suspended sediment (SS) (mg L<sup>-1</sup>)

925 measured in the control catchment (CC) and the study catchment (SC) from February

926 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

927

928

929

930

931

932

933

934

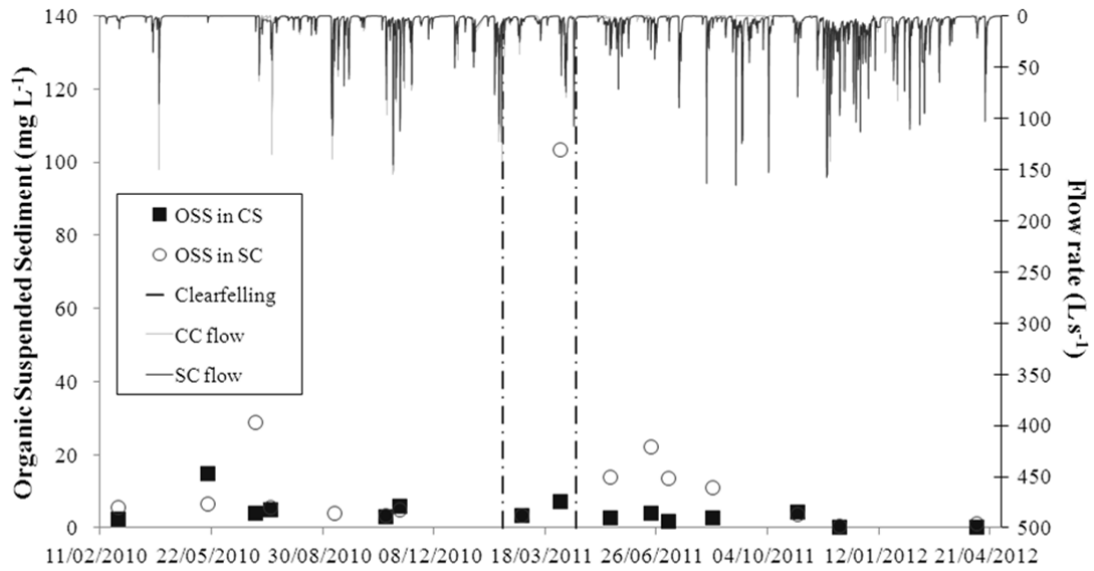
935

936

937

938

939



940

941

942 **Figure 8.** Flow-weighted mean concentrations of organic suspended sediment (OSS) (mg  
 943 L<sup>-1</sup>) measured in the control catchment (CC) and the study catchment (SC) from  
 944 February 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

945

946

947

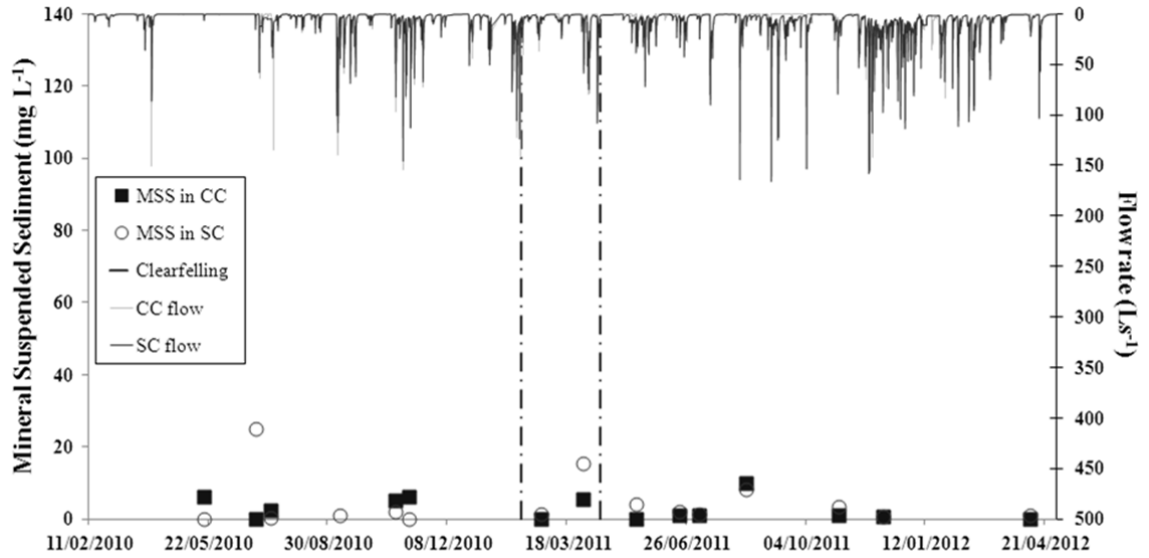
948

949

950

951

952



953

954

955 **Figure 9.** Flow-weighted mean concentrations of mineral suspended sediment (MSS)  
 956 (mg L<sup>-1</sup>) measured in the control catchment (CC) and the study catchment (SC) from  
 957 February 2010 to May 2012. Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

958

959

960

961

962

963

964

965

966

967

968

969

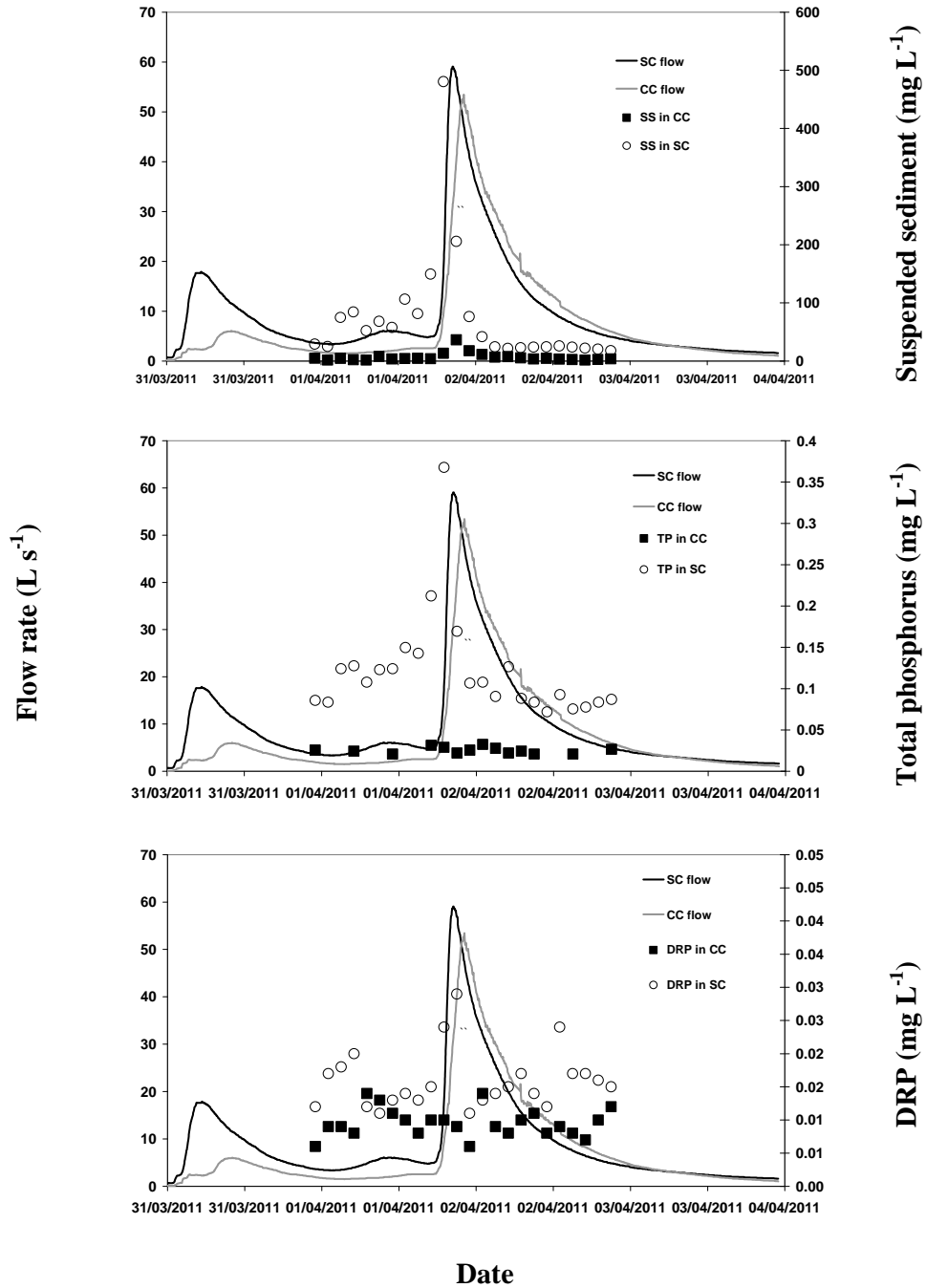
970

971

972

973

974



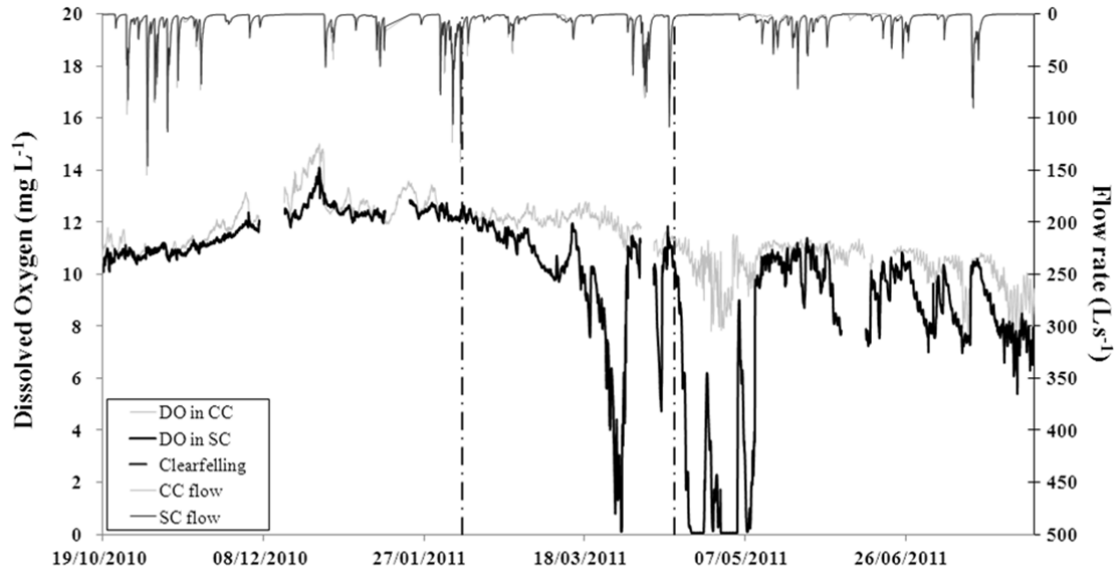
975

976 **Figure 10.** Suspended solids (top), total phosphorus (middle) and dissolved reactive  
 977 phosphorus (DRP; bottom) release in a storm event towards the end of clearfelling.

978

979

980



981

982

983 **Figure 11.** Dissolved oxygen (DO) (mg L<sup>-1</sup>) at 5-minute intervals measured in the  
 984 control catchment (CC) and the study catchment (SC) from October 2010 to July 2011.

985 Flow rate (L s<sup>-1</sup>) is on the inverted secondary axis.

986

987

988

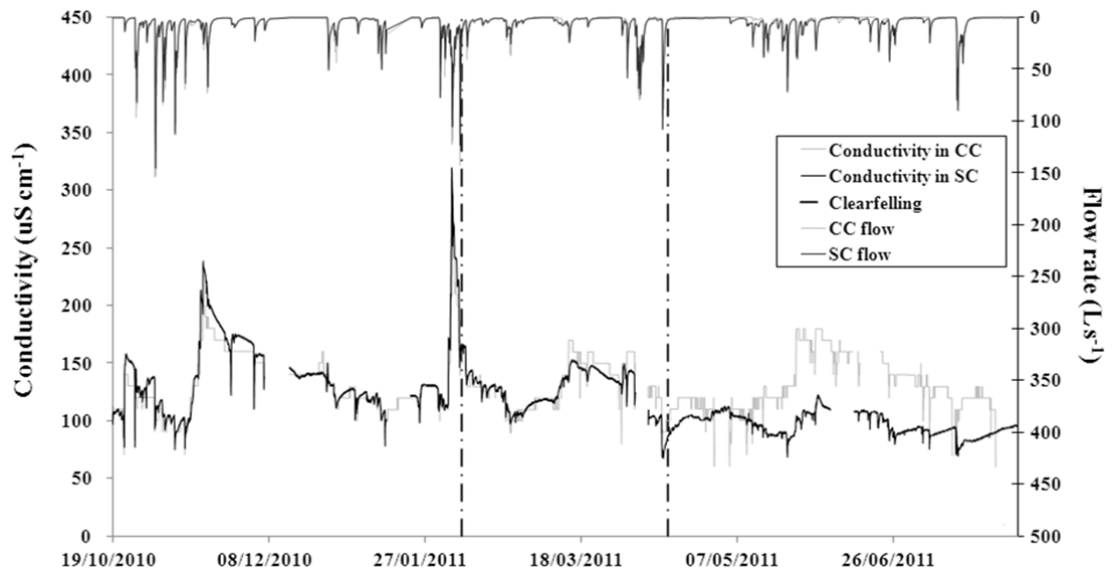
989

990

991

992

993



994

995

996 **Figure 12.** Electrical conductivity (EC) ( $\mu\text{S cm}^{-1}$ ) at 5-minute intervals measured in the  
 997 control catchment (CC) and the study catchment (SC) from October 2010 to July 2011.

998 Flow rate ( $\text{L s}^{-1}$ ) is on the inverted secondary axis.

999

1000

1001

1002

1003

1004

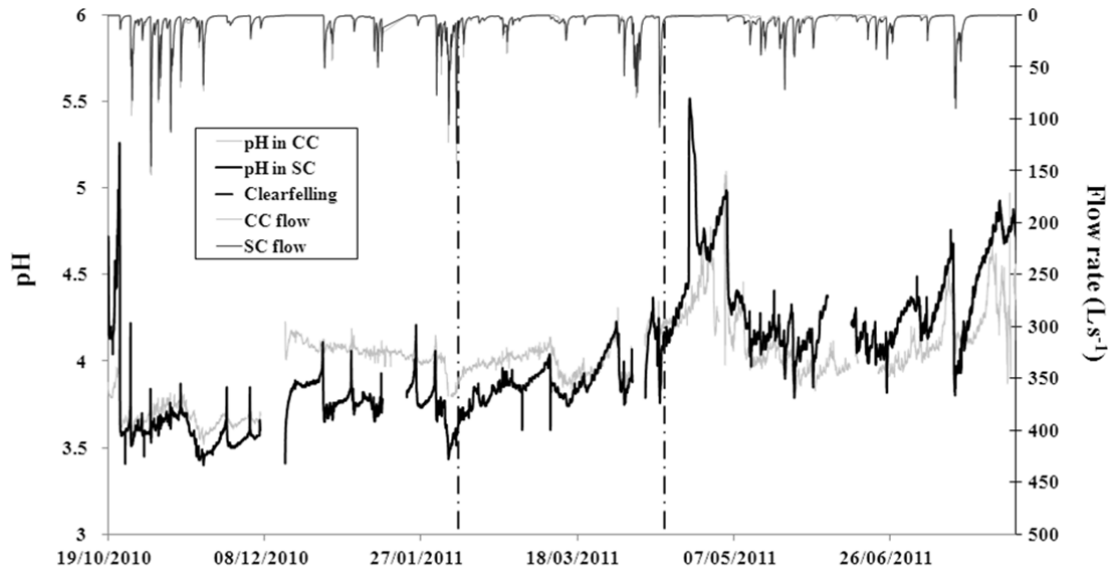
1005

1006

1007

1008

1009



1010

1011

1012 **Figure 13.** pH at 5-minute intervals measured in the control catchment (CC) and the  
 1013 study catchment (SC) from October 2010 to July 2011. Flow rate (L s<sup>-1</sup>) is on the  
 1014 inverted secondary axis.

1015

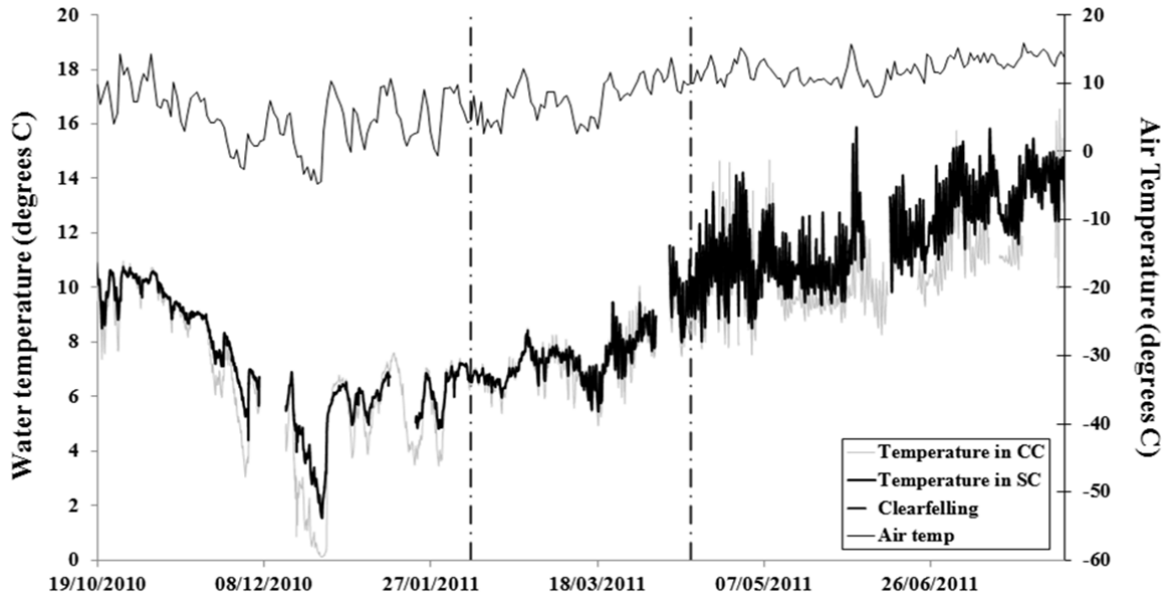
1016

1017

1018

1019

1020



1021

1022

1023 **Figure 14.** Stream water temperatures (°C) at 5-minute intervals measured in the control

1024 catchment (CC) and the study catchment (SC) from October 2010 to July 2011. Air

1025 temperatures (°C) from the weather station are on the inverted secondary axis.

1026

1027

1028

1029

1030

1031

1032

1033

1034

1035

1036

1037

1038

1039

1040

1041

1042 **Table 1:** Best management practices (BMPs) from ‘Forest Harvesting and the Environmental Guidelines’ (Forest Service, 2000c) and ‘Forest  
 1043 and Water Quality Guidelines’ (Forest Service, 2000a) with applied BMPs at the Glennamong study site.

Best Management Practice	Compliance (Yes / No)	Comments
<u>Harvest planning</u>		
• Establish relevant environmental issues and liaise with authorities	Yes	
• Terrain inspection and draft harvest plan for size and shape of felling coupe	Yes	• Terrain inspection and harvest plan drafted with appropriate felling size and shape
• Felling sequence and contingency plan	Yes	• Felling sequence followed as per plan
• Equipment to be used and structures required	Yes	
<u>Harvest operation</u>		
• Adequate brash mats to limit damage to soil from heavy machinery	No	• Use of brash mats, but rutting occurred due to heavy rainfall and lack of maintenance
• Installation of ancillary structures and provision of buffer zones to watercourses	No	• Temporary silt traps installed but only at end of clearfelling, so SS was released during clearfelling
• Limit load size	Yes	
• Prevent accumulation of brash in drains and aquatic zones	No	• Brash allowed to gather in stream on site
• Establish new buffer zones at end of clearfelling operations and clean drains	No	• No cleaning of brash from stream in SC post-CF due to a risk of increased sediment
• Consider suspending operations during periods of heavy rain	No	• No suspension of clearfelling during wet weather due to time constraints
<u>Harvest site restoration</u>		
• Repair to road and drains	N/A	• Road repair was not necessary and brash was removed from road drains
• Remove temporary structures and install permanent ones if necessary	Yes	• Permanent silt traps installed
• Remove hazardous compounds	Yes	• All logging equipment was removed from site
• Carry out water management on extraction routes	Yes	• Extra brash placed on rutted areas on extraction routes
<u>Road planning</u>		
	N/A	• Not necessary
<u>Road construction</u>		
	N/A	• Not necessary
<u>Machine servicing</u>		
• Storage of materials and maintenance and refuelling away from watercourses (min 50 m)	Yes	• Servicing and maintenance away from watercourses, and any spillages were cleaned with pollution control kits

1044

1045

1046

1047 **Table 2:** Maximum concentrations ( $\mu\text{g L}^{-1}$ ) pre- and post- clearfelling for dissolved reactive phosphorus (DRP), total phosphorus (TP), total  
 1048 oxidised nitrogen (TON) and ammonium-nitrogen ( $\text{NH}_4^+\text{-N}$ ) from the current study site and comparable study sites worldwide.  
 1049

Reference	Location	Area of CF (ha)	Type of harvesting	Soil type	Average Annual Rainfall	Max concentrations pre-clearfelling ( $\mu\text{g L}^{-1}$ )				Max concentrations post-clearfelling ( $\mu\text{g L}^{-1}$ )			
						TP	DRP	TON	$\text{NH}_4\text{-N}$	TP	DRP	TON	$\text{NH}_4\text{-N}$
Cummins and Farrell (2003 a, b)	Galway, Ireland	1	Bole only clearfelling	Peat	1600	-	13 <sup>a</sup>	$\approx 400^b$	$\approx 300$	-	4164 <sup>a</sup>	2500 <sup>b</sup>	$\approx 1800$
Ensign and Mallin (2001)	Northern Carolina, USA	52.6	Clearcut with track cutter and shovel logger	Swamp soils	1270	188	47 <sup>a</sup>	581 <sup>b</sup>	146	427	297 <sup>a</sup>	191 <sup>b</sup>	440
Neal (2004)	Plynlimon, Mid-Wales	< 1	Bole only clearfelling	Peaty gley	2500	-	30 <sup>a</sup>	-	160	-	550 <sup>a</sup>	-	1120
Nieminen (2003)	Southern Finland	7	Bole only clearfelling	Peat	600	-	< 10 <sup>c</sup>	< 20 <sup>b</sup>	< 25	-	100 <sup>c</sup>	< 20 <sup>b</sup>	< 15
Rodgers et al. (2010) <sup>d</sup>	Mayo, Ireland	14.5	Bole only clearfelling	Peat	2000	28	-	-	-	201	-	-	-
Present study	Mayo, Ireland	9.4	Bole only clearfelling	Peat	3000	80	33	128	182	611	471	194	1336

1050 <sup>a</sup> measured as molybdate reactive phosphorus in these studies.

1051 <sup>b</sup> measured as  $\text{NO}_3^-\text{-N}$  by ion chromatography in these studies.

1052 <sup>c</sup> measured as  $\text{PO}_4^{3-}\text{-P}$  by ion chromatography in these studies.

1053 <sup>d</sup> reported as flow-weighted mean concentrations.

1054 **Table 3:** Comparison of nutrient and sediment loads exiting harvested peat areas.

1055

Reference	Location	Area of CF (ha)	Duration of study after felling (yr)	Type of harvesting	BMP used?	Exports from site (kg ha <sup>-1</sup> yr <sup>-1</sup> )							
						Control (unharvested)				Study (harvested)			
						Tot-P	DRP	TRP	SS	Tot-P	DRP	TRP	SS
Rodgers et al. (2010 <sup>a</sup> )	Mayo, Ireland	14.5	4	Bole only clearfelling	Yes			< 0.06				≈ 1.3	
Present study	Mayo, Ireland	10	1	Bole only clearfelling	Yes	0.6	0.2		202	0.9	0.4		200

1056 <sup>a</sup> Total reactive phosphorus (TRP) loads peaked in the second year (2.3 kg ha<sup>-1</sup>), but decreased in the third and fourth years of their study. Value quoted is study average.

1057

