Water Air Soil Pollut (2011) 221:1–11
DOI 10.1007/s11270-011-0764-2

A Potential Solution to Mitigate Phosphorus Release Following Clearfelling in Peatland Forest Catchments

Connie O'Driscoll · Michael Rodgers · Mark O'Connor · Zaki-ul-Zaman Asam · Elvira de Eyto · Russell Poole · Liwen Xiao

Received: 19 October 2010 / Accepted: 26 January 2011 / Published online: 16 February 2011

Abstract Since the 1950s, large areas of upland peat have been afforested in northern European countries. Due to the poor phosphorus (P) adsorption capacity and low hydraulic permeability in blanket peat soil and increased labile P sources, harvesting these blanket peat forests can significantly increase P concentrations in the receiving aquatic systems. This paper briefly reviews the current management practices on the control of P releases from forestry in Ireland and the UK, and proposes a possible novel practice—grass seeding clearfelled areas immediately after harvesting, which should reduce P release from blanket peat forest harvesting. The study was conducted in the Burrishoole Catchment in the west of Ireland. A field trial was carried out to identify the successful native grass species that could grow quickly in the blanket peat forest. The two successful grass species—*Holcus lanatus* and *Agrostis capillaris*—were sown in three blanket peat forest study plots with areas of 100, 360, and 660 m^2 immediately after harvesting. Areas without grass seeding were used as controls. One year later, the P content in the aboveground vegetation biomass of the three study plots were 2.83, 0.65, and 3.07 kg $P ha^{-1}$, respectively, which were significantly higher than the value of 0.02 kg $P ha^{-1}$ in the control areas. The water extractable phosphorus in the three study plots were 8.44, 9.83, and 6.04 mg(kg dry soil)$^{-1}$, respectively, which were lower than the value of 25.72 mg(kg dry soil)$^{-1}$ in the control sites. The results indicate that grass seeding of the peatland immediately after harvesting can quickly immobilize significant amounts of P and warrants additional research as a new Best Management Practice following harvesting in the blanket peatland forest to mitigate P release.

Keywords P release · Blanket peat · Forest harvesting · Grass seeding · *Holcus lanatus* · *Agrostis capillaris*

C. O'Driscoll · M. Rodgers · M. O'Connor · Z.-u.-Z. Asam · L. Xiao (✉)
Civil Engineering, National University of Ireland, Galway, Republic of Ireland
e-mail: liwen.xiao@nuigalway.ie

E. de Eyto · R. Poole
Marine Institute, Newport, County Mayo, Republic of Ireland

1 Introduction

Forest harvesting disrupts the phosphorus (P) cycle of forest ecosystems and increases labile P sources in the soil, which could result in an increase of P release. P at concentrations of 30 μg l^{-1} could trigger eutrophication in freshwaters (Boesch et al. 2001). Eutrophication has been identified as the most important water quality problem in the UK and Ireland (EPA 2004), particularly for the generally oligotrophic salmonid rivers and lakes, which are very sensitive to pollution. Therefore, P release after harvesting is of significant concern in upland blanket peat forest catchments, such as the Burrishoole catchment in the west of

Ireland, which contains salmonids and has a great risk of P release due to the poor P adsorption capacity and low hydraulic permeability of the peat soil. Since the 1950s, large areas of upland peat have been afforested in northern European countries. Previous studies have documented the effects of peatland forest harvesting on P release. In Southern Finland, Nieminen (2003) found an increase in phosphorus release at three out of four peatland forest study sites after harvesting. In the west of Ireland, Cummins and Farrell (2003) investigated the biogeochemical impacts of clearfelling with regard to phosphorus on blanket peatland streams and noted that in three drains the molybdate-reactive phosphorus (MRP) increased from 9, 13, and 93 μg l^{-1} before harvesting to 265, 3,530, and 4,164 μg l^{-1}, respectively, 1 year after harvesting. Recently, Rodgers et al. (2010) carried out a study in the Burrishoole catchment in the west of Ireland and found that the daily mean total reactive phosphorus (TRP) concentration in a study stream increased from about 6 μg l^{-1} preharvesting to 429 μg l^{-1} 1 year after harvesting, even though best management practices were strictly implemented. Four years after clearfelling, the P concentrations returned to the preharvesting concentrations. In the first 3 years after harvesting, up to 5.15 kg ha^{-1} of TRP was released from the harvested catchment to the receiving water; in the second year alone, 2.3 kg ha^{-1} of TRP was released. These results indicated that the water quality of lakes, rivers, and streams in the blanket peat forest catchments could be threatened by possible increases of P in runoff water arising from forest harvesting.

1.1 Current Mitigation Methods

Buffer zones, which can filter the runoff before it reaches the receiving water, are widely used by forestry practitioners in the management of freshwater aquatic systems. They can protect aquatic systems by controlling runoff: (1) mechanically, by increasing deposition through the slowing down of flow; (2) chemically, through reactions between incoming nutrients and soil matrices and residual elements; and (3) biologically, through plant and microbial nutrient processes. Buffer zones have been recognized as an efficient method to remove suspended solids and attached P and could remove 14% to 91.8% of total phosphorus (TP; Table 1). However, its effectiveness on dissolved reactive phosphorus (DRP) removal has been controversial. In their study, Vought et al. (1994) found that buffer strips were very efficient in DRP removal, with the removal efficiency of 95%. In contrast, Uusi-Kämppä (2005) found that their naturally vegetated buffer zone became a P release source, responsible for 70% of DRP release. Stutter et al. (2009) indicated that vegetated buffer zones increased soil P solubility and the potential amount P release. In Ireland and the UK, many of the earlier afforested upland blanket peat catchments were established without any riparian buffer areas, with trees planted to the stream edge (Ryder et al. 2010). Ryder et al. (2010) carried out a study on the creation of riparian buffer zones in three blanket peat forest in the west of Ireland and concluded that it was a technically challenging felling operation. In their study, Rodgers et al. (2010) found that in the Burrishoole catchment, most of the P release after harvesting occurred in soluble form during storm events, raising concerns about the effectiveness of buffer zones in blanket peatland catchments.

In order to reduce nutrient sources, whole-tree harvesting (WTH) is recommended (Nisbet et al. 1997). In the UK, WTH is usually achieved by removing the whole tree (i.e., all parts of the tree above the ground) from the site in a single operation (Nisbet et al. 1997). In Ireland, in experimental trails conducted by Coillte, an adapted WTH procedure was adopted where the forest harvest residues are bundled and removed from the selected sites after the conventional harvesting of stem wood (Dr. Philip O'Dea, Coillte Teoranta, 2010, personal communication). Needles and branches have much higher nutrient concentrations than stem wood, and whole-tree harvesting may reduce nutrient sources by 2–3 times more than bole-only harvesting (Nisbet et al. 1997). Rodgers et al. (2010) found higher water extractable P content in the areas below windrow/brash material than the brash-free areas in the harvested upland peat forest catchment and indicated that whole-tree harvesting could be used as a mean to decrease P release. Yanai (1998) reported negligible P loss to streams over 3 years from harvesting using the whole-tree harvesting method (all parts of tree above the ground) at the Hubbard Brook Experimental forest in New Hampshire. However, whole tree harvesting can remove most of the nutrients as well as base cations (Nisbet et al. 1997), which could have a negative impact on the next crop rotation, especially

Table 1 Performance of buffer zones on P removal

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

in blanket peat catchments. Walmsley et al. (2009) found that removal of forest residues can reduce second rotation productivity through nutrient shortage.

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

1.2 A Possible Novel Practice—Grass Seeding

The increase of P release is due to the disruption of the P cycle after harvesting, which reduces the catchment's P conservation capacity. The conservation of nutrients is dependent on a functional balance within the intrasystem cycle of the ecosystem, and critical to this balance is the uptake of water and nutrients by plants. Previous studies have indicated that vegetation can retain the available P in situ and reduce P release from forest activities. In Finland, Silvan et al. (2004) demonstrated that plants are effective in retaining P in peatlands. In China and Australia, vetiver grass in buffer zones and wetlands has shown a huge potential for removing P from wastewater and polluted water (Wagner et al. 2003). Loach (1968) found that *Molinia caerulea* could uptake 3.4 kg TP ha^{-1} in the wet-heath soils. Sheaffer et al. (2008) reported a P uptake of 30 kg ha^{-1} by *Phalaris arundinacea* in their wastewater treatment sites. However, recovery of blanket peat vegetation following forest harvesting usually takes several years. Connaghan (2007) found that *Juncus effusus* could develop in riparian areas within 3 years of clearfelling, whereas further away from the river where peat depth increased and soil fertility decreased vegetation took 6 to 10 years to recover.

It appears that natural re-vegetation arising from the seed bank is likely to be too slow to mitigate significantly against the P from felling, which mainly occurs in the first 3 years after harvesting (Rodgers et al. 2010; Cummins and Farrell 2003). In order to minimize the release of nutrients to receiving waters after harvesting, a rational approach is to maximize the ground vegetative growth over the first year after harvesting. This can be achieved by seeding the clearfelled area with fast-growing suitable native vegetation. Sowing herbaceous species to reduce soil erosion has been widely used during the first year after forest fire (Ruby 1989). However, no study has been done on the possibility of sowing grass immediately after harvesting to mitigate nutrient release. In this study, we examined if seeding grasses immediately after harvesting would have potential as a new forestry best management practice (BMP). It is hypothesized that by sowing the appropriate grass species in the blanket peat forest area immediately after harvesting, significant amounts of P will be quickly taken up and conserved in situ, which will result in reduced P release. To test this hypothesis, a trial experiment was first carried out to identify the successful germination grass species in the blanket peatland. The grass species were then sown in three harvested blanket peat forest plots. The biomass and P content of the aboveground vegetation were tested 1 year after grass seeding. In order to compare P uptake by vegetation in seeded versus natural re-vegetated areas, vegetation surveys were also carried out in nine blanket peat forest sites which were harvested 1–5 years ago in the west of Ireland.

2 Material and Methods

2.1 Site Description

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

2.2 Trial and Plot-Scale Experiment

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

Previous to the field trial test, a sample of seeds was tested for viability using a controlled laboratory germination test (Rao et al. 2006). For each species, 25 seeds were placed in a Petri dish on 42-mm-diameter Whatman filter paper, with eight replicates. Three milliliters of distilled water was added, and the dishes were arranged in cultivation chambers with fluorescent tubes of white light and a light/darkness timer, at 15–25°C. Dishes were sampled daily during 3 weeks. A seed was considered germinated when the radicle emerged. Distilled water was added whenever moisture loss was detected.

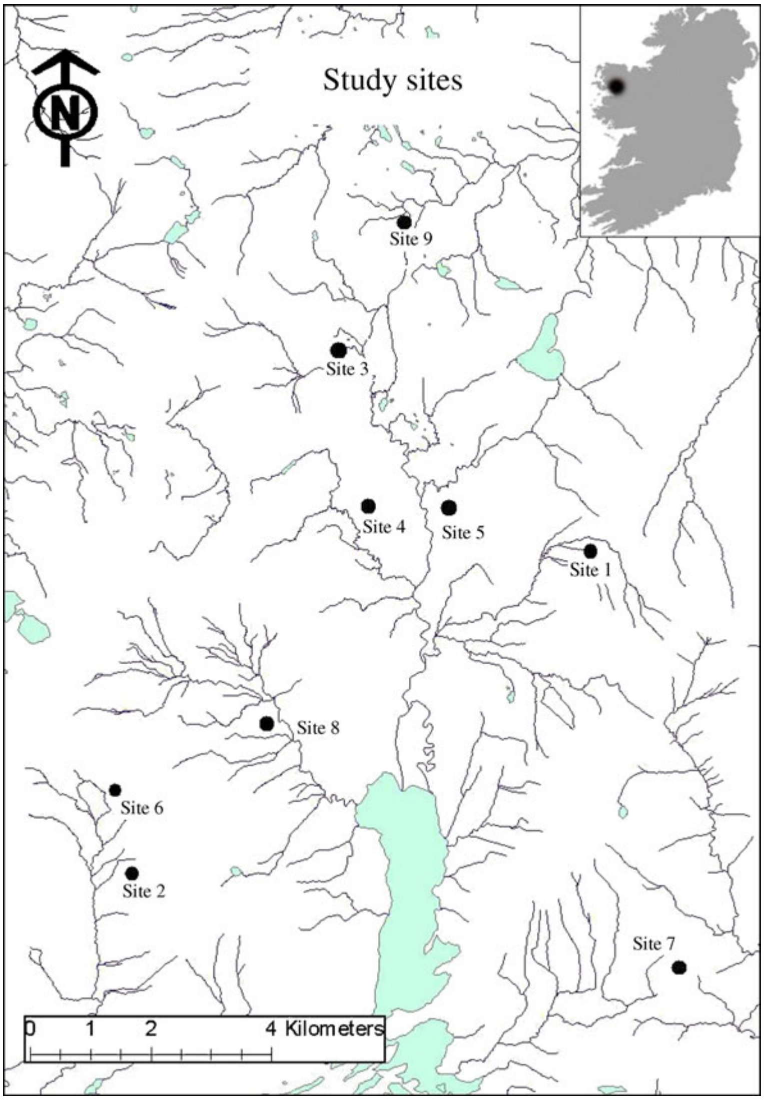

Fig. 1 Locations of the study sites (*Site 1* Srahrevagh, *Site 2* Glendahurk-2, *Site 3* Altahoney, *Site 4* Maumaratta, *Site 5* Goulaun, *Site 6* Glendahurk-1, *Site 7* Teevaloughan, *Site 8* Glennamong, *Site 9* Tawnynahulty)

In the field trial test, a total of 33 plots with an area of 900 cm^2 each were defined in the brash free area in Teevaloughan site (Site 7 in Fig. 1 and Table 2). Three hundred seeds of each of the 10 candidate species were scattered on three replicate plots (10×3 plots). Three replicate control plots were also included. The plots were surveyed weekly for 4 months. Percent seedling emergence was calculated as the number of visible seedlings divided by the total number of seeds scattered on each plot.

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

Table 2 Background information on the study sites

Site no.	Site name	Tree species before harvesting	Year of planting	Year of harvesting	Main vegetation type
1	Srahrevagh	Lodgepole pine	1971	2005	*C. vulgaris*, *M. caerulea*, *E. angustifolium*
2	Glendahurk-1	Lodgepole pine	1975	2006	*M. caerulea*, *C. vulgaris*, *Juncus bulbous*
3	Altahoney	Sitka spruce	1965	2006	*C. vulgaris*, *J. effusus*
4	Maumaratta	Lodgepole pine and Sitka spruce	1969	2007	*M. caerulea*
5	Goulaun	Lodgepole pine	1956	2008	*C. vulgaris*, *J. bulbous*, *Sphagnum* sp.
6	Glendahurk-2	Lodgepole pine	1975	2008	*M. caerulea*, *C. vulgaris*
7	Teevaloughan	Lodgepole pine and Sitka spruce	1972	2009	–
8	Glennamong	Lodgepole pine	1971	2009	–
9	Tawnynahulty	Lodgepole pine	1968	2009	–

2.3 Aboveground Vegetation Biomass and P Content Measurement

To estimate the aboveground vegetation biomass in nine study sites, 32 0.25-m×0.25-m quadrats were randomly sampled (Moore and Chapman 1986) in each site in August 2010. All vegetation lying within the quadrat was harvested to within 1 cm and dried at 80°C in the laboratory on the day of collection for 48 h. Samples were then weighed, and the biomass was calculated by using Eq. 1. TP content of the vegetation was measured in accordance with Ryan et al. (2001). About 1 g of dry matter from each sample was weighed, ground, and put into a furnace at a temperature of 550°C overnight, then 5 ml of 2 N HCl was added to extract the P and subsequently diluted to 50 ml with deionized water. P in the solution was analyzed using a Konelab 20 Analyser (Konelab Ltd.).

$$B_p = \frac{Wt}{St} \times 10,000 \tag{1}$$

where B_p is the biomass production (kilogram per hectare), Wt is the total dry weight of the samples (kilogram), and St is the total area (square meter).

2.4 Soil Water Extractable Phosphorus Measurement

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

2.5 Data Analysis

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

3 Results

3.1 Biomass and P Content of Natural Re-Vegetation in Blanket Peat Forests after Harvesting

Figure 2 shows the biomass and P content of natural re-vegetation in nine study sites. The biomass of the aboveground vegetation has a strong linear relationship with years after harvesting (Fig. 2a). Vegetation appears to begin recolonizing about one and half years after harvesting. Five years later, the aboveground vegetation linearly increased to about 6,000 kg biomass per hectare. P content in the aboveground vegetation also linearly increased and reached 3.5 kg TP ha^{-1} 5 years after harvesting (Fig. 2b).

3.2 Successful Germination Grass Species

Figure 3 shows the germination rates of 10 grass species examined in laboratory conditions. Most species germinated successfully within 3 weeks. *A. capillaris*, *P. arudinacea*, *P. australis*, and *H. lanatus* have the highest viable rates of 99%, 68.5%, 64%, and 60.5%, respectively. *M. caerulea* has the lowest rate of only 2%. Low *M. caerulea* germination rates of 3% and 9% were also reported by other researchers (Grime et al. 1981; Grime et al. 1988; Brys et al. 2005). In their study, Grime et al. (1981) believed that the low germination percentage could be due to the low temperature.

During the 16-week field trial study in Teevaloughan, no grass growth was observed in the control plots. In the study plots, 7 out of 10 grass species successfully germinated. At the end of the study, *H. lanatus*, *A. capillaris*, *F. rubra*, *P. australis*, *P. arudinacea*, *L. perenne*, and *E. angustifolium* had the germination rates of 44%, 41%, 57%, 8%, 11%, 18%, and 3%, respectively (Fig. 4). *H. lanatus*, *A. capillaris*, and *F. rubra* had the highest germination rates. However, *F. rubra* was observed to be discolored toward the end of the study period, as was noted by O'Toole et al. (1964), which could be due to poor nutrients concentrations in the soil. Similar phenomena were also found in *P. australis* and *L. perenne*, which died back after week 7 and week 9, respectively. Only two species—*H. lanatus* and *A. capillaris*—germinated successfully in the forested peatland habitat, and continued to grow and thrive up to 13 weeks after seeding and are considered to be suitable for the purpose of this study.

3.3 Impact of Grass Seeding on the Biomass and P Content of Aboveground Vegetation

Figure 5 shows the aboveground biomass and P content in the sown and control plots. Seeding of *H. lanatus* and *A. capillaris* increased the aboveground vegetation biomass and P content 1 year after grass seeding. While there was very little vegetation growth in the control plots (22 kg biomass ha^{-1} with P content of 0.02 kg TP ha^{-1}), vegetation biomass of 2,753, 723, and 2,050 kg ha^{-1} were observed in the three study plots, giving the TP content of 2.83, 0.65, and 3.07 kg ha^{-1}, respectively (Fig. 5). The aboveground biomass and P content in the sown plots were significantly higher than in the control plots (*t* test, $p<0.01$). The vegetation collected for testing was cut to 1 cm aboveground level so these estimates could in fact be higher when taken below ground biomass production into account which has been estimated at 30% of the total plant biomass (Scholes and Hall 1996). In the UK, Goodwin et al. (1998) found that *H. lanatus* produced biomass of 3,405 kg ha^{-1} with P concentrations of 1.64 mg TP (g biomass)$^{-1}$, giving the total P content of 5.58 kg Pha^{-1}.

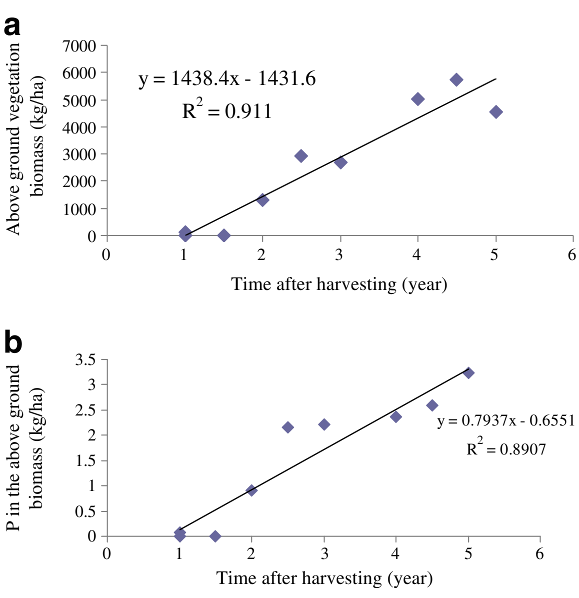

Fig. 2 Relationship between biomass and P content of the aboveground vegetation and years after harvesting

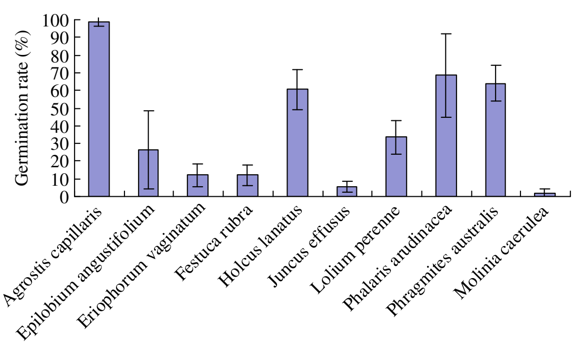

Fig. 3 Successful germination rates of 10 grass species examined in laboratory conditions (*error bars* indicate standard deviation)

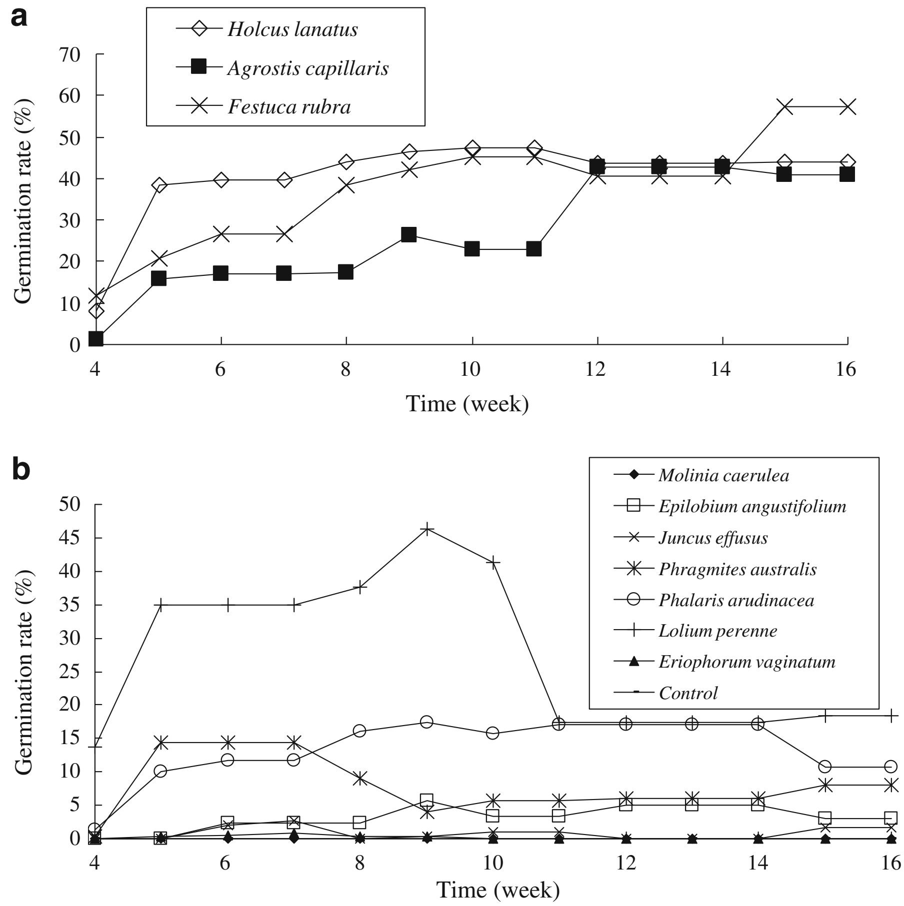

Fig. 4 Germination rates of 10 grass species planted in the trial experimental

3.4 Impact of Grass Seeding on Soil Water Extractable Phosphorus

Figure 6 shows the WEP concentrations in the sown plots and the control plots. The WEP in the three study plots were 9, 12, and 6 mg P (kg dry soil)$^{-1}$, respectively, which was significantly lower than the value of 27 mg P (kg dry soil)$^{-1}$ in the control areas (Fig. 6; *t* test, $p<0.01$).

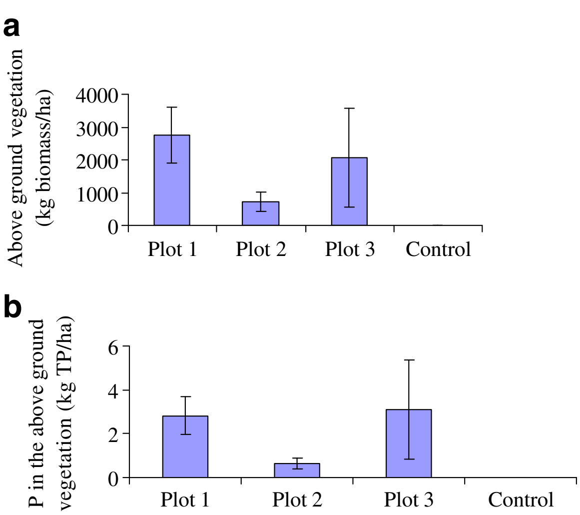

Fig. 5 Biomass and P content of aboveground vegetation in the study plots and control in the Glennamong (*Plot 1* 100 m^2, *Plot 2* 360 m^2, *Plot 3* 660 m^2; the *bars* indicate the standard deviation)

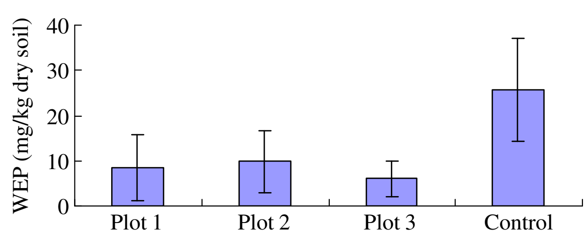

Fig. 6 Water extractable phosphorus (*WEP*) in the study plots and control area in Glennamong (*Plot 1* 100 m^2, *Plot 2* 360 m^2, *Plot 3* 660 m^2; the *bars* indicate the standard deviation)

4 Discussion

In this study, *Calluna vulgaris*, *M. caerulea*, and *J. effusus* are the main species presenting at the natural re-vegetation sites. Similar findings were reported by Connaghan (2007). Recovery of blanket peat vegetation following forest harvesting usually takes several years (Connaghan 2007). In this study, it took 5 years for the natural re-vegetation to have the aboveground biomass of 6,000 kg ha^{-1}. In a study by Allison and Ausden (2006) where plots were established on pine plantation heathland, which was recently clearfelled, it took 4 years for an increase in percentage frequency of *C. vulgaris*—a native heathland species—to appear. In the west of Ireland, Connaghan (2007) carried out grass surveys in eight blanket peat sites and found that bare soil could still account for 35% 1 year after harvesting. The slow vegetation recovery of the harvested blanket peat forest sites could be due to (1) a significant reduction of the seed bank, (2) the burial of the seed bank by a thick layer of needle litter, and (3) the slow germination characteristics of the seeds typically found at these sites (Pywell et al. 2003).

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

Piirainen et al. (2007) found that as ground vegetation develops, P uptake and recycling can be expected to diminish leaching over time. In this study, the relatively low WEP in the study plots is likely to be a result of P uptake by the seeded grasses. *H. lanatus* and *A. capillaris* have been reported to have high P uptake capacity. Veresoglou and Fitter (1984) carried out a study on nutrient uptake in five coexisting grasses and found that *H. lanatus* and *A. capillaris* could uptake 16.9 and 2.7 mg TP $(m^2 .day)^{-1}$, respectively. As WEP has strong linear relationship with TP concentrations in the runoff (Schindler et al. 2009) and has been proved to be a useful indicator of soluble P concentrations in peat soil runoff water (Daly and Styles 2005), it is expected that the reduction of WEP in the grass seeded plots could result in reduction of P runoff release.

5 Future Research

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

Sowing grass immediately after harvesting may affect forest regeneration. The interspecific interactions between seeded grasses and the replanted seedlings can be positive and negative, and require further studies (Goldberge 1990; Maestre et al. 2004; Liu and Wang 2008; Maestre et al. 2009). The seeded grasses store significant amount of P released from the peat and the logging residues. When the canopy of the next forest crop gradually closes over, the vegetation decays and releases the nutrients for uptake by the growing trees, which will facilitate forest regeneration. In fact, these nutrients slowly released from grass could be critical for the reforestation in peatlands, because of the poor nutrients of the soil and the low fertilization rate limited by forest guidelines (Forest service 2000). In contrast, the sowing grasses may compete for nutrients and lights with replanted seedlings in the first few years after seeding (Li et al. 2010). However, this negative impact can be diminished by choosing the right seeding rates and seeding distance from the seedlings. Future research could be carried out on an appropriate seeding rate, to ensure the nutrient release to the receiving water and the competition with the replanted seedlings, and so that the costs can be minimized.

6 Conclusion

The results of this study indicate that (1) *H. lanatus* and *A. capillaris* can be quickly established in blanket peat forest areas after harvesting and (2) sowing *H. lanatus* and *A. capillaris* immediately after harvesting has the potential to immobilize the P that would otherwise be available for leaching. One year after sowing, the P contents in the aboveground vegetation biomass could be up to 3.07 kg $\mathrm{P\,ha^{-1}}$. Further research into the feasibility of grass seeding as a potential new BMP is clearly warranted. Sowing the right grass species at appropriate rates should diminish the deleterious effects of forest harvesting on surface water quality and facilitate the forest regeneration.

Acknowledgments The authors gratefully acknowledge the funding from the Department of Agricultural, Fisheries and Food in Ireland, COFORD, Ireland EPA, Coillte and the Marine Institute. They also acknowledge the assistance of Dr. Philip O'Dea, Mary O'Brian, Mary Dillane, and Liz Ryder.

References

Abu-Zreig, M., Ramesh, P. R., Hugh, R. W., Manon, N. L., & Narinder, K. K. (2003). Phosphorus removal in vegetated filter strips. *Journal of Environmental Quality, 32*, 613–619.

Allison, M., & Ausden, M. (2006). Effects of removing the litter and humic layers on heathland establishment following plantation removal. *Biological Conservation, 127*(2), 177–182.

Bhattarai, R., Kalita, P. K., & Patel, M. K. (2009). Nutrient transport through a vegetative filter strip with subsurface drainage. *Journal of Environmental Management, 90*(5), 1868–1876.

Boesch, D. F., Brinsfield, R., & Magnien, R. (2001). Chesapeake Bay eutrophication: scientific understanding, ecosystem restoration, and challenges for agriculture. *Journal of Environmental Quality, 30*, 303–320.

Brys, R., Jacquemyn, H., & De Blust, G. (2005). Fire increases aboveground biomass, seed production and recruitment success of Molinia caerulea in dry heathland. *Acta Oecologica, 28*(3), 299–305.

Connaghan, J. (2007). Management options for forests on western peatlands: vegetation survey. A report to Coillte Teoranta by John Connaghan (unpublished).

Cummins, T., & Farrell, E. P. (2003). Biogeochemical impacts of clearfelling and reforestation on blanket peatland streams I. Phosphorus. *Forest Ecology and Management, 180*(1–3), 545–555.

Daly, K., & Styles, D. (2005). *Eutrophication from agricultural sources—Phosphorus Chemistry of Mineral and Peat Soils in Ireland*. Technical report: Irish EPA, Published by the Environmental Protection Agency, Ireland.

Dillaha, T. A., Reneau, R. B., Mostaghimi, S., & Lee, D. (1989). Vegetative filter strips for agricultural nonpoint source pollution control. *Transactions of the ASAE, 32*(2), 513–519.

EPA. (2004). *Eutrophication of inland and estuarine waters. In the report: 'Ireland's Environment 2004'*. Dublin, Ireland: Published by Ireland EPA.

Fernández-Abascal, I., Tárrega, R., & Luis-Calabuig, E. (2004). Ten years of recovery after experimental fire in a heathland: effects of sowing native species. *Forest Ecology and Management, 203*(1–3), 147–156.

Forest Service. (2000). *Forestry and Water Quality Guidelines*. Dublin: Department of the Marine and Natural Resources.

Forestry Commission. (1988). Forests and water guidelines. 1st edn. London: HMSO. Revised (2nd edn. 1991, 3rd edn. 1993. 4th edn. 2003).

Goldberge, D. E. (1990). Components of resource competition in plant communities. In J. Grace & D. Tilman (Eds.), *Perspectives in plant competition*. New York: Academic.

Goodwin, M. J., Parkinson, R. J., Williams, E. N. D., & Tallowin, J. R. B. (1998). Soil phosphorus extractability and uptake in a Cirsio-Molinietum fen-meadow and an adjacent Holcus lanatus pasture on the culm measures, north Devon, UK. *Agriculture, Ecosystems & Environment, 70*(2–3), 169–179.

Grennan, E., & Mulqueen, J. (1964). Grass production on blanket peat I. Phosphorus requirements. *Irish Journal of Agricultural Research, 3*, 37–49.

Grime, J. P., Hodgson, J. G., & Hunt, R. (1988). *Comparative plant ecology: A functional approach to common British species*. London: Unwin Hyman.

Grime, J. P., Mason, G., Curtis, A. V., Rodman, J., Band, S. R., Mowforth, M. A. G., et al. (1981). A comparative study of germination characteristics in a local flora. *Journal of Ecology, 69*, 1017–1059.

Li, Q., Liang, Y., Tong, B., Du, X., & Ma, K. (2010). Compensatory effects between Pinus massoniana and broadleaved tree species. *Journal of Plant Ecology, 3*(3), 183–189.

Liu N.S., & Wang, S.Q. (2008). Warming changes species competitive hierarchy in a temperate steppe of northern China. *Journal of Plant Ecology, 1*, 103–110.

Loach, K. (1968). Seasonal growth and nutrient uptake in a Molinietum. *Journal of Ecology, 56*(2), 433–444.

Lowrance, R., Todd, R., Fail, J., Hendrickson, O., Leonard, R., & Asmussen, L. (1984). Riparian forest as nutrient filters in agricultural watersheds. *Bioscience, 34*, 374–377.

Macrae, M. L., Redding, T. E., Creed, I. F., Bell, W. R., & Devito, K. J. (2005). Soil, surface water and ground water phosphorus relationships in a partially harvested Boreal Plain aspen catchment. *Forest Ecology and Management, 206*, 315–329.

Maestre, F. T., Callaway, R. M., & Valladares, F. (2009). Refining the stress-gradient hypothesis for competition and facilitation in plant communities. *Journal of Ecology, 97*, 199–205.

Maestre, F. T., Cortina, J., & Bautista, S. (2004). Mechanisms underlying the interaction between *Pinus halepensis* and the native late-successinal shrub *Pistacia lentiscus* in a semi-arid plantation. *Ecography, 27*, 776–786.

Magette, W. L., Brinsfield, R. B., Palmer, R. E., & Wood, J. D. (1989). Nutrient and sediment removal by vegetated filter strips. *Transactions of the ASAE, 32*(2), 663–667.

Mander, Ü., Kuusemets, V., Lohmus, K., & Mauring, T. (1997). Efficiency and dimensioning of riparian buffer zones in agricultural catchments. *Ecological Engineering, 8*(4), 299–324.

Mankin, K. R., Ngandu, D. M., Barden, C. J., Hutchinson, S. L., & Geyer, W. A. (2007). Grass-shrub riparian buffer removal of sediment, phosphorus, and nitrogen from simulated runoff. *JAWRA Journal of the American Water Resources Association, 43*, 1108–1116.

Marttila, H., & Kløve, B. (2010). Managing runoff, water quality and erosion in peatland forestry by peak runoff control. *Ecological Engineering, 36*(7), 900–911.

Moore, P. D., & Chapman, S. B. (1986). *Methods in plant ecology*. Oxford: Alden Press.

Nieminen, M. (2003). Effects of clear-cutting and site preparation on water quality from a drained Scots pine mire in southern Finland. *Boreal Environment Research, 8*, 53–59.

Nisbet, T., Dutch, J., & Moffat, A. (1997). *Whole-tree harvesting. A guide to good practice*. Edinburgh, UK: Forestry Commission Practice Guide, Forestry Commission.

O'Toole, M. A., O'Hare, P. J., & Grennan, E. J. (1964). *Renovation of peat and hill land pastures*. Dublin, Ireland: An Foras Taluntais.

Piirainen, S., Finér, L., Mannerkoski, H., & Starr, M. (2007). Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. *Forest Ecology and Management, 243*(1), 10–18.

Pywell, F. R., Bullock, J. M., David, B. R., Warman, L. I. Z., Walker, K. J., & Rothery, P. (2003). Plant traits as predictors of performance in ecological restoration. *Journal of Applied Ecology, 40*(1), 65–77.

Rao, N. K., Hanson, J., Dulloo, M. E., Ghosh, K., Nowel, D., & Larinde, M. (2006). *Manual of seed handling in genebanks. Handbooks for Genebanks No. 8*. Rome, Italy: Bioversity International.

Rodgers, M., M. O'Connor, M. G. Healy, C. O'Driscoll, Z. Asam, M. Nieminen, R. Poole, M. Muller, and L. Xiao. (2010). Quantification of erosion and phosphorus release from a peat soil forest catchment. *Forest Ecology and Management*. (In press).

Ruby, E.C. (1989). Rational for seeding grass on the Stanislaus Complex bum Proceedings of the Symposium on Fire and Watershed Management. *USDA General Technical Report* PSW-109.

Ryan, J., George, E., & Abdul, R. (2001). *Soil and plant analysis laboratory manual* (2nd ed.). Available from ICARDA, Aleppo, Syria: Jointly published by the International Center for Agricultural Research in the Dry Areas and the National Agricultural Research Center.

Ryder, L., E. de Eyto, M. Gormally, M. Sheehy-Skeffington, M. Dillane and R. Poole. (2010). Riparian zone creation in established coniferous forests in Irish upland peat catchments: physical, chemical and biological implications. *Biology and Environment: Royal Irish Academy*. (In press).

Schindler, F. V., Guidry, A. R., German, D. R., Gelderman, R. H., & Gerwing, J. R. (2009). Assessing extractable soil phosphorus methods in estimating phosphorus concentrations in surface run-off from Calcic Hapludolls. *Soil Use and Management, 25*(1), 11–20.

Scholes, R. J., & Hall, D. O. (1996). The carbon budget of tropical savannas, woodlands and grasslands. In A. I. Breymeyer, D. O. Hall, J. M. Melillo, & G. I. Agren (Eds.), *Global change: Effects on coniferous forests and grasslands, SCOPE Volume 56*. Chichester: Wiley.

Sheaffer, C. C., Rosen, C. J., & Gupta, S. C. (2008). Reed canarygrass forage yield and nutrient uptake on a year-round wastewater application site. *Journal of Agronomy and Crop Science, 194*(6), 465–469.

Silvan, N., Vasander, H., & Laine, J. (2004). Vegetation is the main factor in nutrient retention in a constructed wetland buffer. *Plant and Soil, 25*, 179–187.

Stutter, M. I., Langan, S. J., & Lumsdon, D. G. (2009). Vegetated buffer strips can lead to increased release of phosphorus to waters: a biogeochemical assessment of the mechanisms. *Environmental Science and Technology, 43*, 1858–1863.

Syversen, N., & Borch, H. (2005). Retention of soil particle fractions and phosphorus in cold-climate buffer zones. *Ecological Engineering, 25*(4), 382–394.

Uusi-Kämppä, J. (2005). Phosphorus purification in buffer zones in cold climates. *Ecological Engineering, 24*(5), 491–502.

Veresoglou, D. S., & Fitter, A. H. (1984). Spatial and temporal patterns of growth and nutrient uptake of five co-existing grasses. *Journal of Ecology, 72*(1), 259–272.

Vought, L. B. M., Lacoursière, J. O., & Voelz, N. J. (1994). Nutrient retention in riparian ecotones. *Ambio, 23*(6), 342–348.

Wagner, S., P. Truong, A. Vieritz, and C. Smeal. (2003). Response of vetiver grass to extreme nitrogen and phosphorus supply. In: Proceedings of Third International Vetiver Conference, Guangzhou, China. October 2003.

Walmsley, J. D., Jones, D. L., Reynolds, B., Price, M. H., & Healey, J. R. (2009). Whole tree harvesting can reduce second rotation forest productivity. *Forest Ecology and Management, 257*(3), 1104–1111.

Yanai, R. D. (1998). The effect of whole-tree harvest on phosphorus cycling in a northern hardwood forest. *Forest Ecology and Management, 104*(1–3), 281–295.

Yates, C. R., & Prasher, S. O. (2009). Phosphorus reduction from agricultural runoff in a pilot-scale surface-flow constructed wetland. *Ecological Engineering, 35*(12), 1693–1701.