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Phosphorus in surface runoff and soil water following fertilization of afforested cutaway peatlands

Florence Renou-Wilson and Edward P. Farrell

School of Biology and Environmental Science, Agriculture and Food Science Centre, University College Dublin, Belfield, Dublin 4, Ireland (e-mail: Florence.Renou@ucd.ie)

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This study retraced the fate of phosphorus (P) applied to various types of afforested cutaway peatlands and examined the spatial and temporal trends in the concentration of soluble molybdate reactive phosphorus (MRP) in surface runoff water and soil water. Edaphic characteristics had a critical role to play in the occurrence of P loss. The occurrence and magnitude of P loss also depended on the rate and method of application of the fertilizer and transport factors such as surface runoff, which is directly related to hydrological processes and climatic conditions. Due to low P-binding capacity, immediate P loss is inevitable from newly fertilized deep peat unless edaphic properties can be altered, e.g. by mixing the peat with calcareous sub-peat mineral soil. P loss can be reduced by (1) applying the initial fertilizer in band rather than broadcast, (2) splitting in two applications and applying the minimum rate of fertilizer necessary at planting, and (3) establishing a vegetation cover. The fate of lost P is still unknown as low MRP concentrations were recorded in the drain water two years after fertilization. Finally, P losses have been confirmed to be temporary as no P losses were recorded in plantations which had been established and fertilized ten years previously.

Introduction

Forest cover in Ireland has increased from 1% of the land surface in 1900 to 10% in 2005. The interaction of these new forests and the environment has raised concern with regard to surface water quality, especially in terms of the acidification (Farrell *et al*. 2001) and eutrophication (Forest Service 2001, McCabe *et al*. 2005) of surface water bodies. With current policy proposals to further increase the forest cover to 17% by 2030 (Department of Agriculture Food and Forestry 1996), a better understanding of the potential impacts of these new forests on the environment is necessary, particularly within the context of sustainable forest management. In addition, the implementation of the EC Water Framework Directive (2000/60/EC) gave a new impetus to the monitoring of nutrient movement, especially phosphorus (P), from all potential sources of pollution.

Industrial cutaway peatlands form a substantial land cover, part of which (ca. 30 000 ha), has been earmarked for future afforestation (McNally 1997). Cutaway peatland forests could have a significant productive potential for timber and biomass, as well as providing a valuable amenity for recreation and a contribution to regional biodiversity. Drainage, cultivation and fertilization are practices often required for the satisfactory establishment of trees on these sites (Renou and Farrell 2005). In particular, the application of phosphatic fertilizer is critical for the survival of the new plantations (Carey *et al.* 1985, Kaunisto and Aro 1996). The possibility that applied P will be lost from cutaway peat soils to drainage water is important for the efficient use of fertilizer materials, the overall economics of this afforestation scheme, and the potentially deleterious effect that P runoff may have on the ecology of downstream water bodies.

The transfer of P from terrestrial to aquatic ecosystems has been a priority concern worldwide and in Ireland particularly over the last two decades. The negative impact of P entering aquatic ecosystems has been demonstrated through its contribution to eutrophication of surface waters and the subsequent degradation of water quality. Additions of P typically lead to undesirable aquatic plant growth, resulting in the depletion of oxygen in the water due to the heavy oxygen demand by micro-organisms as they decompose the organic material. Today, anthropogenically-induced eutrophication has been identified as the greatest threat to the quality of rivers and lakes in Ireland and elsewhere (Lucey *et al.* 1999, Mainstone and Parr 2002). The Irish Phosphorus Regulations set the threshold of below 0.030 mg l^{-1} of Molybdate Reactive Phosphorus (MRP) for a stream to be of good quality. MRP is considered to represent free and biologically available P (e.g. Sharpley *et al.* 1991, Ekholm 1998).

Ombrotrophic peatlands offer very few mechanisms for retaining applied inorganic P. This is because they contain low concentrations of aluminium (Al) and iron (Fe) oxides — which form complexes with phosphate (Kaila 1959, Larsen *et al.* 1959, Fox and Kamprath 1971, Cuttle 1983, Nieminen and Jarva 1996). The leaching of P from peatlands is likely to occur especially following certain forestry operations such as drainage, site preparation, fertilization and clear-felling (Kenttämies 1981, Ahti 1983, Malcolm and Cuttle 1983, Nieminen and Ahti 1993, Lepistö and Saura 1998, Nieminen 2000, Joensuu *et al.* 2002, Renou and Cummins 2002, Cummins and Farrell 2003, Nieminen 2003, Åström *et al.* 2004). Similarly, P losses have been found to occur from mined and cutover peatlands (Sallantaus 1992, Nilsson and Lundin 1996, Wind-Mulder *et al.* 1996, Kløve 2001). Peat found in Irish cutaway peatlands is very nutrient-poor in relation to P and potassium (K) concentrations. Concentrations of Al and Fe are also low in these soils (Walsh and Barry 1958, Barry *et al.* 1973). In addition to this low capacity to sorb P, cutaway peatlands present a high risk of nutrient loss due to their physiography.

The intensity of the drainage system together with the fact that cutaway peatlands are often devoid of vegetation cover (upon exiting peat harvesting) makes surface runoff an important pathway for applied-P loss. The runoff and erosion risks of these site types are also accentuated by the fact that the remaining peat is often compacted, has a very low hydraulic conductivity (Boelter 1969, Galvin 1976) and that the cutaway peat fields are often cambered and sloping towards the drains as a result of the milled-peat harvesting process. Climatic conditions exacerbate the risk of particulate loss as high levels of precipitation together with mild temperatures in the autumn and winter time can enhance the dissolution of fertilizer and the removal of any mobile P present in the soil matrix.

It is apparent that several factors can control the movement of P from afforested cutaway peatlands. This study, which includes four experiments across six sites, aimed to ascertain the influence of soil preparation and different rates and methods of fertilizer application, on the occurrence and magnitude of P loss in surface waters and soil waters.

The questions that this study endeavours to answer are as follows:

1. What are the effects of soil preparation and fertilization with different rates and methods of application on MRP concentrations in surface runoff water on deep peat?
2. What are the effects of rates of fertilizer and methods of application on MRP concentrations in soil water on a mixed peat/sub-peat mineral soil matrix?
3. What are the effects of initial fertilization on MRP concentrations in soil water ten years after fertilization on deep peat and does aerial re-fertilization increase loss of P?

4. What are the effects of initial fertilization on MRP concentrations in ditch water two years after fertilization within a deep cutaway peatland, as compared with those in ditch water in unfertilized areas?

Material and methods

General description of the monitored sites

In 1999, a series of experiments was set up in the Irish midlands: 53°13´N, 7°42´W, at about 60 m a.s.l. elevation, in a basin-type landscape where precipitation averages 875 mm per annum (Collins and Cummins 1996) with cool summers (July and August are the warmest months with an average of 14.5 °C) and mild winters (January is the coldest month with an average of 4.1 °C). The quantity of P in rainfall is minimal (Boyle *et al*. 2000). A description of each site is given in Table 1. Planting was carried out manually on flat ground and vegetation control was omitted from the experimental areas in order to avoid loss of P via mineralization of the decomposing vegetation.

Experiment 1

Experiment 1 was located across a 15 ha cutaway peatland that typically consisted of a series of peat fields (15 m wide) separated by ditches (approximately 1-m deep) (Fig. 1). The thickness of the remaining peat layer varied between 60 cm and > 200 cm and consisted mainly of *Phragmites* peat (pH 4.8), directly overlying glacial silty clay (pH 7.7). The site was divided into two comparable plots: Plot A received no soil treatments while Plot B was treated using contemporary practice, i.e. ripped and disced up to 40 cm deep followed by levelling. Both areas were planted with Norway spruce (*Picea abies*) in May 1999. Initial fertilization took place in July 1999 with 25 kg ha^{-1} P as unground mineral rock phosphate (Table 2), applied manually in 50-cm-wide bands along the rows of trees. This was half of the contemporary recommended rate of application for forestry on peatlands in Ireland (Forest Service 2000). In July 2002, the site received an additional 25 kg ha^{-1} P of rock phosphate, this time in granulated form (Table 2). Experiment 1 permitted the study of the spatial and temporal variation in P concentrations in the cultivated and non-cultivated fertilized cutaway peatland. Peat samples were taken prior to any site preparation and the chemical composition of the peat can be found in Table 3. These concentrations are in the range found in cutaway peatlands in Canada (Andersen *et al*. 2006), Norway (Nilsson and Lundin 1996) and Finland (Aro 2003).

Experiment 2

Experiment 2 consisted of a one-hectare fertilizer trial adjacent to Experiment 1. The site

Table 1. Background information about the four cutaway peatland experiments located across six sites.

Exp.	Site	Cultivation	Planting	Species[1]	Fertilizer[2] (ha^{-1})	Method of application	Sampling period
1	Tumduff (*see* Fig. 1)	Ripped and disced *vs.* no cultivation	1999	NS	1999: 175 kg UMP 2002: 175 kg RP	1999: band 2000: broadcast	May 1999 to July 2004
2	Tumduff West	Ripped and disced	2000	NS	3 rates of RP (*see* Fig. 2)	2000: band or broadcast 2002: broadcast only	May 2000 to July 2004
3	Mount Lucas	Ripped and disced	2000	Oak	3 rates of SP (*see* Fig. 2)	2000: band or broadcast 2002: broadcast only	May 2000 to July 2004
4	(1) Noggus (2) Clong (3) Clonsast	No cultivation	1989	SS	1989: 600 kg 0-10-20 2001: 350 kg RP	1989: broadcast 2001: helicopter	May 2001 to July 2004

[1] NS = Norway spruce, SS = Sitka spruce.

[2] UMP = unground rock phosphate, RP = granulated rock phosphate, SP = superphosphate (*see* Table 2).

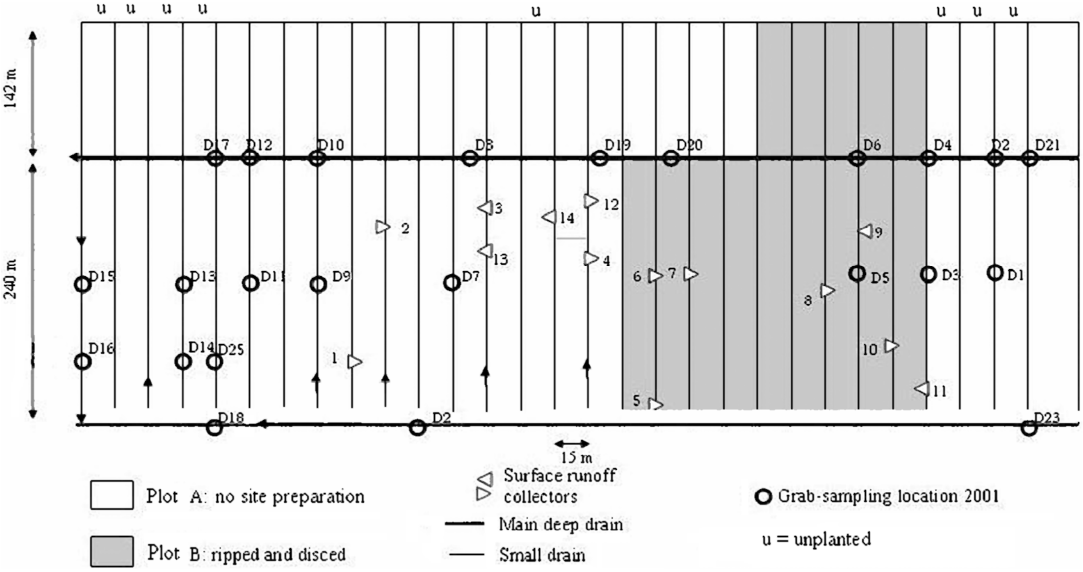


Fig. 1. The experimental lay out of Experiment 1 where surface runoff and ditch water were sampled.

Table 2. Some chemical properties of the fertilizers used in the experiments.

Type of fertilizer	Total P (%)	P soluble in		
		Water (% of total P)	2% citric acid	2% formic acid
Unground rock phosphate*	14.5	< 0.1	40	70
Granulated rock phosphate*	12	0.53	33	8
Superphosphate	16	14.74	na	na

* Moroccan origin; na = not analysed.

was ripped and disced and planted with Norway spruce in 2000. Thirty-six experimental plots, separated by unfertilized buffer zones were established (Fig. 2). Initial fertilization took place in mid June 2000 with three rates of granulated rock phosphate and two methods of application (Fig. 2).

Table 3. Some chemical properties of the surface peat layer (0–20 cm) in Experiment 1 (SD in parentheses).

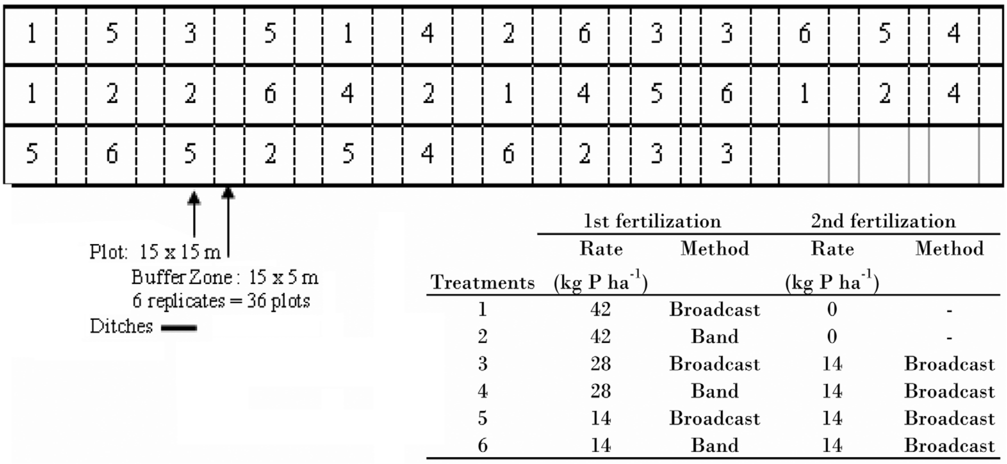
n	14
pH	4.9 (0.9)
N (%)	2.18 (0.23)
P (mg kg^{-1})	118 (44)
K (mg kg^{-1})	118 (44)
Al (mg kg^{-1})	170 (51)
Fe (mg kg^{-1})	4300 (1183)
Ca (mg kg^{-1})	2625 (1261)

Experiment 3

Experiment 3 followed the same experimental design and fertilization treatments as Experiment 2 (Fig. 2) but was planted with pedunculate oak (*Quercus robur*) in 2000. It was located in a woody-fen (pH 5.4) cutaway peatland that was deep-ploughed and levelled, filling the drains. As the remaining peat was shallow (average = 51 cm), various amounts of sub-peat mineral soil (alkaline silty clay and gravel) were brought to the surface and mixed through the peat. Initial fertilization took place mid June 2000.

Experiment 4

In Experiment 4, three stands of Sitka spruce (*Picea sitchensis*) planted in 1989 and fertilized



	1st fertilization		2nd fertilization	
Treatments	Rate (kg P ha^{-1})	Method	Rate (kg P ha^{-1})	Method
1	42	Broadcast	0	-
2	42	Band	0	-
3	28	Broadcast	14	Broadcast
4	28	Band	14	Broadcast
5	14	Broadcast	14	Broadcast
6	14	Band	14	Broadcast

Fig. 2. The experimental lay out and treatments (inset) for Experiments 2 and 3.

at establishment with 600 kg ha^{-1} of 0-10-20 NPK mineral fertilizer, were investigated. Background information on stand and peat properties can be found in Renou and Farrell (2007). In 2000, the three stands, which had not closed canopy, were diagnosed by foliar analysis as being severely P deficient with a mean foliar P concentration across sites of 0.89 ± 0.04 g kg^{-1} — a Sitka spruce crop was deemed severely P deficient with a mean P concentration below 1.2 g kg^{-1} (Everard 1973, Savill *et al*. 1997). Granulated rock phosphate (42 kg ha^{-1} P) was then applied by helicopter in July 2001.

Sampling methods

Due the complexity of the drainage systems (of different age and design) present in these cutaway peatlands, it was not possible to sample water using separate catchment areas. Surface runoff is one major pathway of P movement which can be considered at a ‘site’ or ‘point’ scale. This lateral movement of water is significant in cambered peat field with regular ditches. Another hydrological pathway associated with P loss can occur at the ‘soil’ scale via percolation of water through the soil. Soil water is the first stage in the hydrochemical transfer process of soluble P and is perhaps more significant than surface runoff in sites which have been ploughed, where ditches have been filled in and surface levelled or where the vegetation cover (including tree crop) is sufficient to intercept most of the precipitation.

In order to sample surface waters, specially-designed collectors were positioned at randomly-selected drain-edge positions to allow surface runoff water to be collected as it moves freely into the drains (Fig. 3). Fourteen collectors were located across the whole site in Experiment 1 while one collector was located in each of the 36 experimental plots in Experiment 2. Measurements started immediately after planting in both experiments and the first ten weeks prior to fertilization were a calibration period with no fertilization effect. Water samples were collected every week for the first year, and thereafter every two weeks for the remaining of the sampling period (Table 1).

In Experiments 3 and 4, drainage ditches were either absent or had filled up or dried out. Surface flow was not visible and soil water flow below the root zone was deemed the main pathway through which P loss may be expected. In order to investigate variation in P concentrations in the soil water extracted from peat below the root zone, Teflon quartz lysimeters (Prenart Equipment Aps) were positioned in the horizon between 30 cm and 40 cm deep, using a screw auger at an oblique angle so as to avoid disturbing the soil directly above the sampler. Two lysimeters were installed per plot and linked to one bottle. After a period of calibration of two

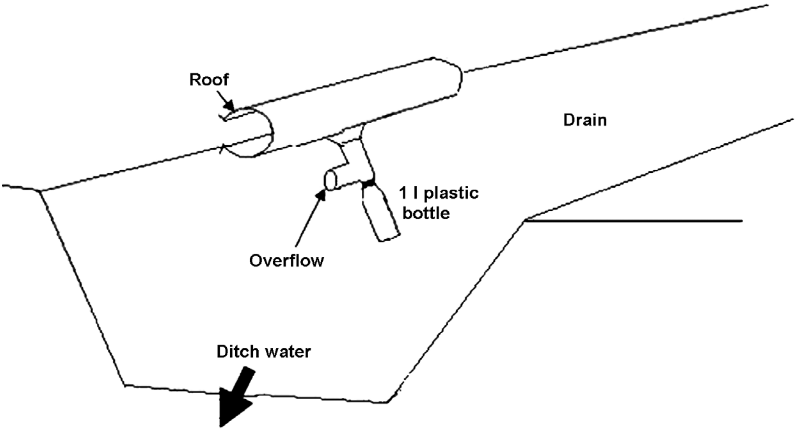


Fig. 3. Surface runoff collector, used in Experiments 1 and 2, allowing free movement of water to the drains.

weeks, soil water contained in the pore spaces of the soil matrix was extracted by suction at 600 hPa. Sampling was carried out once a week for the first year and thereafter every two weeks for the remaining sampling period.

In order to analyse P concentrations in the ditches (Experiment 1) grab water samples (1 l) were taken at weekly interval from several drains around the site (Fig. 1). It should be noted that main ditches (horizontal) were much deeper than the internal drains (vertical), making the latter act as mini-catchments. This monitoring study was carried out during a period of eight weeks in summer 2001, two years after initial fertilization).

Laboratory analyses

Surface and soil water samples were stored at 4 °C for a maximum period of 24 hours prior to analysis for pH and molybdate reactive phosphorus (MRP). The pH of the water samples was measured using a Schott pH combination electrode prior filtration. The samples were then filtered through a membrane filter (0.5 μm) and soluble MRP was determined by colorimetric measurement at 880 nm (UV-Vis spectrophotometer) using ascorbic acid as the reductant (Murphy and Riley 1962). Due to the high amount of suspended material colouring the water, it was not possible to analyse total MRP on unfiltered samples using this method.

Data analyses

In this paper, seasons correspond to the following Julian dates: autumn starts 1 August, winter starts 1 November, spring starts 1 February and summer starts 1 May. There was considerable variation between the volumes of water collected from individual sampling points and from week to week as this depended mainly on precipitation. No data were collected in spring 2001 due to access restriction to the field during the foot and mouth disease outbreak. Analyses of the data were carried out using the Statistical Analysis System (SAS Institute Inc. 2002). All data were tested for normality and homogeneity of variances. The effect of treatments on MRP concentrations was analysed using repeated analysis of variance, with time as the repeated factor in a mixed model. An unstructured covariance on residuals was used.

Results and discussion

What are the effects of soil preparation and fertilization with different rates and methods of application on P concentrations in surface runoff water on deep peat?

General effects of fertilization (Experiments 1 and 2)

MRP concentrations measured in the filtered surface runoff water before fertilization aver-

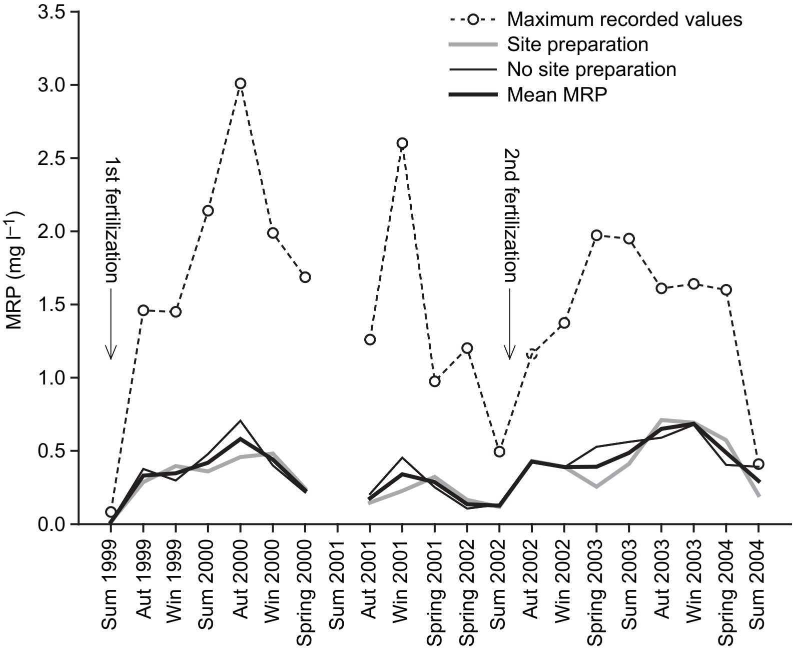
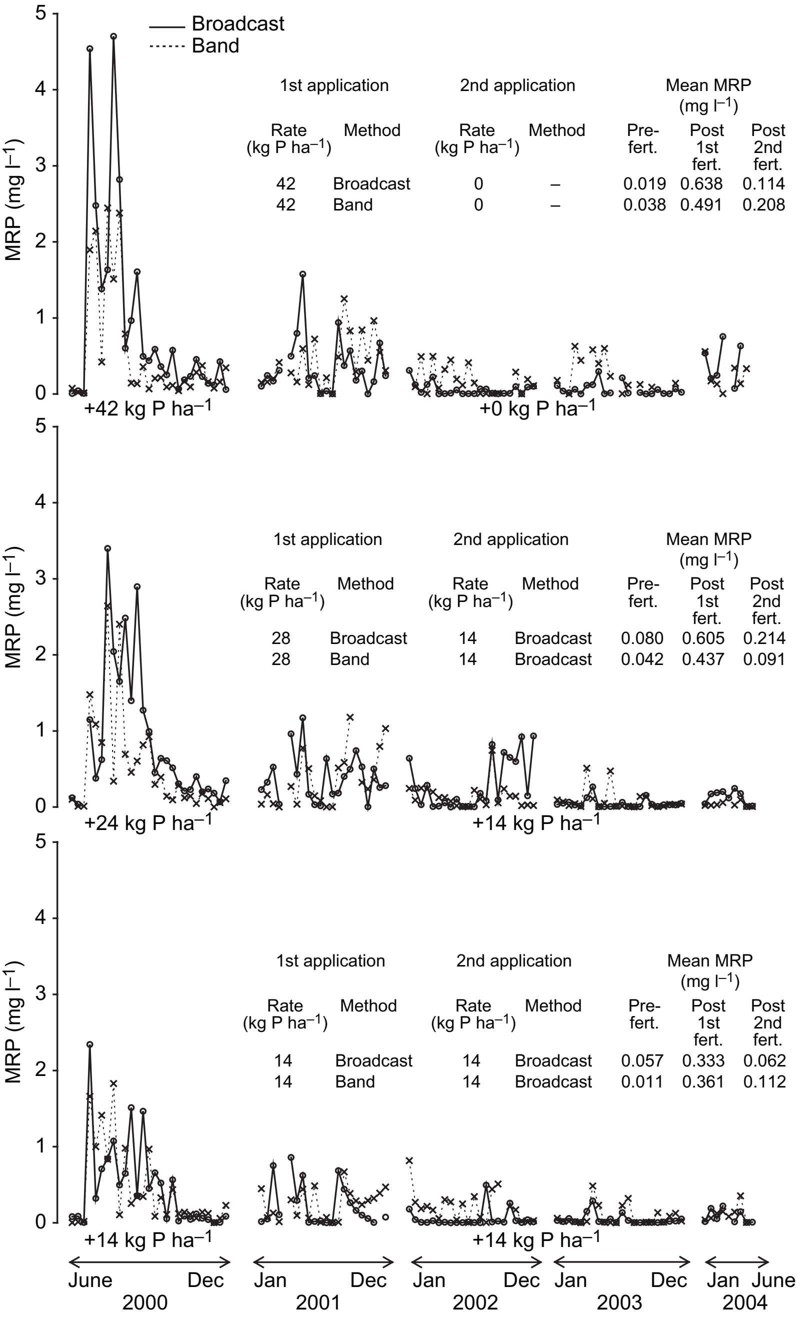


Fig. 4. Seasonal MRP concentrations (means, cultivated and not cultivated) measured in the surface runoff in Experiment 1, together with maximum values recorded at a sampling point level.

aged 0.014 mg l^{-1} in Experiment 1 and 0.036 mg l^{-1} in Experiment 2. These concentrations were of the same order of magnitude as values reported from unfertilized old-drainage peatland water: about 0.020 mg l^{-1} (Kenttämies 1981, Paavilainen and Päivänen 1995). Higher values measured in Experiment 2 may be due to a better drainage system shown by the lower mean water table (40 cm) than in Experiment 1 (31 cm). The drainage of peatlands usually aerates large volumes of peat thereby increasing the potential for mineralization of organically-bound elements and leading to higher P concentrations compared to undrained peatlands (e.g. Malcolm and Cuttle 1983, Wind-Mulder *et al*. 1996). However, an increase of P in runoff following drainage of peatlands does not always happen: studies by Joensuu *et al*. (2002) showed a slight decrease in total P three years after ditching.

In Experiments 1 and 2, the first application of rock phosphate led to an immediate increase in MRP concentrations at all sampling points (Figs. 4 and 5). During the first four months (autumn) following fertilization in Experiment 1, the average MRP concentration increased from 0.014 mg l^{-1} to 0.332 mg l^{-1}, while the maximum value recorded at a sampling point was 1.46 mg l^{-1}. MRP concentrations increased again during events recorded in spring and summer 2000. The highest concentration recorded during the whole monitoring period (5 years) was observed in May 2000 (maximum of 3.01 mg l^{-1}) (Fig. 4). By contrast, in Experiment 2, the maxima recorded over the whole sampling period (4 years) occurred during the three months following fertilization (autumn 2000). After this period, there was a clear decrease in concentrations for all treatments (Fig. 5).

The immediate high peaks in P concentrations following fertilizer application may be explained by the type of fertilizer used as well as climatic and surface conditions including absence of vegetation. Increased P concentrations occurring soon after fertilizer application may reflect the easily-dissolved water-soluble P, the amount of which should be limited in a control-release phosphate fertilizer such as rock phosphate. However, Nieminen (1997) argued that materials with citric acid-soluble P content over 30% are usually regarded as possible alternatives to water-soluble phosphatic fertilizers for direct application. Based on Boland *et al*. (1993), the rock phosphate used in Experiments 1 and 2 (Table 2) can be classified in the 'most reactive'



1st application Rate (kg P ha–1)	 Method	2nd application Rate (kg P ha–1)	 Method	Mean MRP (mg l–1) Pre-fert.	 Post 1st fert.	 Post 2nd fert.
42	Broadcast	0	–	0.019	0.638	0.114
42	Band	0	–	0.038	0.491	0.208

1st application Rate (kg P ha–1)	 Method	2nd application Rate (kg P ha–1)	 Method	Mean MRP (mg l–1) Pre-fert.	 Post 1st fert.	 Post 2nd fert.
28	Broadcast	14	Broadcast	0.080	0.605	0.214
28	Band	14	Broadcast	0.042	0.437	0.091

1st application Rate (kg P ha–1)	 Method	2nd application Rate (kg P ha–1)	 Method	Mean MRP (mg l–1) Pre-fert.	 Post 1st fert.	 Post 2nd fert.
14	Broadcast	14	Broadcast	0.057	0.333	0.062
14	Band	14	Broadcast	0.011	0.361	0.112

Fig. 5. MRP concentrations in surface runoff sampled during 5-year study in Experiment 2.

group. Climatic and surface conditions may also have contributed to the immediate loss of P via movement of fertilizer particles and increased dissolution. High precipitations were recorded in the months of August and September 1999 (Experiment 1) and in September 2000 (Experiment 2) (Fig. 6). In addition, undissolved particles of fertilizer were observed in the collectors.

The absence of vegetation was probably a critical factor in this process which is spatially limited and temporarily confined to high magnitude, high intensity rainfall events (Heathwaite and Dils 2000). High precipitation immediately following fertilizer application on bare peat can enhance both the movement of phosphatic fertilizer and its dissolution. While it has been found

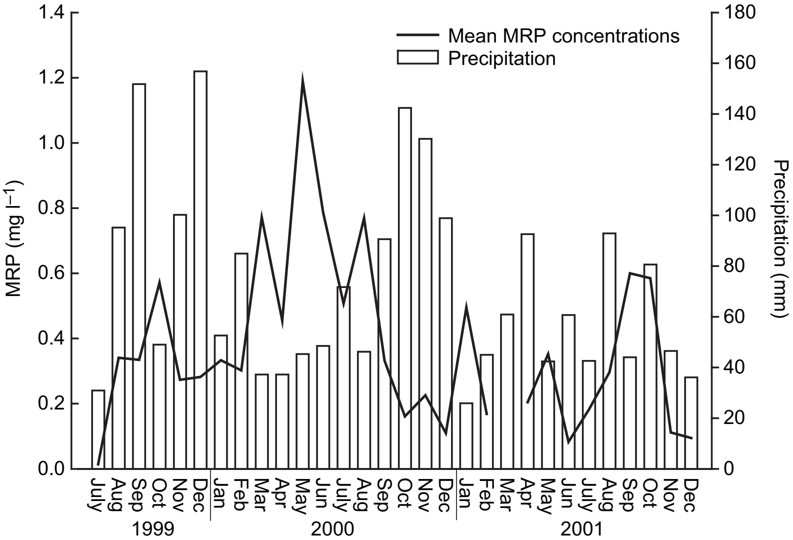


Fig. 6. Monthly means of MRP concentrations in Experiment 1 and monthly precipitations during the first 30 months following fertilization.

that dissolution can be hampered by limited moisture supply (Boland and Gilkes 1995) or sub-zero temperatures (Nieminen 1997), high precipitation following fertilization will promote the rapid removal of the released phosphate ions away from the surfaces of fertilizer particles. As the concentration of $H_2PO_4^-$ remains low, more fertilizer is being dissolved.

Following on this hypothesis, less P loss events should be recorded following the second application of fertilizer a couple of years after planting, assuming vegetation and tree biomass developed. In Experiment 2, peaks following the second application were much lower than after applying the same amount at planting (Fig. 5). In Experiment 1, MRP concentrations increased in a similar fashion (max 1.16 mg l^{-1}) as after initial fertilization (Fig. 4). In contrast with Experiment 1 which was slowly recolonised by vegetation and suffered high tree mortality, Experiment 2 cutaway site was colonized readily by willow, birch and sedge species, which together with good tree survival and growth, may have decreased surface runoff while at the same time increasing P uptake, in accordance with this hypothesis.

After the initial peak, P concentrations displayed temporal variations in a saw-tooth pattern. When examining monthly MRP concentrations in Experiment 1 against monthly precipitation for the area (Boora meteorological station, Bord na Móna), there was a general trend showing peak P concentrations in the surface runoff when precipitation was low (Fig. 6). This is in agreement with observations by Sallantaus (1983) and Kløve (2001) who reported a negative correlation between P concentrations and runoff in mined peatlands. P concentrations in leachates from a drained and fertilized raised peatland were also higher in summer in a study reported by Malcolm and Cuttle (1983).

Effects of cultivation (Experiment 1)

In Experiment 1, MRP concentrations during the pre-fertilization period were the same in both cultivated and non-cultivated plots (0.014 mg l^{-1}). High MRP concentrations (max 0.740 mg l^{-1}) were recorded immediately after fertilizer application in all uncultivated sampling points while MRP concentrations of similar magnitude (max 0.791 mg l^{-1}) occurred in the cultivated area a week later. Overall, while some higher MRP concentrations peaks were recorded in the untreated plot (Fig. 4), there was no significant difference ($p > 0.05$) between the two areas when the weekly means were analysed with repeated measures over time or as period-averaged means.

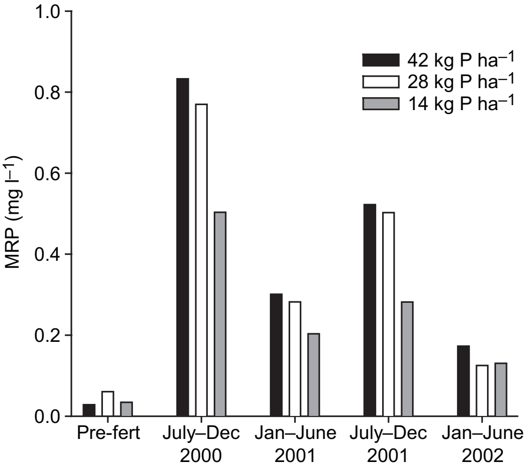


Fig. 7. Period-averaged Molybdate Reactive Phosphorus (MRP) concentrations in surface runoff water for each fertilizer rate treatment in Experiment 2.

Effects of fertilizer rates and methods of application (Experiment 2)

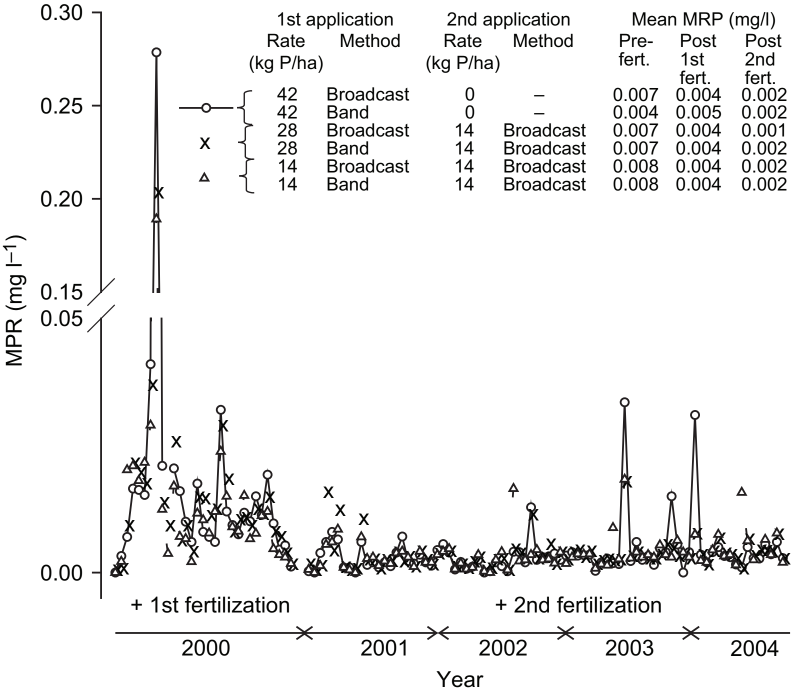
Peaks (Fig. 5) and means (Fig. 7) during the year and half following initial fertilization indicated that MRP concentrations were related to the rate of fertilizer applied and the method of application. P concentrations were significantly affected by the rate of application ($p = 0.023$) and the method of application ($p = 0.005$); the interaction between the two factors was not significant. Both maxima and period means recorded after initial fertilization were higher for broadcast application than for band application regardless of the rate applied (Fig. 5). Broadcast application may have favoured P dissolution (more scattered particles) and risk of transport of both dissolved P and fertilizer particles into the adjacent ditches. Since peat soils have low sorption capacity there is no advantage in broadcasting fertilizer for the purpose of increasing the bulk soil P to adequate levels. On the other hand, band application will increase P in specific zones around the trees thus maximizing the short-term P efficiency.

The rate of fertilizer also affected MRP concentrations in the surface runoff water. The highest P concentration (4.7 mg l^{-1}) was recorded with the highest rate of fertilizer and was twice as great as with the lowest rate (Fig. 5). Concentrations of this magnitude did not however re-occur during the four-year monitoring period. Cummins and Farrell (2003) reported a maximum P concentration of 2.3 mg l^{-1} in water collected from a drain in a replanted blanket peatland fertilized with 70 kg ha^{-1} P. An exceptional concentration of 4.9 mg l^{-1} was also found in the leachates four months after application of 50 kg ha^{-1} P of rock phosphate on a drained raised peatland (Malcolm and Cuttle 1983). Despite producing higher MRP concentration maxima, the higher-rate application had a mean P concentrations similar to that of the medium-rate application. In contrast, average MRP concentrations were reduced by almost 50% for the lower rate (Figs. 5 and 7).

What are the effects of rate of fertilizer and method of application on P concentrations in soil water on a mixed peat/sub-peat mineral soil matrix?

In Experiment 3, MRP concentrations measured in the soil water during the pre-fertilization period averaged 0.012 mg l^{-1} ranging from non-detectable to 0.049 mg l^{-1}. Mean MRP concentrations did not increase following the first or second fertilizer application (Fig. 8). MRP concentrations were not significantly different ($p > 0.05$) between the rates of fertilizer and the methods of application.

The retention of P in any soil matrix is closely connected with levels of Fe and Al oxides as well as calcium carbonate. In peat soils, any Al and Fe is tightly bound with the organic matter and reaction with P fertilizer is thus quite limited, allowing any added soluble P to remain mobile in the peat matrix. In Experiment 3, the presence of sub-peat calcareous soil within the soil matrix permitted the excess soluble P applied as superphosphate to be retained. Rannikko and Hartikainen (1980) found that liming *Sphagnum* peat significantly decreased the amount of fertilizer-P found in the water fraction. It is also likely that the increase of pH improved microbiological fixation, thus decreasing the amount of soluble P (Ghoshal and Jansson 1975). In Experiment 3, pH of the soil water averaged 7.3 before fertilization and increased to 7.7 at the end of the monitoring period. This is in contrast with values recorded in the soil water from the



	1st application Rate (kg P/ha)	1st application Method	2nd application Rate (kg P/ha)	2nd application Method	Mean MRP (mg/l) Pre-fert.	Mean MRP (mg/l) Post 1st fert.	Mean MRP (mg/l) Post 2nd fert.
○	42	Broadcast	0	–	0.007	0.004	0.002
	42	Band	0	–	0.004	0.005	0.002
×	28	Broadcast	14	Broadcast	0.007	0.004	0.001
	28	Band	14	Broadcast	0.007	0.004	0.002
△	14	Broadcast	14	Broadcast	0.008	0.004	0.002
	14	Band	14	Broadcast	0.008	0.004	0.002

Fig. 8. Soil water MRP concentrations during the 5-year study in Experiment 3. Inset: period-averaged concentrations for each treatment.

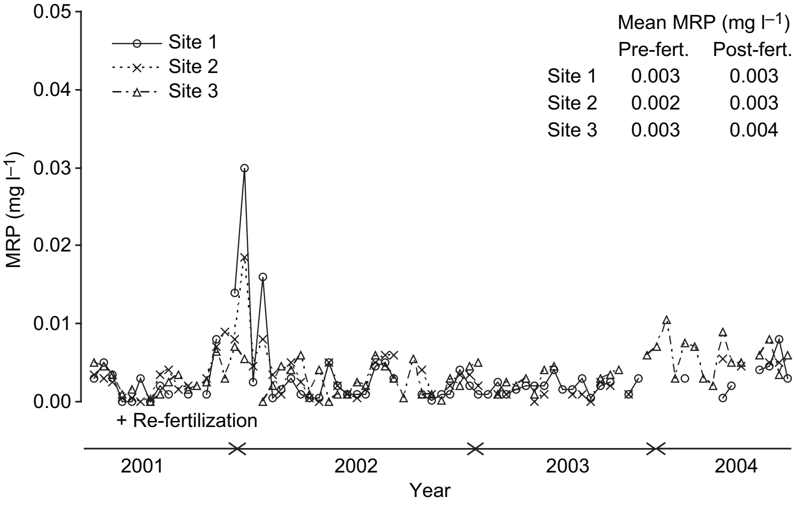
peat-only sites which ranged from 4.1 to 5.6 (data not shown).

The retention capacity of a peat/mineral soil matrix was limited however when water-soil interaction was minimized such as during high intensity rainfall events as observed during the week following initial application (Fig. 8). This phenomenon was captured because soil water included soil solution and water percolating through soil at a rate precluding the attainment of this equilibrium (Wolt 1994). Peaks were recorded only once and MRP concentrations returned to pre-fertilization levels the following week and remained below 0.05 mg l^{-1} for the remaining monitoring period regardless of the fertilizer rate and method of application.

What are the effects of initial fertilization on P concentrations in soil water ten years after fertilization on deep peat and does aerial re-fertilization increase loss of P?

The range of MRP concentrations measured in the soil water prior to re-fertilization was low at all sites (average 0.003 mg l^{-1}) (Fig. 9). This demonstrated that no P was being leached via soil water percolating below the root zone ten years after initial broadcast fertilization with rock phosphate. A chronological examination of the Sitka spruce needles at these three sites showed that the stands were P deficient between six and ten years after planting (Renou and Farrell 2007). The initial application of fertilizer had only a short term effect and following results from Experiments 1 and 2, loss of P from non cultivated deep peat cutaway sites may have occurred in the early years following initial fertilization.

During the four months following aerial re-fertilization, MRP concentrations did not increase in the soil water (Fig. 9). In two of the three monitored sites, small short-term peaks occurred in winter 2001, but remained below 0.030 mg l^{-1}. For the whole duration of the monitoring period, values remained comparable to pre-fertilization levels (average 0.003 mg l^{-1} ranging between non-detectable to 0.020 mg l^{-1}). The highest concentrations were recorded during winter 2003 which coincided with the fragmentation of *Campylopus introflexus*, the main ground species. This phenomenon is known to occur when the moss carpet reaches a certain thickness and also when fertilizer is applied (van



	Pre-fert.	Post-fert.
Site 1	0.003	0.003
Site 2	0.002	0.003
Site 3	0.003	0.004

Fig. 9. MRP concentrations measured in the soil water from three sites (Experiment 4). Inset: Averaged MRP concentrations at the three sites over the pre-fertilization period and post-fertilization period.

der Meulen *et al*. 1987). The following spring, the moss gave way to *Calluna vulgaris*, *Betula pubescens* and *Salix* spp.

Overall, MRP concentrations present in the soil water leaving the root zone of a deep peat Sitka spruce plantations were below 0.05 mg l^{-1}, ten years after initial application and aerial re-fertilization did not lead to significant increase of MRP concentrations in the soil water below the root zone.

What are the effects of initial fertilization on P concentrations in ditch water two years after fertilization within a deep cutaway peatland, as compared with those in ditch water in unfertilized areas?

In Experiment 1, the depth of water varied from ditch to ditch, and also depended greatly on rainfall. MRP concentrations measured in the grab samples across the site remained low throughout the monitoring period (Table 4) and did not significantly vary between the 'cultivated', 'uncultivated' and 'control' areas (p = 0.559). MRP concentrations remained below the 0.030 mg l^{-1} threshold for a good quality stream (Lucey *et al*. 1999).

While ditch water sampling did not occur necessarily just below a surface runoff collector, a comparison of the two water types during summer 2001 showed that MRP concentrations recorded in the surface runoff were several orders magnitude higher than in the ditches which acted as mini-catchments (Fig. 6 and Table 4). This confirms results from other studies carried out in post-harvested peatlands in Canada (Wind-Mulder *et al*. 1996) and in mined peatlands in Finland (Kløve 2001) where P concentrations in water from surface hollows and water level pipes were higher than in the ditches. It can be speculated that as surface runoff water enters the ditch, soluble P can be removed from the soil solution by several processes such as adsorption, precipitation, immobilization and biological uptake. The sorption to mineral surfaces (clay, Fe and Al oxides and Ca carbonate) is likely to occur due to the proximity of the sub-peat mineral soil

Table 4. Molybdate reactive phosphorus (MRP) concentrations (mg l^{-1}) in the ditch water and surface runoff collected during summer 2001 in Experiment 1.

	All drains	Cultivated area	Uncultivated area	Control
Ditch water				
Mean	0.006	0.005	0.006	0.006
SD	0.003	0.003	0.003	0.004
Min	0.001	0.001	0.001	0.001
Max	0.038	0.016	0.038	0.020
n	197	80	95	27
Surface runoff				
Mean		0.194	0.122	
SD		0.130	0.240	
n		18	16	

(sometimes exposed) at the bottom of the ditch. The average pH of the water samples collected from the twenty-five ditch locations over the eight-week period was 7.86. By comparison, the pH of surface runoff water entering the ditches averaged 5.8 over the whole site. Precipitation into secondary compounds (e.g. CaP) is likely to take place as well as immobilization into organic P (through microbial and humic substance). The presence of vegetation growing at the bottom of the drains (macrophytes such as *Eriophorum vaginatum*, *Typha latifolia*, *Betula pubescens* and microphytes including filamentous algae) is the proof that P input took place but plants can play an important role in removing soluble leached P via uptake. Silvan *et al*. (2004, 2005) found that vegetation of constructed wetland buffer assimilated effectively added P from throughflowing water. In addition, drain water from afforested cutaway peatland would be expected to be diluted with water from unfertilized parts of a catchment before reaching a substantial water body. The importance of each of these processes in retaining applied P in the cutaway ditches should be directly assessed in order to ascertain the fate of applied P to cutaway peatland.

Further remarks

It has been argued that MRP (extracted with ascorbic acid) may in fact be equal to total P in high organic matter content matrix. For example, Nieminen and Jarva (1996) found no difference between ICP-P (total P) and ascorbic acid P (MRP) from water samples where no organic matter was removed. It has also been argued that the really soluble reserves of P should be measured after filtration through 0.2 μm as P attached to colloidal particles may pass through the 0.5 μm filter and be hydrolysed to phosphate in ascorbic acid analysis (Yli-Halla *et al*. 1995, Hartikainen and Simojoki 1997). Thus MRP measured in this study may include the readily available, dissolved reactive P as well as P bound to dissolved organic matter which constitutes a longer-term reserve of lower availability (Ekholm 1994). The interaction between the particulate and dissolved P in the runoff is very dynamic and the mechanism of transport is complex. Therefore it is difficult to predict the transformation and ultimate fate of P as it moves through the landscape. In the snapshot study of drain water during the summer two years after fertilization, MRP concentrations were found to be low and comparable to unfertilized cutaway peatlands. MRP concentrations measured at the same time in surface runoff were several orders of magnitude higher. If a significant proportion of the leached P is held up in the drain network, ditches should be optimised to promote P retention. Improving channel capacity to retain P may include simply digging drains down to the coarse boulder till sub-peat mineral soil. This should also promote the colonization by plants and shrubs which, in the long-term, will lock up any P present in the ditches. The presence of silt pond (from previous peat harvesting activity) may act as a sink for suspended solids that may be removed following such site preparation.

Finally, it is clear that problems and solutions regarding P leaching on cutaway peatlands will be site specific and should be integrated into the silvicultural practices defined for these site types. Alternatives to 'normal' fertiliser application for this kind of site type exist and merit further investigation. (1) Applied fertilizer could be incorporated into the surface soil, away from the zone of immediate removal in surface runoff. (2) Trials in Irish nurseries have shown that the use of biostimulants may improve growth while reducing fertilizer requirements (Thompson 2004). (3) Although not allowed by the Irish Environmental Protection Agency, wood and peat ash application to peatlands has been encouraging in Scandinavian countries. Minor effects on streamwater P concentrations were recorded for the first five years following application of different ash fertilizer (Nilsson and Lundin 1996, Piirainen and Domisch 2004), but long-term monitoring is required since ash fertilizers have very slow dissolution rate (Nieminen *et al*. 2005). (4) The use of specially formulated fertilizer containing Fe and Al has shown to effectively reduce leaching from peat soils by increasing the adsorption of soluble MRP (Nieminen 2002).

As well as preventing the leaching process, there exists mitigating measures which would help controlling the excessive P in the water leaving an afforested cutaway peatland. A solution is to restore part of the cutaway peatlands or create a wetland and use it as biofilter. The restoration of drained peatlands has been shown to be a successful 'buffer' where the vegetation was the main factor in nutrient retention (Laine *et al*. 2004, Silvan *et al*. 2004, Silvan *et al*. 2005). However, a recent study showed that some restored Irish cutaway areas can have either strong or low nutrient barrier capacities depending on soil characteristics and the extent of re-vegetation (Higgins and Colleran 2004, 2006). Further research is required to develop appropriate protective measures to be adopted for local stream ecosystems and to determine the efficacy of these measures at both micro- and sub-catchment scale.

Conclusions

P loss from cutaway peat soils is a phenomenon closely related to soil properties. Fe, Al and Ca content are critical in binding applied P and low concentrations of these elements in peat are the most important factor predisposing peatlands to P loss. Results from this study confirmed that the occurrence and magnitude of P losses from afforested cutaway peatlands depends on edaphic characteristics, fertilization variables and transport factors such as surface runoff which is directly related to hydrological processes and climatic conditions.

P losses will occur when applying phosphatic fertilizer to peat soil unless edaphic properties are altered. Application of superphosphate in the current recommended practice (42 kg ha^{-1} P) did not affect the MRP concentrations of the soil water when the peat was mixed with sub-peat calcareous mineral soil. This provided the soil matrix with a strong P-binding ability. The same phenomenon can occur in the deep ditches which cut through the sub-peat mineral soil horizon. In conditions where surface runoff is limited, superphosphate and rock phosphate can thus be applied with minimal risk on peat mixed with calcareous subsoil which is the main type of subsoils present under cutaway peatlands in Ireland (Barry 1980).

Surface runoff was found to be a very important pathway for P loss. The risk of P loss from cutaway peatland is high after initial fertilization because of the cambered surface and the absence of vegetation cover. High precipitation following phosphatic fertilization inevitably enhances the physical movement of particles of fertilizer as well as its dissolution. This is more likely to occur in autumn, immediately after application. While the movement of particles of fertilizer into the nearby ditches was observed in this study, it has not been quantified. The use of cold storage plants has allowed the planting season to be extended, thus delaying the application of fertilizer. This practice runs the risk of inducing high P loss events because of low uptake due to a shorter growing season and poorer climatic conditions. The establishment of a vegetation cover would also be beneficial.

Fertilization variables, which can easily be controlled, can affect the magnitude of P leaching. On deep bare peat, rock phosphate should be applied at the lowest rate possible. In all cases, a split application of the fertilizer (at planting and 2 to 3 years later) would reduce the severe excess of soluble P during the initial years when MRP uptake is low and risk of erosion and runoff high. The implication of such management operations in the context of stand productivity is currently being investigated. For the same reasons, broadcast application is not recommended at planting.

Best practices to avoid high P concentrations events should include band or spot application of the lowest possible rate of fertilizer at planting followed by broadcast application of higher rates a couple of years later (as the roots have grown to explore larger ground surface). This is of course assuming that the site has been colonised by vegetation and that the trees are growing satisfactorily. In the event that vegetation is absent and trees are not growing satisfactorily (often in combination), fertilization should be abstained until the cause of such poor growth is ascertained.

Finally, a catchment study investigating all water pathways within the system should be initiated in order to ascertain the real magnitude of P loss following fertilization on cutaway peatland forestry.

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