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

Connie O'Driscoll[1], Michael Rodgers[1], Mark O'Connor[1], Zaki-ul-Zaman Asam[1], Elvira de Eyto[2], Russell Poole[2] and Liwen Xiao[1*]

[1] Civil Engineering, National University of Ireland, Galway, Republic of Ireland

[2] Marine Institute, Newport, Co. Mayo, Republic of Ireland

[*] Corresponding author: Liwen Xiao; Email: liwen.xiao@nuigalway.ie; Tel: +353 91 494188; Fax: +353 91 494507

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 m^2, 360 m^2 and 660 m^2 immediately after harvesting. Areas without grass seeding were used as controls. One year later, the P content in the above ground vegetation biomass of the three study plots were 2.83 kg P ha^{-1}, 0.65 kg P ha^{-1} 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 (WEP) in the three study plots were 8.44 mg (kg dry soil)$^{-1}$, 9.83 mg (kg dry soil)$^{-1}$ 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.

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

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 phosphorus (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 μg l^{-1}, 13 μg $l^{-1}$and 93 μg l^{-1} before harvesting to 265 μg l^{-1}, 3530 μg l^{-1}, and 4164 μg l^{-1}, respectively, one 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} pre-harvesting to 429 μg l^{-1} one year after harvesting, even though best management practices were strictly implemented. Four years after clearfelling, the P concentrations returned to the pre-harvesting concentrations. In the first three 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.

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: (i) mechanically, by increasing deposition through the slowing down of flow; (ii) chemically, through reactions between incoming nutrients and soil matrices and residual elements; and (iii) 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 sitse after the conventional harvesting of stem wood (personal communication, Dr. Philip O'Dea, Coillte Teoranta, 2010).

Needles and branches have much higher nutrient concentrations than stem wood and whole-tree harvesting may reduce nutrient sources by 2 to 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 three 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 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 (Forest 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 minimise 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 ha 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 10m 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 µg TRP l^{-1} 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).

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 intra-system 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 in the wet-heath soils. Sheaffer *et al*. (2008) reported a P uptake of 30 kg/ha 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 three years of clearfelling, whereas further away from the river where peat depth increased and soil fertility decreased vegetation took six to ten years to recover.

It appears that natural re-vegetation arising from the seed bank is likely to be too slow to significantly mitigate against the P from felling, which mainly occurs in the first three years after harvesting (Rodgers et al. 2010; Cummins & Farrell 2003). In order to minimise the release of nutrients to receiving waters after harvesting, a rational approach is to maximise 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 above ground vegetation were tested one year after grass seeding. In order to compare P up take 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.

MATERIAL AND METHODS

Site description

The study was carried out in nine sites in County Mayo in the west of Ireland (Figure 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.

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) *Molinia 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 8 replicates. 3 ml 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 three weeks. A seed was considered germinated when the radicle emerged. Distilled water was added whenever moisture loss was detected.

In the field trial test, a total of thirty three plots with an area of 900 cm^2 each were defined in the brash free area in Teevaloughan site (Site 7 in Figure 1 and Table 2). 300 seeds of each of the ten candidate species were scattered on three replicate plots (10 x 3 plots). Three replicate control plots were also included. The plots were surveyed weekly for four 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 Figure 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 of a 50:50 ratio of *Holcus lanatus* and *Agrostis 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 which was not seeded was used as control.

Above ground vegetation biomass and P content measurement

To estimate the aboveground vegetation biomass in nine study sites, thirty two 0.25 m x 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 hours. Samples were then weighed and the biomass was calculated by using Equation 1. Total phosphorus (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 $550^{o}C$ overnight, then 5 ml of 2 N

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

$$B_p = \frac{Wt}{St} \times 10000 \qquad \text{Equation 1}$$

Where Bp is the biomass production (kg/ha); Wt is the total dry weight of the samples (kg) and St is the total area (m^2).

Soil water extractable phosphorus (WEP) measurement

100-mm-deep soil cores consisting of the humic and upper peat layers were collected using a 30-mm-diameter gouge auger in the Glennamong site. 4, 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 deionised 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).

Data analysis

In order to investigate the effects of grass seeding on total above ground 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.

RESULTS

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 9 study sites. The biomass of the above ground vegetation has a strong linear relationship with years after harvesting (Figure

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

Successful germination grass species

Figure 3 shows the germination rates of ten grass species examined in laboratory conditions. Most species germinated successfully within three weeks. *Agrostis capillaris, Phalaris arudinacea, Phragmites australis and Holcus lanatus* have the highest viable rates of 99%, 68.5%, 64% and 60.5%, respectively. *Molinia caerulea* has the lowest rate of only 2%. Low *Molinia 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, *Holcus lanatus*, *Agrostis capillaris*, *Festuca rubra*, *Phragmites australis*, *Phalaris arudinacea*, *Lolium perenne* and *Epilobium angustifolium* had the germination rates of 44%, 41%, 57%, 8%, 11%, 18% and 3%, respectively (Figure 4). *Holcus lanatus*, *Agrostis capillaris* and *Festuca rubra* had the highest germination rates. However, *Festuca rubra* was observed to be discoloured towards 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 *Phragmites australis* and *Lolium perenne*, which died back after week 7 and week 9, respectively. Only 2 species –*Holcus lanatus* and *Agrostis 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.

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

Figure 5 shows the above ground biomass and P content in the sown and control plots. Seeding of *Holcus lanatus* and *Agrostis capillaris* increased the above ground vegetation biomass and P content one year after grass seeding. While there was very little vegetation growth in the control plots (22 kg biomass ha^{-1} with P content of 0.02kg TP ha^{-1}) , vegetation biomass of 2753 kg ha^{-1}, 723 kg ha^{-1} and 2050 kg ha^{-1} were observed in the three study plots, giving the TP content of 2.83 kg ha^{-1}, 0.65 kg ha^{-1} and 3.07 kg ha^{-1}, respectively (Figure 5). The above ground biomass and P content in the sown plots was significantly higher than in the control plots (t test, $p < 0.01$). The vegetation collected for testing was cut to 1cm 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 *Holcus lanatus* produced biomass of 3405 kg ha^{-1} with P concentrations of 1.64 mg TP (g biomass)$^{-1}$, giving the total P content of 5.58 kg P ha^{-1}.

Impact of grass seeding on soil water extractable phosphorus

Figure 6 shows the water extractable phosphorus (WEP) concentrations in the sown plots and the control plots. The WEP in the three study plots were 9 mg P (kg dry soil)$^{-1}$, 12 mg P (kg dry soil)$^{-1}$ 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 (Figure 6) (t-test, $p < 0.01$).

DISCUSSION

In this study, *Calluna vulgaris, Molinia caerulea* and *Juncus 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 five years for the natural re-vegetation to have the above ground biomass of 6000 kg ha^{-1}. In a study by Allison & Ausden (2006) where plots were established on pine plantation heathland, which was recently clearfelled, it took four years for an increase in percentage frequency of *Calluna vulgaris* - a native heathland species - to appear. In the west of Ireland, Connaghan (2007) carried out grass surveys in 8 blanket peat sites and found that bare soil could still account for 35% one 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. 2002).

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 (*Lolium 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 2 grass species - *Holcus lanatus* and *Agrostis 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 *Holcus 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 *Festuca rubra* appears before *Agrostis capillaris* and dies back earlier also. They deemed *Agrostis capillaris* a more suitable species than *Festuca rubra.* In a study investigating spatial and temporal patterns of growth and nutrient uptake of five co-existing grasses, Veresoglou and Fitter (1984) found that *Holcus lanatus* displays a maximum nutrient uptake when soil moisture content and extractable P were high. In contrast, they found *Agrostis 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 up-take by the seeded grasses. *Holcus lanatus* and *Agrostis capillaris* have been reported to have high P uptake capacity. Veresoglou and Fitter (1984) carried out a study on nutrient uptake in five co-existing grasses and found that *Holcus lanatus* and *Agrostis capillaris* could uptake 16.9 mg TP $(m^2 .d)^{-1}$ and 2.7 mg TP $(m^2 .d)^{-1}$, 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.

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 inter-specific interactions between seeded grasses and the replanted seedlings can be positive and negative, and require further studies (Goldberg 1990; Maestr et al. 2004; Niu and Wan 2008; Maestr 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 fertilisation 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, the competition with the replanted seedlings and the costs can be minimized.

CONCLUSION

The results of this study indicate that (1) *Holcus lanatus* and *Agrostis capillaris* can be quickly established in blanket peat forest areas after harvesting and (2) sowing *Holcus lanatus* and *Agrostis 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 above ground vegetation biomass could be up to 3.07 kg 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.

ACKNOWLEDGEMENTS

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

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

Bhattarai, R., P. K. Kalita, and M. K. Patel. (2009). Nutrient transport through a Vegetative Filter Strip with subsurface drainage. *Journal of Environmental Management, 90*(5), 1868-1876.

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

Brys R., Jacquemyn H. and De Blust G. (2005). Fire increases aboveground biomass, seed production and recruitment success of Molinia caerulea in dry heahland. *Acta Oecological, 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., and E. P. Farrell. (2003). Biogeochemical impacts of clearfelling and reforestation on blanket peatland streams I. phosphorus. *Forest Ecology and Management, 180*(1-3), 545-555.

Daly, K., and D. Styles. (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., R. B. Reneau, S. Mostaghimi, and D. Lee. (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'. Published by Ireland EPA, Dublin, Ireland

Fernández-Abascal, I., R. Tárrega, and E. Luis-Calabuig. (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.

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

Forest Service. (2000). Forestry and Water Quality Guidelines. Department of the Marine and Natural Resources, Dublin.
Goldberge DE (1990) Components of resource competition in plant communities. In Grace J. Tilman D (eds). Perspectives in plant competition. New York: Academic press.

Goodwin, M. J., R. J. Parkinson, E. N. D. Williams, and J. R. B. Tallowin. (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., and J. Mulqueen. (1964). Grass production on blanket peat I. Phosphorus requirements. *Irish Journal of Agricultural Research, 3*, 37-49.

Grime, J.P., Hodgson, J.G. and Hunt, R. (1988). In: *Comparative Plant Ecology: A Functional Approach to Common British Species*, Unwin Hyman, London.

Grime, J.P., Mason G., Curtis A.V., Rodman J., Band S.R., Mowforth M.A.G., Neal A.M. and Shaw S. (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

Loach, K. (1968). Seasonal Growth and Nutrient Uptake in a Molinietum. *Journal of Ecology, 56*(2), 433-444.

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

Macrae, M. L., T. E. Redding, I. F. Creed, W. R. Bell, and K. J. Devito. (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 FT., Callaway RM., Valladares F. (2009). Refining the stress-gradient hypothesis for competition and facilitation in plant communities. *Journal of Ecology, 97*, 199-205.

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

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

Mankin, K. R., D. M. Ngandu, C. J. Barden, S. L. Hutchinson, and W. A. Geyer. (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. and B. Kløve. (2010). Managing runoff, water quality and erosion in peatland forestry by peak runoff control. *Ecological Engineering, 36*(7), 900-911.

Moore, P. D. and S.B. Chapman. (1986). *Methods in Plant Ecology*, Alden Press, Oxford.

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

Nisbet, T., J. Dutch, and A. Moffat. (1997). *Whole-Tree Harvesting. A Guide to Good Practice.* Forestry Commission Practice Guide, Forestry Commission, Edinburgh, UK.

Niu SL. and Wang SQ (2008). Warming changes species competitive hierarchy in a temperate steppe of northern China. *Journal of Plant Ecology*, *1*, 103-110

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

Piirainen, S., L. Finér, H. Mannerkoski, and M. Starr. (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, J. M. Bullock, David B. R,, LIZ Warman, K. J. Walker and P. Rothery (2003) Plant traits as predictors of performance in ecological restoration. *Journal of Applied Ecology, 40*(1), 65-77

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

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., E. George, and R. Abdul. (2001). Soil and plant analysis laboratory manual. Second edition. Jointly published by the International Center for Agricultural Research in the Dry Areas and the National Agricultural Research Center. Available from ICARDA, Aleppo, Syria.

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., A. R. Guidry, D. R. German, R. H. Gelderman, and J. R. Gerwing. (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. and D. O. Hall. (1996). The carbon budget of tropical savannas, woodlands and grasslands. In: Breymeyer A.I., D. O. Hall, J. M. Melillo, and G. I. Agren. (Eds.) *Global Change: Effects on Coniferous Forests and Grasslands,* SCOPE Volume 56. Wiley, Chichester.

Sheaffer C.C., Rosen C.J. and 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., H. Vasander, and J Laine. (2004). Vegetation is the main factor in nutrient retention in a constructed wetland buffer. *Plant soil, 25,* 179-187.

Stutter, M. I., S. J. Langan, and D. G. Lumsdon. (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. and H. Borch. (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. and A. H. Fitter. (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., J. O. Lacoursière, and N. J. Voelz. (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., D. L. Jones, B. Reynolds, M. H. Price, and J. R. Healey. (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. and S. O. Prasher (2009). Phosphorus reduction from agricultural runoff in a pilot-scale surface-flow constructed wetland. *Ecological Engineering, 35*(12), 1693-1701.

Table list

Table 1 Performance of buffer zones on P removal

Soil	Total P removal	Dissolved reactive P removal	Vegetations	Width (m)	References
Clay	40%	0	Grass	10	Uusi-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)

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	*Calluna vulgaris, Molinia carulea, Eriophorum angustifolium*
2	Glendahurk-1	*lodgepole pine*	1971	2006	*Molinia caerulea, Calluna vulgaris, Juncus bulbous*
3	Altahoney	*lodgepole pine*	1971	2006	*Calluna vulgaris, Juncus effusus*
4	Maumaratta	*lodgepole pine*	1971	2007	*Molinia caerulea*
5	Goulaun	*lodgepole pine*	1971	2008	*Calluna vulgaris, Juncus bulbous, Sphagnum sp.*
6	Glendahurk-2	*lodgepole pine*	1971	2008	*Molinia caerulea, Calluna vulgaris,*
7	Teevaloughan	*lodgepole pine and Sitka spruce*	1971	2009	-
8	Glennamong	*lodgepole pine*	1971	2009	-
9	Tawnynahulty	*lodgepole pine*	1971	2009	-

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

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

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

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

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

Figure 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)

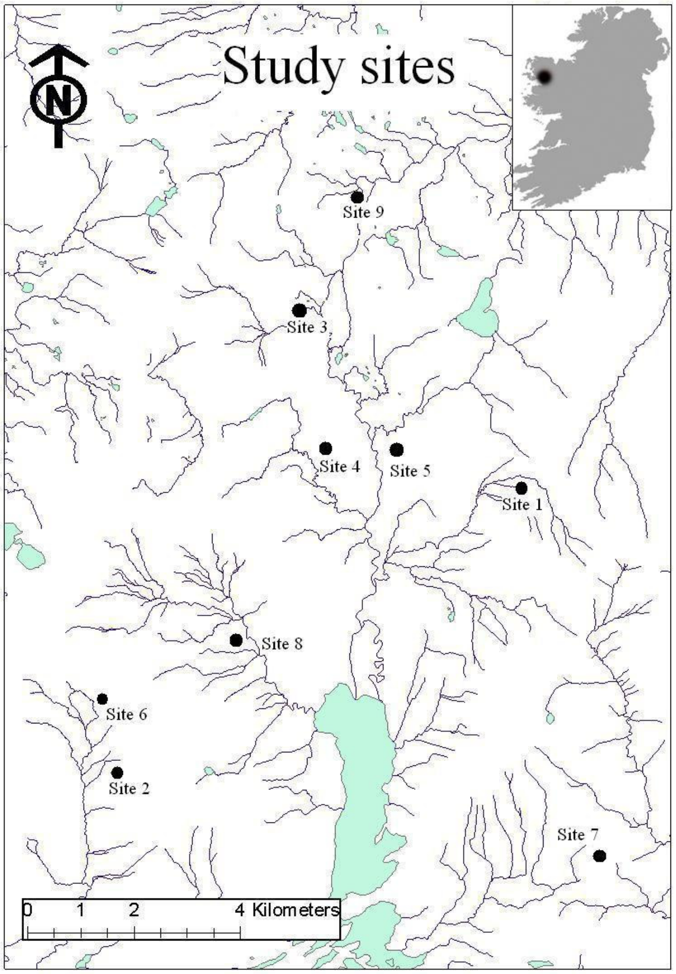

Study sites
N
Site 9
Site 3
Site 4
Site 5
Site 1
Site 8
Site 6
Site 2
Site 7
0 1 2 4 Kilometers

Figure 1

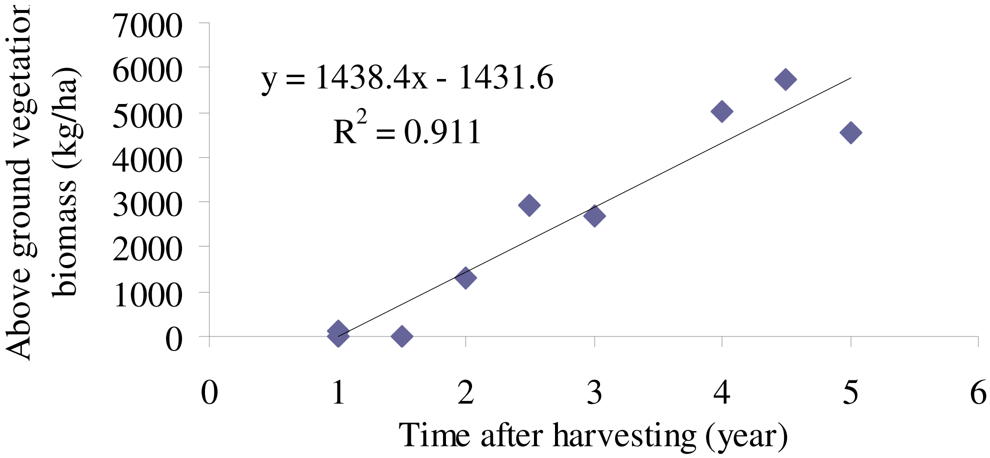


Figure 2a

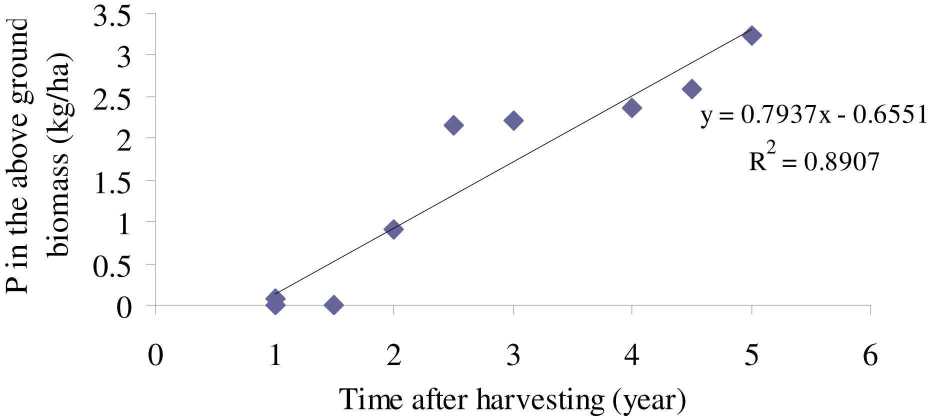
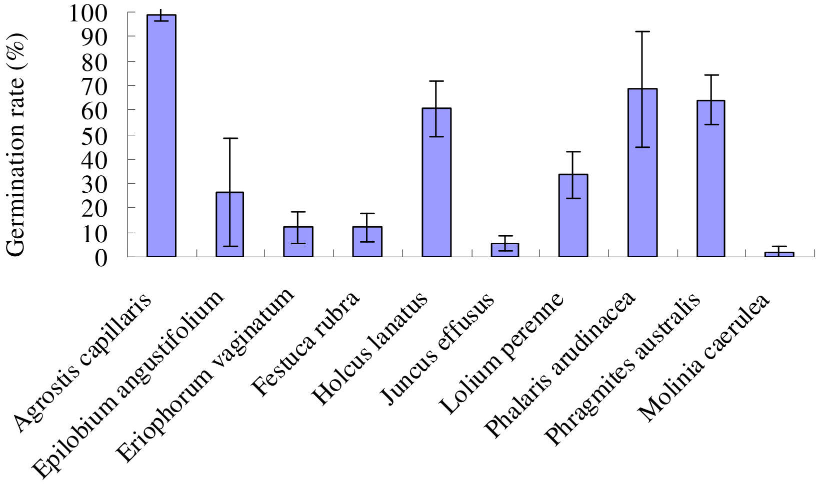


Figure 2b



Germination rate (%)
100
90
80
70
60
50
40
30
20
10
0
Agrostis capillaris
Epilobium angustifolium
Eriophorum vaginatum
Festuca rubra
Holcus lanatus
Juncus effusus
Lolium perenne
Phalaris arudinacea
Phragmites australis
Molinia caerulea

Figure 3

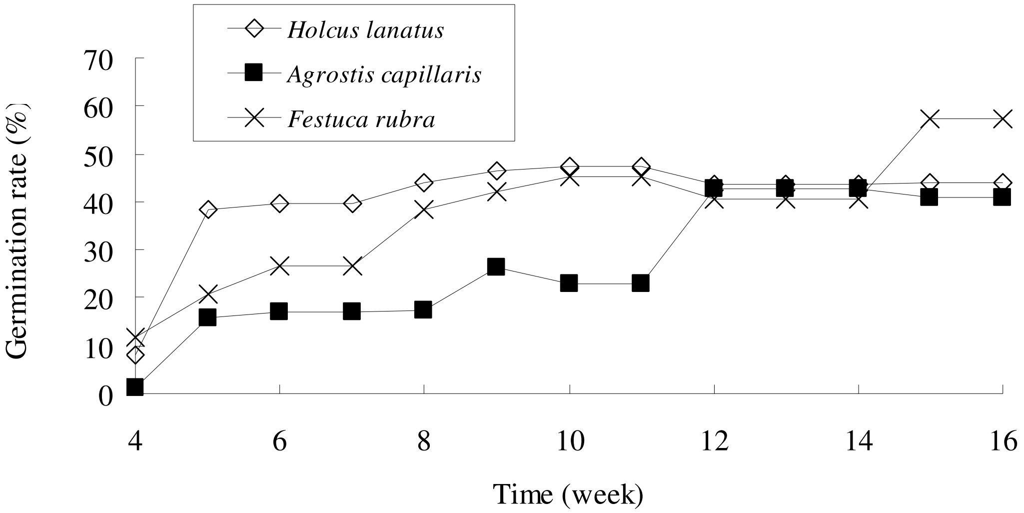


Figure 4a

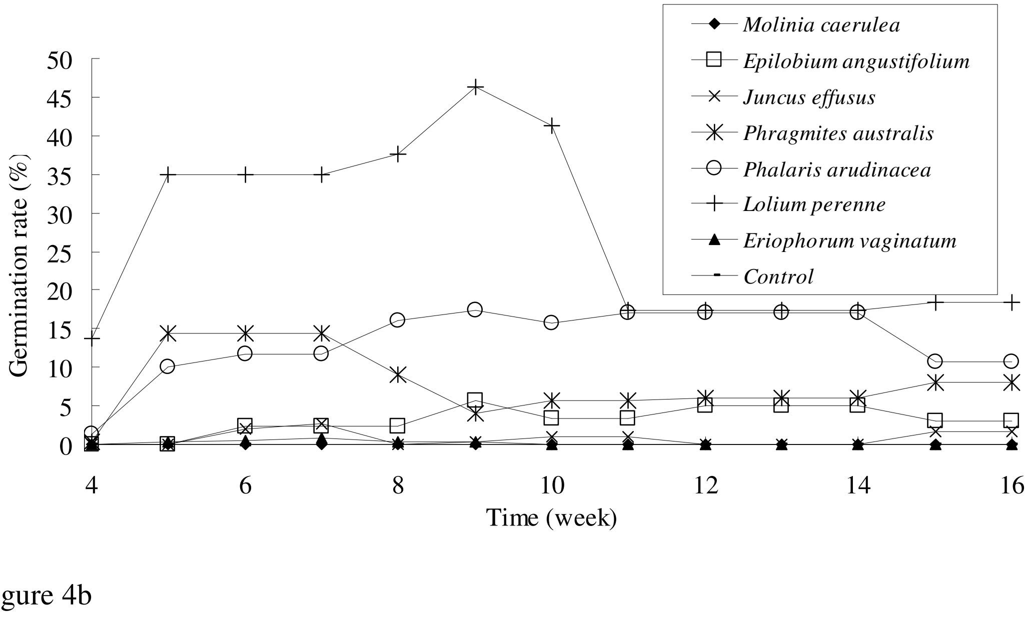


Figure 4b

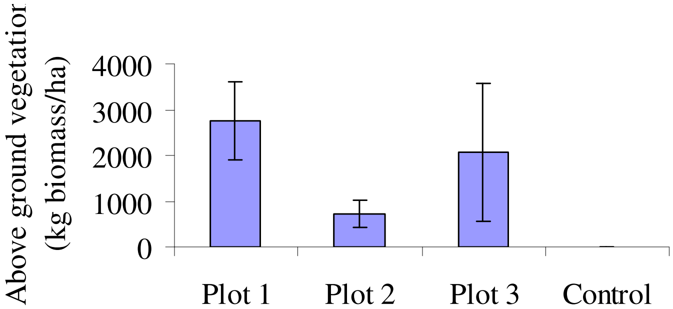


Figure 5a

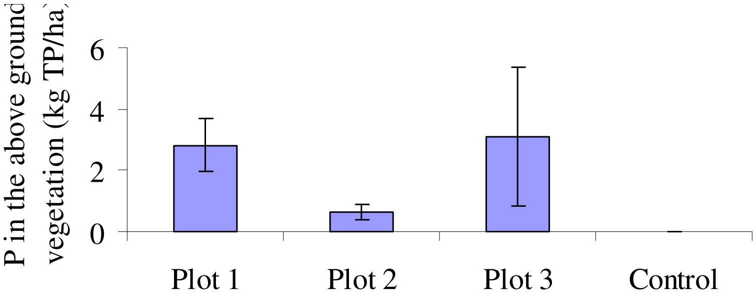


Figure 5b

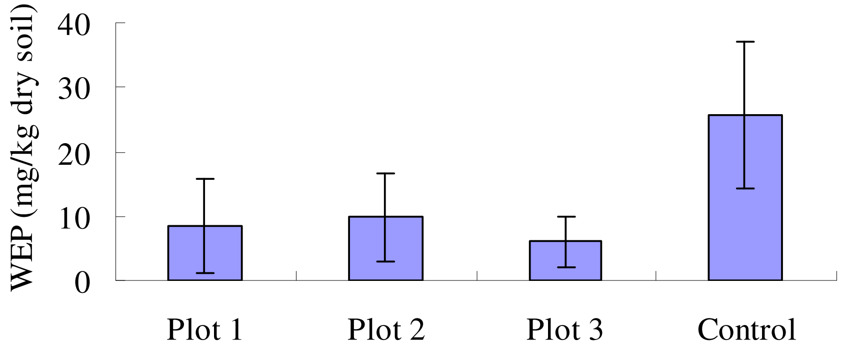


Figure 6