Phosphorus release from forest harvesting on an upland blanket peat catchment

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ABSTRACT

The aim of this study was to investigate the release of phosphorus (P) to receiving waters resulting from harvesting 34-year-old lodgepole pine trees in an upland peat catchment. The study site was within a 25.3-hectare (ha) area, and was drained by a stream that received flows from ploughed furrows, mainly, via collector drains, and discharged directly to the salmonid Shrahrevagh River, Burrishoole, Co. Mayo, Ireland. The study site was divided in two parts: the upstream part was left intact and the downstream part was harvested in early Autumn 2005 following implementation of forest guidelines. Good management practices such as proper use of brash mats and harvesting only in dry weather were implemented. Two instrumented stations were established – one just upstream (US) and the other just downstream (DS) of the clearfelled area. The measurement of P concentrations at the two stations commenced in May 2005, two months before the harvesting started. The daily mean P concentration at the DS station increased from about 6 $\mu g\ L^{-1}$ of total reactive phosphorus (TRP) during pre-clearfelling to 429 $\mu g\ L^{-1}$ in August 2006. By October 2009, four years after clearfelling, the P concentrations at the DS station had returned to pre-clearfelling levels. In the first three years after harvesting, up to 5.15 kg ha^{-1} of TRP were released from the harvested catchment to the receiving water; in the second year alone, 2.3 kg ha^{-1} of TRP were released. Linear regression can be used to describe the relationship between TRP load and water discharge. About 80 % of the total phosphorus (TP) in the study stream was soluble and more than 70 % of the P release occurred in storm events, indicating that traditional buffer strips with widths of 15-20 m might not be efficient for P immobilization. The P concentrations were affected by antecedent weather conditions and highest concentrations occurred during storm events following prolonged drought periods. The water extractable phosphorus (WEP) contents in the soil were significantly higher below windrow/brash

material than in brash-free areas, and whole-tree harvesting should be studied as one of the means to decrease P export from blanket peats.

Keywords: Phosphorus release; blanket peat forest; storm flow; buffer strip; forest harvesting; good management practice

1. INTRODUCTION

Phosphorus (P) at a concentration of about 30 $\mu g\ L^{-1}$ is the limiting nutrient for algal growth in freshwaters (Carpenter et al., 1998; Boesch et al., 2001). According to the U.S. Environmental Protection Agency (USEPA, 2004), agriculture is the primary source of non-point source pollution degrading the quality of streams and lakes. In Ireland, almost half the eutrophication of rivers is due to agricultural sources (EPA, 2004). It was reported that in the Shannon River catchment, about 50 % of the export load of P – measured as molybdate reactive phosphorus (MRP) - comes from diffuse sources (Kirk et al., 1999).

Forests and forest management practices have been identified as potentially important diffuse sources of water pollution in upland areas of the United Kingdom (Nisbet, 2001). Forest operations such as drainage, fertilisation, harvesting and reforestation result in increased P release (Lebo and Hermann, 1994; Ensign and Mallin, 2001; Cummins and Farrell, 2003), and may increase the P concentration of receiving water bodies (Paavilainen and Päivänen, 1995; Ahtiainen and Huttunen, 1999; Nisbet, 2001; Cummins and Farrell, 2003). Clearfelling disrupts P cycling and significantly reduces the uptake of P by plants, resulting in an increased labile P pool in the harvested area (Walbridge and Lockaby, 1994;

Herz, 1996). The decomposition of logging residues (i.e. needles, twigs, roots and branches) left on the harvested area further increases the labile P pool in the surface soil layer (Hyvönen et al., 2000; Piirainen et al., 2004).

Blanket peat has extremely low P adsorption capacity, low hydraulic conductivity, and is anaerobic to within a few centimetres of the surface (Tamm et al., 1974; Cummins and Farrell, 2003). P in peat soil can be easily transferred to receiving water by runoff (Cummins and Farrell, 2003). With the fluctuation of the water table, soluble P in peat soil can also be transferred into deeper ground water layers and, subsequently, to drainage channels (Sapek et al., 2007). Since the 1950s, large areas of upland peat were afforested in northern European countries. It was estimated that about 500,000 ha of peatland were afforested between the 1950s and 1990s in the UK, and 300,000 ha in Ireland (Farrell, 1990; Hargreaves et al., 2003; EEA, 2004). Many of these blanket peat forests are now reaching harvestable age and concerns have been raised about the potential release of P to the receiving aquatic systems as a result of harvesting.

In this paper, P release from an upland blanket peat forested area in the Burrishoole Catchment, Co. Mayo, Ireland was studied for four years after harvesting. We hypothesize that P release is increased significantly due to a combination of poor P adsorption capacity in blanket peat soil, high rainfall (>2000 mm) and runoff in the study area, and labile P sources being available after harvesting. Buffer strips with a width of 15-20 m are recommended as one of the means to reduce P release to recipient water courses. However, their effect may be limited if most of the P release occurs in storm events, when there would be low residence times for the vegetative uptake of soluble P. Thus, a specific aim of the study was to investigate the P release pattern in storm events, and to quantify the P release occurring during storm events and base flow conditions. Whole-tree harvesting has been recommended as another means of decreasing P release. To increase the understanding of the effect of whole-tree harvesting on P release, a small-scale pilot survey was also performed to investigate if the water extractable P (WEP) contents in soil below windrow/brash material are significantly higher than for areas without windrow/brash material.

2. STUDY SITE DESCRIPTION

The Burrishoole catchment, located in County Mayo in the west of Ireland, consists of important salmonid productive rivers and lakes (Figure 1). About 18 % of the catchment is covered by forests that were planted in the 1970s and which are now being, or about to be, harvested. The study site (9°55’W 35°55’N), which is a sub-catchment of the Burrishoole catchment, is drained by a small first-order stream (Figure 1) and was planted with lodgepole pine (*Pinus contorta*) between January and April, 1971. The stream is equipped with two flow monitoring stations at stable channel sections, one upstream (US) and the other downstream (DS) of the experimental area (Figure 1). A H-flume, a water level recorder and a data logger were installed at both US and DS stations, along with a tipping bucket rain gauge at the DS station. The water levels in the H-flumes at both stations were recorded every 5 minutes, facilitating the quantification of water flowing through the two stations. The maximum flow rate for the two H-flume was 158 L s^{-1}. The US station measures flows from the control area of 10.8 ha (area A in Figure 1) and the DS station receives flow from the control and experimental areas, giving a total combined area of 25.3 ha (areas A and B in Figure 1). The blanket upland peat soil in the study area was double-mouldboard ploughed by a Fiat tractor on tracks creating furrows and ribbons (overturned turf ridges) with a 2-m-spacing, aligned down the main slope, together with several collector drains aligned close to the contour. The trees were planted on the ribbons at 1.5-m-intervals, giving an approximate soil area of 3 m^2 per tree. The initial stand density was about 2800 trees per ha, but was reduced to about half by thinning in the late 1980s and natural die-off before clearfelling. The area was fertilized manually immediately after planting at a rate of 80 kg ground mineral phosphate (GMP) per ha - equivalent to 12 kg P per ha. This rate is low comparing with the normal rate of 250 kg GMP per ha. The catchment has an average peat depth of more than 2 m above bedrock of quartzite, schist and basic volcanic rock, and the peat typically has a gravimetric water content of more than 80 %. Rocks are found in some sections of the study stream bed. The depth of the water table fluctuates between 0.2 and 0.7 m from the soil surface. In the catchment, the mean annual rainfall is more than 2000 mm and the mean air temperature is about 11 ^{o}C. Hillslope gradients in areas A and B (Figure 1) average 8^{o} and range between 0^{o} – 16^{o}.

The volume of lodgepole pine upon harvesting in area B (Figure 1) was about 400 m^3 ha^{-1}. Bole-only harvesting was conducted in area B (Figure 1) from July 25th to September 22nd, 2005. The timber was harvested using a Valmet 941 Harvester, and some of the tree residues (i.e. needles, twigs and branches) were collected together to form the brash material mats, thus protecting the soil surface, and reducing erosion. The rest were left on the soil surface and collected together to form windrows. During harvesting, the boles were stacked beside the windrow for collection. A Valmet 840 Forwarder delivered the boles to truck collection points beside the forest road. To minimise soil damage, clearfelling and harvesting were conducted only in dry weather conditions during the period from July to September, 2005. This time period is recommended for harvesting since ground conditions tend to be drier (Forest Service, 2000). Mechanised operations were suspended during and immediately after periods of particularly heavy rainfall. Another important good management practice used during the harvesting operation was the proper use of brash material mats for harvesting machine travelling.. In the lowest part of the site where the stream is deeply incised, the trees were cut with a chain saw and left behind. In the harvested area, the brash mats/windrows- formed from the harvest residues – lie parallel to the study stream and furrows, which is at right angles to the contours. The width of the windrows/brash mats is about 4 m. The distance between two adjacent brash mats/windrows mats is about 12 m. The surface water flows along the furrows, is collected by collector drains (Arrows in Figures 1), and joins the study stream.

The second rotation of lodgepole pine was planted in December, 2005 at a density of 2,800 per ha with no cultivation and no new drainage. No fertilizer was applied in the replanting operation. A buffer zone was established by replanting birch, rowan, alder and willow (instead of pine), in a 15-20 m-wide strip on each side of the stream. Furrows, ribbons, drains and brash/windrows were left *in situ*. Very little revegetation was observed in the harvested area until late Summer, 2008.

3. SAMPLING, MEASUREMENT AND DATA ANALYSIS

3.1 Water

From May 2005 to September 2009, water samples at the US and DS stations were taken hourly during flood events and, on selected days, in base flow conditions using a DISCO automated water sampler. Grab water samples were taken above (USC) and below the confluence (DSC) of the study stream and the main river (Figure 1) about once every two weeks. Rainfall water samples were also collected by placing an open and clean plastic container near the DS station during storm events for P analysis. All water samples were frozen at -20^{o}C in accordance with standard methods (APHA, 1995) until water quality analyses were conducted. The following analyses were carried out on the water samples: total reactive phosphorus (TRP), dissolved reactive phosphorus (DRP) – filtered using Whatman Cellulose Nitrate Membrane Filters (pore size 0.45 μm) - and total phosphorus (TP) - after digestion with acid persulfate – using a Konelab 20 Analyser (Konelab Ltd., Finland).

3.2 Soil

Sites of about 1 ha in areas A and B were chosen for soil sampling. Forty and thirty-eight 100-mm-deep soil cores consisting of the humic and upper peat layers were collected using a 30-mm-diameter gouge auger from the ribbons in A and B in May 2005, April 2006, March 2007, April 2008 and March 2009. 15, 26, 25 and 28 more soil cores were taken under the windrow/brash in the DS harvested area in April 2006, March 2007, April 2008 and March 2009, respectively. Since the brash mats/windrows - formed from the harvest residues – are parallel to the study stream and furrows, and along the slope, P from the brash mats/windrows didn't enrich the brash-free soil. 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 distilled 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).

3.3 Analysis methods

Storm flow was defined as the total flow (including the base flow) from the time where stream flow begins to increase on the rising limb to the time when the flow on the falling limb intercepts the separation line with a constant slope of 0.0055 L s^{-1} ha^{-1} $hour^{-1}$ (Yusop et al., 2006). Monthly TRP loading was calculated in base flow and storm flow periods as follows (Yusop et al., 2006):

$$Q_{TRP} = CQ \qquad \text{Equation 1}$$

where Q_{TRP} is monthly TRP load (μg $month^{-1}$); C is the discharge-weighted mean concentration (μg L^{-1}) and Q is the total flow (L $month^{-1}$). For each month, C (μg L^{-1}) values at base flows and storm flows were calculated separately, using the following equation (Fergusson, 1987):

$$C = \sum_{n=1}^{n} c_i q_i / \sum_{i=1}^{n} q_i \qquad \text{Equation 2}$$

where c is the instantaneous concentration (μg L^{-1}), q the corresponding discharge during sampling (L s^{-1}) and n is the number of low flow or storm flow samples in the respective month. Finally, the annual loading is calculated as the summation of monthly loadings during both low and storm flow periods.

The TRP loads were calculated using the following linear equation:

$$Q_{TRP} = \alpha Q + \beta \qquad \text{Equation 3}$$

where Q_{TRP} represents the TRP yield (μg), Q is the water discharge (L), and α (μg L^{-1}) and β (μg) are obtained by the least squares method using observed TRP yield and water discharge data. At the DS station, the values of α and β in the base flow and storm flow were calculated for the following periods: August 2005 - July 2006, August 2006 - July 2007, August 2007 - July 2008, and August 2008 - July 2009. At the US station, because there was no significant change during the study period, the values of α and β in the base flow and storm flow were calculated from August, 2005 to July, 2009.

The differences in WEP in soil in kg ha^{-1} between the areas without windrow and with windrow were calculated by assuming that windrow comprises 25 % of the harvested area and that soil density is similar in areas below windrow and without windrow.

The difference between the daily total reactive phosphorus (TRP) concentrations at the US and DS stations in the first four years after harvesting was analysed using a paired samples t-test at the 95% significance level (P=0.05). The difference between the soil WEP in A and B before harvesting was analysed using an independent samples t-test at the 95% significance level (P=0.05). After harvesting, the differences between the soil WEP in (i) area A and the brash/windrow-free area in B and (ii) under the brash/windrow and in the brash/windrow-free area in B were also analysed using an independent samples t-test at the 95% significance level (P=0.05). All the t-test was done with the SPSS statistical tool (http://www.spss.com).

4. RESULTS AND DISCUSSION

4.1 P concentrations in the stream water after harvesting

4.1.1 General trends

The average P concentrations in the rainfall were 13 ± 6 μg L^{-1} of TP and 4 ± 3 μg L^{-1} of TRP. Figure 2 shows the daily discharge-weighted mean TP and TRP concentrations at US and DS stations during the study period. Measured P concentrations at the US station were low during the study period, with average values of 14 ± 10 μg L^{-1} of TP and 6 ± 5 μg L^{-1} of TRP, which were close to the values in the rainfall. Four weeks after harvesting operations began, daily discharge-weighted mean P concentrations at the DS station started to increase and increased gradually to about 123 μg

L^{-1} of TP and 73 μg L^{-1} of TRP at the end of harvesting period, and, on 28th October, 2005, they reached peak mean concentrations of about 201 μg L^{-1} of TP and 183 μg L^{-1} of TRP. By the end of December 2005 – 10 weeks after clearfelling - they decreased to about 15 μg L^{-1} of TP and 10 μg L^{-1} of TRP. From the end of July to the middle of August 2006, P concentrations at the DS station increased dramatically to 530 μg L^{-1} of TP and 429 μg L^{-1} of TRP - the highest concentrations recorded in the study. The release pattern of P concentrations - increasing to a clear peak after harvesting, experiencing a distinct declining tail, and then increasing to the maximum peak in the next summer - was also observed by Cummins and Farrell (2003) in a study carried out in a blanket peatland forest in the west of Ireland. The maximum peak in the next summer after harvesting was also observed by Nieminen (2003) in a Scots pine-dominated peatland in southern Finland.

The P concentration peak in Summer 2006 was followed by a long declining tail. The daily discharge-weighted mean P concentrations at the DS station reduced to less than 15 μg L^{-1} of TRP and 20 μg L^{-1} of TP in July 2009, four years after harvesting. Statistical analysis indicated that P concentrations at the DS station were significantly higher than that at the US station ($P=0.05$) in the 4-year period following harvesting.

Figure 3 shows the relationship between the DRP, TRP and TP at the DS station during the study period. Linear regressions were established for DRP and TRP versus TP. TRP and DRP were about 87 % and 77 % of TP, respectively, which indicated that: (1) the majority of TP was reactive and (2) particulate P concentrations were low. Renou-Wilson and Farrell (2007) found that in water samples with high organic matter content, TRP may be equal to TP.

4.1.2 Effect of storm flow events

Over 120 storm events were analysed in this study. Figure 4 (a-d) shows the P concentrations and flow in some storm events during the study period. Along with being influenced by the elapsed time after harvesting (Figure 2), P concentrations were also affected by the flow rates. In over 80 % of the monitored storm events, P concentrations increased at the discharge rising stage, reached the maximum prior to the peak flow rate, and then reduced to a relatively stable value. Figures 4a, 4b and 4c show the P concentrations in the three storm events with highest peak flow rates of more than 158 L s^{-1} in 2005, 2006 and 2007, respectively. The P concentrations at the DS station increased from 131 μg L^{-1} of TRP, 220 μg L^{-1} of TRP and 20 μg L^{-1} of TRP at the beginning of the storm events in 2005, 2006, and 2007, respectively, to peak values of 193 μg L^{-1} of TRP, 300 μg L^{-1} of TRP and 100 μg L^{-1} of TRP, before reducing to about 80 μg L^{-1} of TRP, 110 μg L^{-1} of TRP and 30 μg L^{-1} of TRP at the end of the events. The major part of the P loading in receiving waters after harvesting activities was derived from the P movement from the topsoil to the stream during overland flow events (McDowell and Wilcock, 2004; Monaghan et al., 2007). Shigaki et al. (2006) and Quinton et al. (2001) found that high rainfall intensity resulted in a greater degree and depth of interaction between runoff and surface soil, including high runoff DRP concentrations, compared to what occurs during low rainfall intensities.

The P concentrations were also affected by antecedent weather conditions. In the storm event of November 2nd 2005, peak TRP concentrations were 197 μg L^{-1}, 106 μg L^{-1} and 113 μg L^{-1} in Events 1, 2 and 3 (Figure 4a). The peak TRP concentration in Event 2 was lower than in Event 1, although the flow rate was higher, which could be due to less labile P sources being available for release in Event 2. When a storm event follows immediately after a previous storm event, much of the labile P has already been removed by the previous flood (Bowes et al., 2005). Similar phenomena were also observed in other storm events. Figure 4d shows the storm event in which the highest P concentrations were recorded during the study period. There was a drought period before this storm event, resulting in little release of P by hydrological flushing, and large amounts of the labile P pool had accumulated. The TRP concentrations increased from about 10 μg L^{-1} to about 550 μg L^{-1} when the flow rate increased from about 0.5 L s^{-1} to the peak of 8 L s^{-1}. The P concentrations maintained high values at the end of the storm event, which could be due to the relatively small water discharge that couldn't remove the large amount of mobile P that had accumulated before the storm event.

4.1.3 P concentrations in downstream river

In the present study, the P concentration at the DS station in the study stream did not have a large impact on the P concentration in the main river, which covers an area of 200 ha above its confluence with the study stream and should have a dilution factor of about 8 for the study stream. In their study, Cummins and Farrell (2003) found that the study streams had P concentrations well above critical levels for eutrophication, but they didn't know what implications these pollutions had for downstream river-water quality in larger channels. Figure 5 shows the TRP concentrations at the DS station, DSC and USC in a storm event. When the TRP at the DS station increased from about 3 μg L^{-1} to 292 μg L^{-1}, the TRP concentrations at the DSC increased from about 5 μg L^{-1} to about 11 μg L^{-1}, giving a measured dilution factor of about 26. The higher iron concentrations and pH in the main river, which could increase P precipitation (Seida and Nakano, 2002), might contribute to the higher measured dilution factor.

4.2 Phosphorus loads

Annual TRP loads from the control area were steady and low during the study period, with values of less than 60 g ha^{-1}. Figures 6 and 7 show the water discharges and TRP loads from the harvested area in base flow and storm flow in the 1st, 2nd, 3rd and 4th years after harvesting. A total of about 5.15 kg ha^{-1} of TRP was released from the harvested area in the four years after harvesting, and mainly occurred in the first three years. The highest TRP load of 2303 g ha^{-1} was recorded in the second year after harvesting. During the study period, more than 80 % of annual water discharge occurred in storm flow. Due to the large water discharges, most of the TRP was released in storm events. In the 1st, 2nd, 3rd and 4th years after harvesting, it was calculated that the respective annual storm-flow TRP releases were about 80.3 %, 85.2 %, 82 % and 80.9 % of the total annual TRP release.

A linear regression equation (Equation 3) can be used to describe the relationship between the TRP load and water discharge. Table 1 shows the values of α and β in base and storm events in Equation 3. Parameter α was high in the first three years following harvesting, indicating that more P was released in the first three years. The TRP loads from the harvested area, estimated using Equation 3, were 1920 g ha^{-1}, 2893 g ha^{-1}, 1146 g ha^{-1} and 370 g ha^{-1}, respectively, in the 1st, 2nd, 3rd and 4th years after harvesting, which were close to the values calculated by Equation 1.

4.3 Water extractable P concentrations of the soil after harvesting

Figure 8 shows the WEP of the soil between the windrows and areas under the windrows in the DS harvested area and the US control area in May 2005, April 2006, March 2007, April 2008 and March 2009. The independent samples t-test indicated that (i) before harvesting (in May, 2005), the difference between the WEP concentrations in area A and area B was not significant; (ii) after harvesting (in April, 2006 and March, 2007), WEP concentrations were significantly higher in the brash/windrow-free soils in area B than in area A ($P=0.05$); (iii) in the harvested area B, the WEP concentrations under the windrows/brash were significantly higher than those in the windrow/brash-free area in April 2006, March 2007, April 2008 and March 2009 ($P=0.05$).

Before harvesting, the WEP values in the US and DS areas were similar, at about 17 and 18 mg (kg dry soil)$^{-1}$. Most of this P was cycled in the forest system since very little P was leaving the catchments in runoff (Figure 2). It has been reported that in undisturbed forests, nutrients are effectively retained in the ecosystem, and leaching of P to receiving water is small (Mattson et al., 2003; Finér et al., 2004). After harvesting, both WEP in the soils covered and not covered by brash/windrow material increased, reaching peaks of 67 and 40 mg (kg dry soil)$^{-1}$, respectively, in 2007. The WEP under the windrows/brash was about 136 %, 152.3 %, 235 % and 188.9 % of the WEP in the windrow/brash-free soil in 2006, 2007, 2008 and 2009, respectively. Higher WEP concentrations, found under the windrows/brash material, were due to P release from decomposing logging residues. The WEP was 1.5 kg ha^{-1}, 2.5 kg ha^{-1}, 1.8 kg ha^{-1}, and 1.3 kg ha^{-1} under the widrow/brash material in 2006, 2007, 2008, and 2009, respectively, accounting for about 31 %, 36 %, 39 %, and 34 % of the total WEP in the harvested area. This observation is for soil only and ignores P remaining in the decomposing brash mats/windrows. Hyvönen et al. (2000) found that the logging residues may contribute 8 - 31 kg ha^{-1} of

TP to the harvested area. The high WEP value under the windrows/brash material lasted longer than for the windrow-free areas, which could be due to the relatively low decomposition rates of bark and branches (Ganjegunte et al., 2004). This indicates that whole-tree harvesting could, at least to some extent, be used as a means to decrease P release from blanket peats. Since the windrows/brash lie parallel to the furrows and are at right angles to the contours, it is unlikely that the WEP in the windrow/brash-free area is influenced by P release from brash area. The increase in WEP in the soil not covered by the windrow/brash material after harvesting could be due to the decay of the surface organic layer, dead fine roots and lack of plant uptake. After clearfelling, a rise in soil temperature due to increased light penetration to the forest floor can increase decomposition rates (Messina et al., 1997; Perison et al., 1997), which increases the labile P sources (Walbridge and Lockaby, 1994).

Besides the increase in labile P after harvesting, P transport also strongly links to the P adsorption ability of the soil (Tamm et al., 1974). In a clearfelled and harvested catchment covered with Podzols, Yanai (1998) found that, although the leaching of P from the forest floor organic residues to the soil was 0.7 kg ha^{-1} year^{-1}, only 0.07 kg ha^{-1} year^{-1} was released from the soil in stream water and sediment, due to high P adsorption capacity of the soil. However, in the present study on upland peat soils, P concentrations in the study stream at the DS station increased significantly after harvesting (Figure 2), with most of the P loading taking place during storm events. In wet climates such as in Ireland, there is a great risk of P release from peat forests, due to a combination of poor P adsorption capacity in the peat soil, high runoff, and P sources being available after harvesting.

5. POSSIBLE MITIGATION METHODS

This study showed that the harvesting of the blanket peat forest increased the TRP export in the study stream, and this impact could last for more than four years. P concentrations increased from 6 μg L^{-1} of TRP pre-clearfelling to a peak value of 429 μg L^{-1}, one year after harvesting. The results of this study were well comparable with those of Cummins & Farrell (2003), who monitored P concentrations in forest drains and streams on blanket peatland in western Ireland weekly from 1996 to 2000, by using continuous depth proportional passive sampling. Their study catchment had similar soil type and weather condition as the present study. They found that catchment harvesting led to substantial increases in P concentrations. The molybdate-reactive phosphorus (MRP) in their three study drains with the areas of 100 ha, 1 ha and 1 ha increased from 9 μg L^{-1}, 13 μg L^{-1} and 93 μg L^{-1} before harvesting to peak values of 265 μg L^{-1}, 3530 μg L^{-1} and 4164 μg L^{-1}, respectively, one year after harvesting (Cummins & Farrell, 2003). In Finland, Nieminen (2003) also found that, due to low Al and Fe content of peat, harvesting of peatland forest increased the leaching of P. As most of the blanket peat forests planted in the UK and Ireland before the 1980s are reaching their harvesting age, efficient and feasible practices are required to minimize the possible P release after harvesting to receiving waters.

In order to reduce nutrient sources after harvesting, whole-tree harvesting is recommended (Nisbet et al., 1997). Needles and branches have much higher nutrient concentrations than stem wood. Whole-tree harvesting may reduce nutrient sources by 2 to 3 times more than bole-only harvesting (Nisbet et al., 1997). This study found higher WEP contents in harvested areas below windrow/brash material than for the brash-free sites, indicating that whole-tree harvesting could be used as a means to decrease P release.

A buffer zone is an area adjacent to an aquatic zone and managed for the protection of water quality (Forest Service, 2000). Within buffer zones, natural vegetation and/or planted suitable tree species are allowed to develop. Buffer zone has been widely used by forestry practitioners in the protection of freshwater aquatic systems (Newbold et al., 2010). It can protect aquatic systems by controlling runoff using the following methods: (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. However, this study shows that traditional buffer zones with a width of 15-20 m may not be an efficient method to mitigate the P release from all harvested areas, since, in this study, about 80 % of TP in the study stream was soluble (Figure 3) and more than 70 % of the P release occurred in storm events when there would have been low residence times for the uptake of soluble P in the buffer zones. If buffer zones are used to mitigate P release, larger buffer areas than those used presently may be needed (Väänänen et al., 2008).

Phased felling and limiting size to minimise negative effects have been recommended in the UK (Forestry Commission, 1988) and Ireland (Forest Service, 2000). Harvesting proper proportion of a catchment at any one time can reduce the nutrient concentrations on aquatic systems. This study found that due to the dilution capacity of the main river, the P concentrations in the river were low after harvesting, indicating that catchment-based selection of the harvesting coupe size could limit the P concentrations in the receiving waters after harvesting. However, the management strategy does not reduce the total P load leaving the harvested catchment.

Before the replanted trees grow up, vegetation could immobilize the nutrients throughout the harvested catchment. As ground vegetation develops, P uptake and recycling can be expected to diminish leaching over time (Piirainen et al., 2007). In the present study, vegetation such as *Molinia caerulea* cover was observed in 2008 and became well established in 2009. Since the development of the vegetation, P release to the receiving water reduced, though the WEP in the harvested area was still high. It could take 3 to 4 years for natural re-vegetation of the blanket peat harvested forest area to occur. Stimulation of vegetation cover immediately after harvesting, e.g., through seeding the harvested area with fast growing native grasses, should also be studied as a practice to minimize the P release from the blanket peat forest after clearfelling.

6. CONCLUSIONS

This study showed that the harvesting of the blanket peat forest increased the TRP export in the study stream, and this impact could last for more than four years. In the first three years following harvesting, up to 5.15 kg ha^{-1} of TRP were released from the catchment to the receiving water; in the second year alone after harvesting, 2.3 kg ha^{-1} were released. P concentrations increased from 6 μg L^{-1} of TRP during pre-clearfelling to a peak of 429 μg L^{-1} one year after harvesting. About 80 % of TP in the study stream was soluble and more than 70 % of the P release occurred in storm events. Due to the dilution capacity of the main river, the P concentrations in the river were low during the study period, indicating that rational sizing of the harvesting coupe could be an efficient practice to limit the P concentration in the receiving waters following harvesting. However, the study comprised only one experimental catchment. In future research, more paired sites should be investigated.

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Table 1. The values of α and β in base and storm events in Equation 3 at downstream (DS) and upstream (US) stations during the study period

Time	Storm flow				Base flow			
	Catchment	α (μ g L^{-1})	β (μ g)	R^2	Catchment	α (μ g L^{-1})	β (μ g)	R^2
August 2005 – July 2006	DS (262)*	95.8	20.6	0.85	DS (132)	192.9	-191	0.73
August 2006 – July 2007	DS (577)	129.8	211.1	0.85	DS (151)	141	153.6	0.68
August 2007 – July 2008	DS (266)	63.9	- 284	0.90	DS (171)	77.2	-26.8	0.74
August 2008 – July 2009	DS (234)	12	106	0.41	DS (143)	8.9	91	0.55
August 2005 – July 2009	US (432)	4.5	12.6	0.77	US (379)	6.9	23.7	0.63

*: number of samples is presented in the bracket

Figure 1. Locations of the Burrishool catchment and the study stream (DS: downstream station; US: upstream station; USC: upstream of the confluence; DSC: downstream of the confluence; A: intact area - control site; B: harvested area-study site; arrows: indicating the collector drains and flow direction)

Figure 2. The daily rainfall and daily discharge-weighted mean total phosphorus (TP) and total reactive phosphorus (TRP) concentrations at downstream station (DS) and upstream station (US) during the study period

Figure 3. The relationship between the instantaneous concentrations of dissolved reactive phosphorus (DRP), total reactive phosphorus (TRP) and their linked total phosphorus (TP) concentration at downstream station (DS) during the study period

Figure 4. The instantaneous P concentrations at upstream station (US) and downstream station (DS) with the instantaneous DS flow rate (Q) in storm events (The maximum flow rate of the flow measurement equipment is 158 L s $^{-1}$)

Figure 5. The instantaneous total reactive phosphorus (TRP) concentrations at downstream station (DS), downstream of the confluence (DSC) and upstream of the confluence (USC) with DS flow rate (Q) in a storm event

Figure 6. Yearly water discharged from the harvested area in base flow and storm flow after harvesting

Figure 7. Yearly total reactive phosphorus (TRP) loads from the control site (US) and from the harvested area (DS) in base flow and storm flow after harvesting

Figure 8. Soil water extractable phosphorus (WEP) in non-harvested (A) and harvested areas (B) between the windrow and under the windrow in May 2005, April 2006, March 2007, April 2008 and March 2009 (The bars indicate the standard deviation)

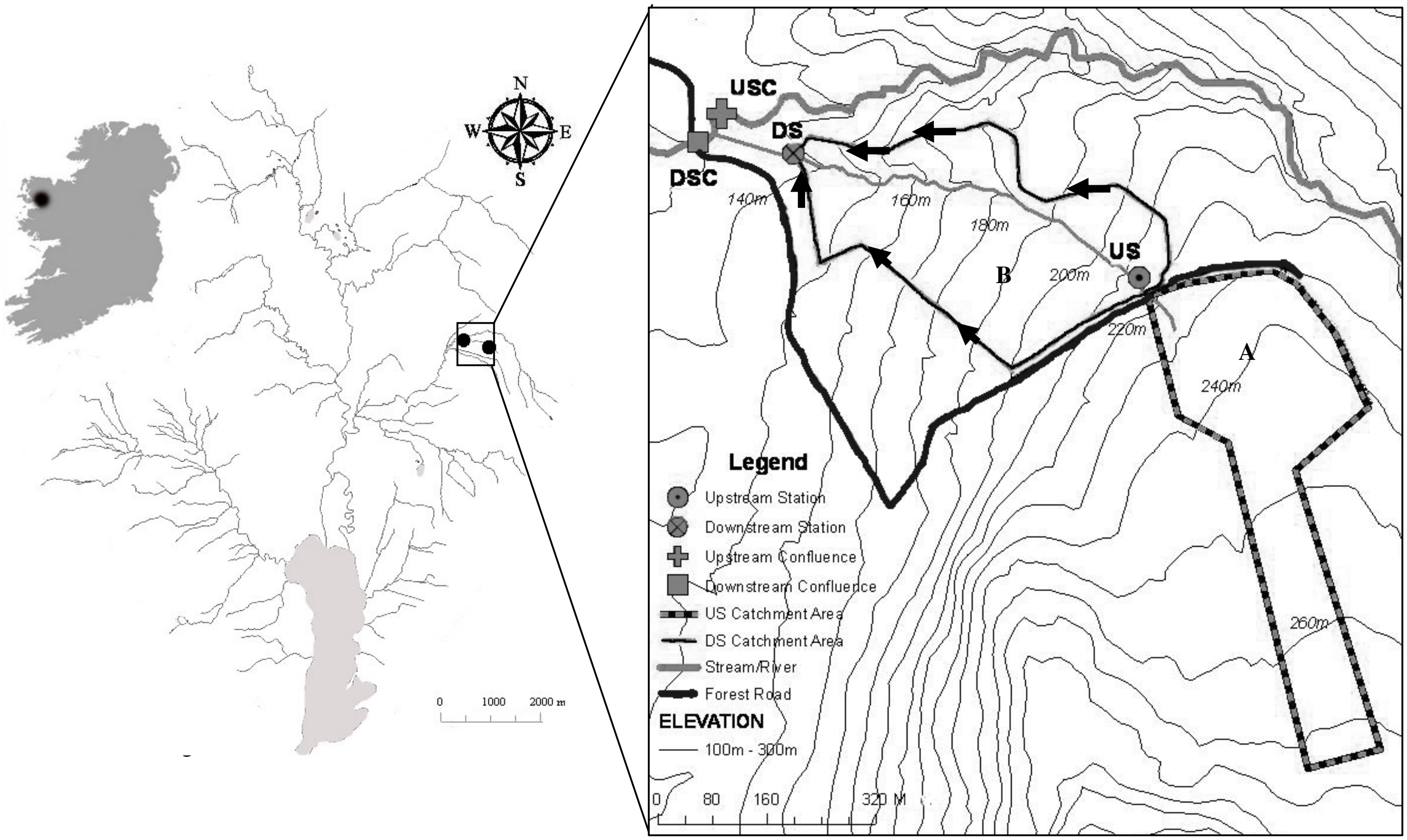

N
W
E
S
0 1000 2000 m
USC
DS
DSC
US
140m
160m
180m
200m
220m
240m
260m
A
B
Legend
Upstream Station
Downstream Station
Upstream Confluence
Downstream Confluence
US Catchment Area
DS Catchment Area
Stream/River
Forest Road
ELEVATION
100m - 300m
0 80 160 320 M

Figure 1

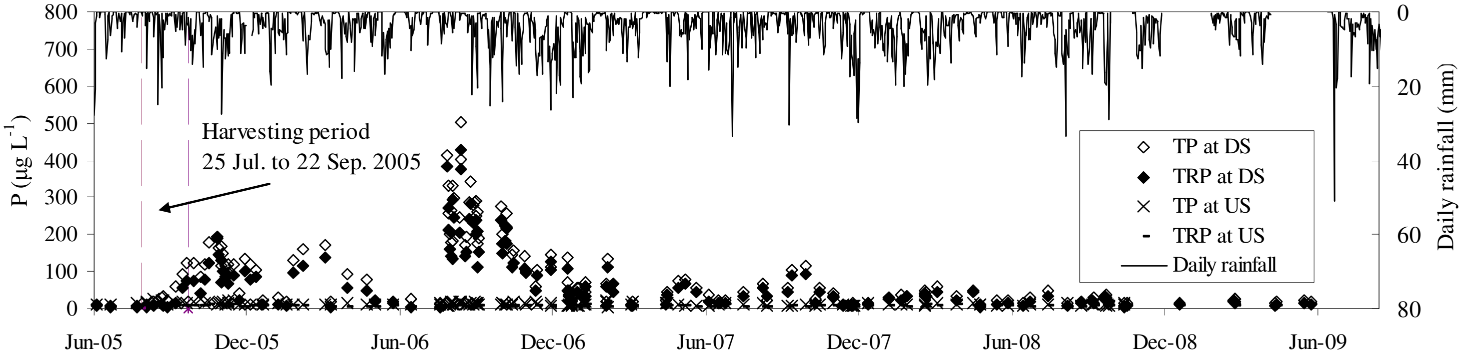

800
700
600
500
400
300
200
100
0
P (µg L^{-1})
Harvesting period
25 Jul. to 22 Sep. 2005
TP at DS
TRP at DS
TP at US
TRP at US
Daily rainfall
0
20
40
60
80
Daily rainfall (mm)
Jun-05
Dec-05
Jun-06
Dec-06
Jun-07
Dec-07
Jun-08
Dec-08
Jun-09

Figure 2

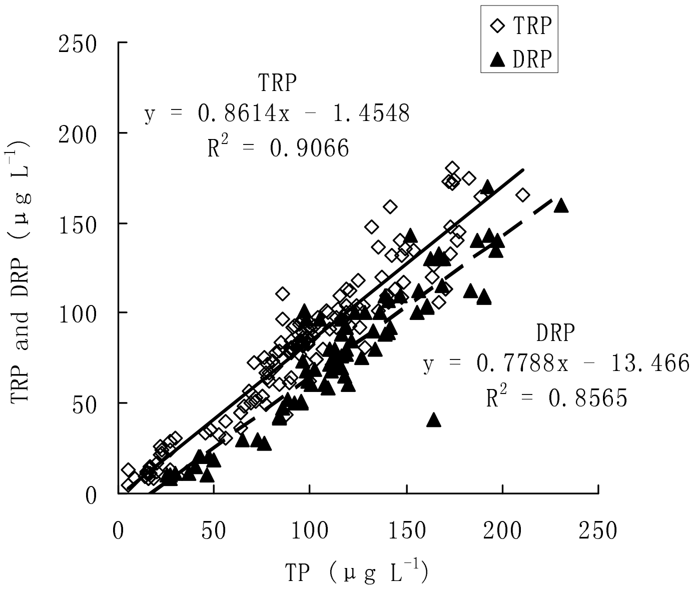
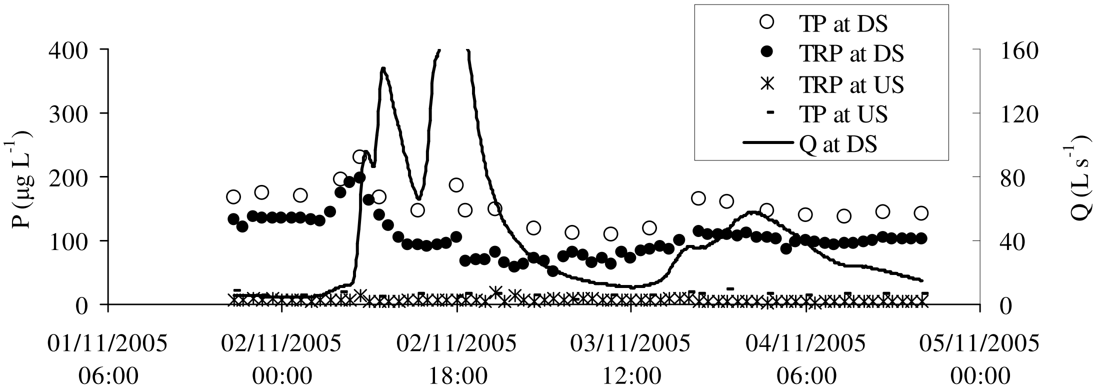
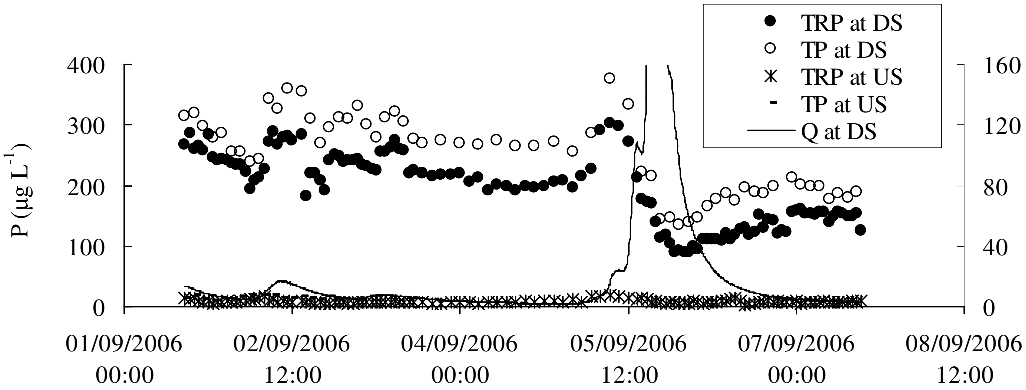

◇ TRP
▲ DRP
TRP
y = 0.8614x - 1.4548
R^2 = 0.9066
DRP
y = 0.7788x - 13.466
R^2 = 0.8565
TRP and DRP (μg L^{-1})
TP (μg L^{-1})
0
50
100
150
200
250
0
50
100
150
200
250

Figure 3



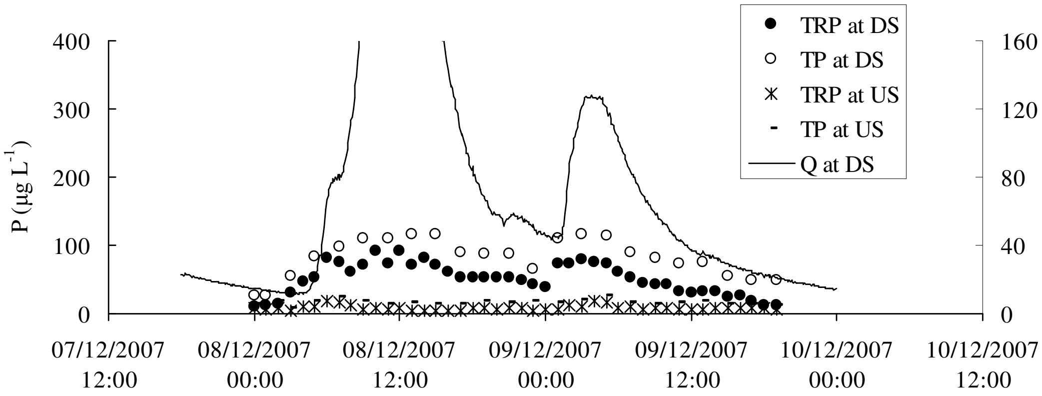
TP at DS
TRP at DS
TRP at US
TP at US
Q at DS
P (µg L^{-1})
Q (L s^{-1})
400
300
200
100
0
160
120
80
40
0
01/11/2005 06:00
02/11/2005 00:00
02/11/2005 18:00
03/11/2005 12:00
04/11/2005 06:00
05/11/2005 00:00

Figure 4a



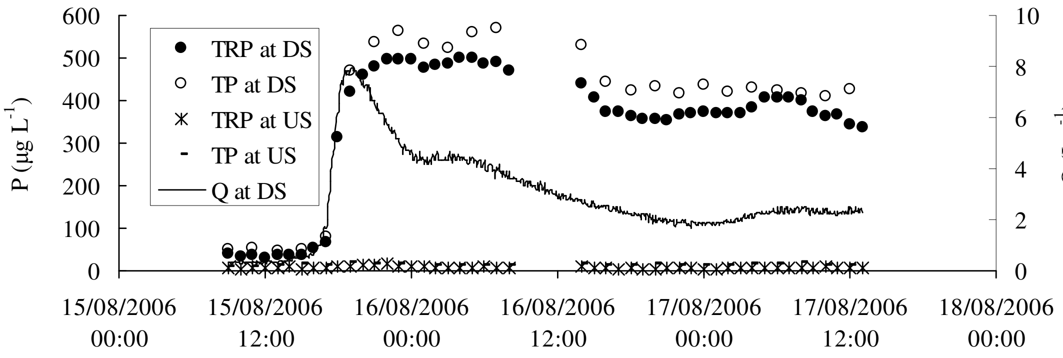
TRP at DS
TP at DS
TRP at US
TP at US
Q at DS
400
300
200
100
0
P (μg L^{-1})
160
120
80
40
0
Q (L s^{-1})
01/09/2006 00:00
02/09/2006 12:00
04/09/2006 00:00
05/09/2006 12:00
07/09/2006 00:00
08/09/2006 12:00

Figure 4b



TRP at DS
TP at DS
TRP at US
TP at US
Q at DS
P (µg L-1)
Q (L s-1)
400
300
200
100
0
160
120
80
40
0
07/12/2007 12:00
08/12/2007 00:00
08/12/2007 12:00
09/12/2007 00:00
09/12/2007 12:00
10/12/2007 00:00
10/12/2007 12:00

Figure 4c



600
500
400
300
200
100
0
P (µg L-1)
TRP at DS
TP at DS
TRP at US
TP at US
Q at DS
10
8
6
4
2
0
Q (L s-1)
15/08/2006 00:00
15/08/2006 12:00
16/08/2006 00:00
16/08/2006 12:00
17/08/2006 00:00
17/08/2006 12:00
18/08/2006 00:00

Figure 4d

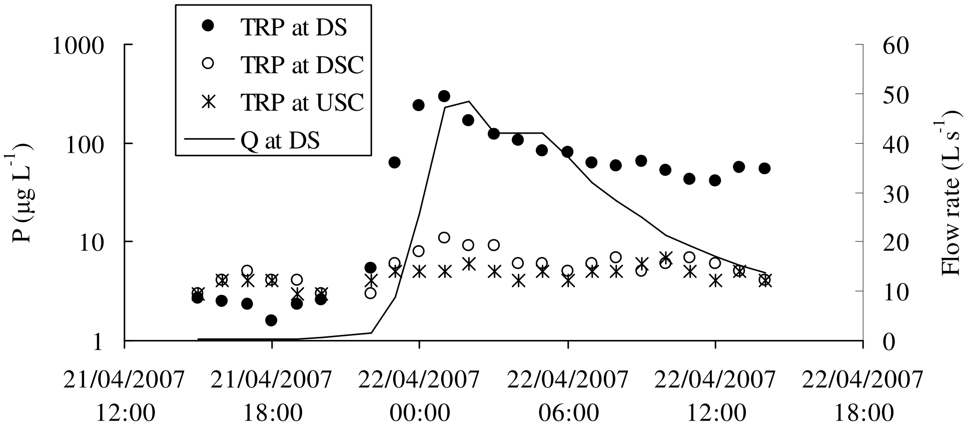
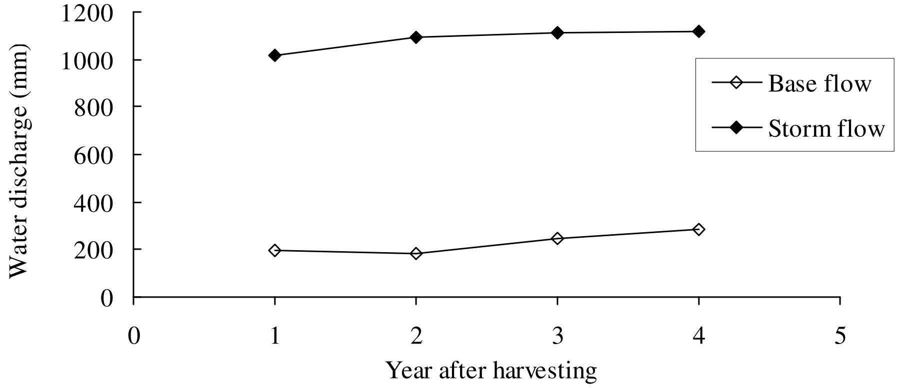
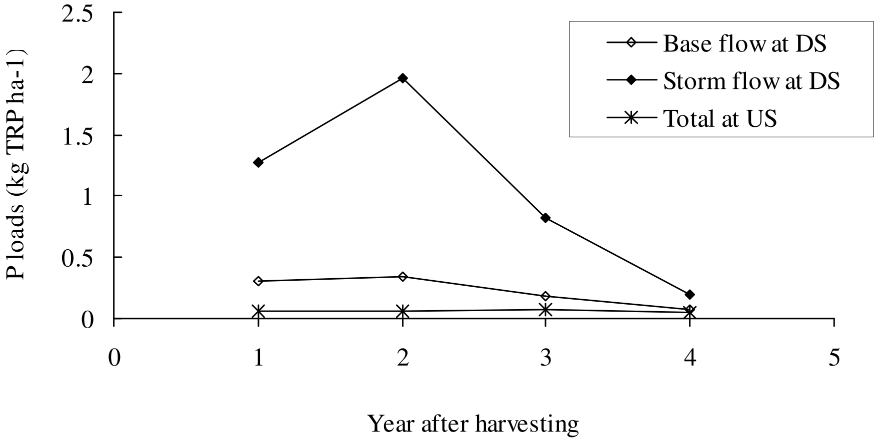

● TRP at DS
○ TRP at DSC
✱ TRP at USC
Q at DS
P (µg L^{-1})
Flow rate (L s^{-1})
1000
100
10
1
60
50
40
30
20
10
0
21/04/2007 12:00
21/04/2007 18:00
22/04/2007 00:00
22/04/2007 06:00
22/04/2007 12:00
22/04/2007 18:00

Figure 5



1200
1000
800
600
400
200
0
Water discharge (mm)
0
1
2
3
4
5
Year after harvesting
◇ Base flow
◆ Storm flow

Figure 6



2.5
2
1.5
1
0.5
0
P loads (kg TRP ha-1)
0
1
2
3
4
5
Year after harvesting
Base flow at DS
Storm flow at DS
Total at US

Figure 7

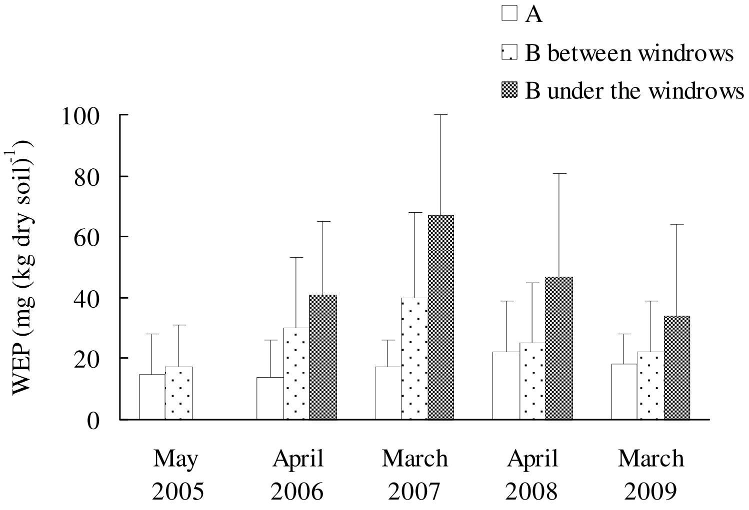

☐ A
▨ B between windrows
▩ B under the windrows
WEP (mg (kg dry soil)$^{-1}$)
100
80
60
40
20
0
May 2005
April 2006
March 2007
April 2008
March 2009

Figure 8