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The impact of catchment conifer plantation forestry on the hydrochemistry of peatland lakes

T.J. Drinan *, C.T. Graham, J. O'Halloran, S.S.C. Harrison

School of Biological, Earth and Environmental Sciences, University College Cork, Distillery Fields, North Mall, Cork, Ireland

HIGHLIGHTS

► We investigated the impact of conifer plantation forestry on lake water chemistry.
► Elevated concentrations of P, N, Al and Fe and reduced dissolved oxygen in afforested lakes.
► We also investigated the stream run-off chemistry from a recently clearfelled site.
► Similar results recorded from the streams at the clearfell site — Glennamong.
► Clearfell has the greatest impact on the water quality of receiving surface waters.

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ABSTRACT

The hydrochemistry of 26 small blanket bog lakes was examined to assess the impact of conifer plantation forestry on lake water chemistry. Lakes were selected from three distinct catchment land use categories: i) unplanted blanket bog only present in the catchment, ii) mature (closed-canopy) conifer plantation forests only present in the catchment and iii) catchments containing mature conifer plantation forests with recently clearfelled areas. All three catchment land uses were replicated across two geologies: sedimentary (sandstone) and igneous (granite). Lakes with afforested catchments across both geologies had elevated concentrations of phosphorus (P), nitrogen (N), total dissolved organic carbon (TDOC), aluminium (Al) and iron (Fe), with the highest concentrations of each parameter recorded from lakes with catchment clearfelling. Dissolved oxygen was also significantly reduced in the afforested lakes, particularly the clearfell lakes. Analysis of runoff from a nearby recently clearfelled site revealed high biological and chemical oxygen demands, consistent with at least part of the elevated concentrations of TDOC emanating from clearfelled sites having higher biochemical lability. Inorganic fertilisers applied at the start of the forest cycle, the decay of the underlying peat soil and accumulated surface tree litter, and leachate from felled trees are the likely sources of the elevated concentrations of plant nutrients, TDOC, heavy metals and major ions, with excessive peat soil disturbance during clearfelling likely exacerbating the runoff into lakes. Our study has demonstrated a clear, deleterious impact of conifer plantations on the water quality draining from blanket bog catchments, with major implications for the management of afforested peatlands.

1. Introduction

Plantation forests currently cover approximately 10% of the Irish landscape, 80% of which is comprised of exotic conifers (NFI, 2007). Forest activities including afforestation, draining, thinning, clearfelling, reforestation and forest road construction, can result in severe alterations to major nutrient sinks and sources, increases in soil temperature and humidity, changes to soil structure caused by harvesting machinery, and increased fluxes of soluble and particulate matter from forested soils to receiving waters (Laiho et al., 1999; Bhatti et al., 2000; Saari et al., 2009; Zummo and Friedland, 2011). Waters draining catchments planted with conifer plantations have been found to have elevated concentrations of plant nutrients, heavy metals, both dissolved and particulate organic matter, major ions, as well as increased acidity (Kortelainen and Saukkonen, 1998; Binkley et al., 1999; Puhr et al., 2000; Neal et al., 2001, 2004a, 2004b; Vuorenmaa et al., 2002; Cummins and Farrell, 2003a, 2003b; Harriman et al., 2003; Feller, 2005; Ågren et al., 2010; Ågren and Löfgren, 2012).

Although the effect of forestry on lentic systems is less frequently studied than for lotic systems (Laird and Cumming, 2001; Northcote and Hartman, 2004), forestry practices can affect the chemical and ecological state of lakes by increasing catchment loadings of plant nutrients, major ions, humic substances and sediment (Rask et al., 1998;

* Corresponding author. Tel.: +353 87 756 0229; fax: +353 21 490 4664.
E-mail address: tomdrinan@gmail.com (T.J. Drinan).

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Carignan and Steedman, 2000; Carignan et al., 2000; Steedman, 2000; Watmough et al., 2003; Feller, 2005; Kreutzweiser et al., 2008). Elevated concentrations of these substances can persist for a long time in lakes and may lead to widespread and pervasive changes to lake ecosystems, in comparison to their impact in streams which may be reduced by overriding factors such as hydraulic disturbance and riparian shading. The few short-term studies of forestry impacts on lakes have reported increases in dissolved organic carbon (DOC), leading to modification of the euphotic depth (Rask et al., 1998; Carignan et al., 2000) and an increase in nutrient loads leading to higher primary production (Planas et al., 2000; Prepas et al., 2001).

Surface water acidification associated with conifer plantation forestry has received greater research effort in comparison to other issues concerning forest–surface water interactions (Nisbet, 2001). Canopy interception of airborne pollutants is deemed to be the main process by which forest plantations contribute to the acidification of surface waters; coniferous trees (especially the needles) are known to be more efficient at scavenging atmospheric pollutants, such as sulphur (S) and nitrogen (N) compounds, in comparison to non-forested sites (Reynolds et al., 1994). Increased scavenging of marine-derived ions, such as sodium (Na) and magnesium (Mg), can also result in acid runoff from plantation forests through the displacement of hydrogen (H^+) and aluminium (Al) cations within the soil, this generally termed the 'sea-salt effect' (Harriman et al., 2003; Hindar, 2005; Larssen and Holme, 2006). The acidification of streams draining afforested catchments, via the interception of both marine and non-marine derived acidifying compounds, has been widely documented throughout poorly-buffered catchments in Britain and Europe (Ormerod et al., 1989; Puhr et al., 2000; Ågren et al., 2010; Neal et al., 2010; Ågren and Löfgren, 2012).

Eutrophication of water bodies in Ireland has become more prevalent in recent years and is attributed mainly to diffuse nutrient runoff from agriculture (Toner et al., 2005). The ability of catchment soils to retain phosphorus (P), applied as fertiliser, is a major determinant of P loadings to receiving waters (Cummins and Farrell, 2003a). Many plantation forests in Ireland, predominantly monoculture stands of exotic conifers, have been planted on peat soil blanket bogs since the 1950s — peat soils being the dominant (42.1%) soil type upon which these forests have been established (NFI, 2007). Peat soils contain very low concentrations of iron (Fe) and aluminium (Al) oxides, and thus have a very low capacity to sorb and retain P (Cuttle, 1983). Any P fertiliser applied to forests on peat bogs may thus pose a high risk to receiving waters, particularly given their inherently nutrient poor status. Although occupying a much smaller surface area than agricultural lands in Ireland, plantation forestry may thus nevertheless pose a considerable risk to naturally oligotrophic aquatic systems (Cummins and Farrell, 2003a; McElarney et al., 2010; Rodgers et al., 2010).

The chemical effects of plantation forests on stream systems may be difficult to discern, due to the pulsed nature of forestry-derived inputs, these being concentrated at times of major disturbance such as planting, thinning and harvesting (Giller and O'Halloran, 2004). Stream-flow concentrations of plant nutrients and other materials are highly dependent on rainfall, which both flushes chemicals into streams and dilutes them, further adding to the difficulty of determining the scale of plantation forestry inputs. Dissolved and particulate substances tend to accumulate however, in downstream lakes, which act as nutrient sinks, due to their enhanced nutrient cycling and internal loading in comparison to streams (Søndergaard et al., 2003). Therefore, lakes may provide a more integrated assessment of catchment chemical influxes associated with forestry operations.

Although the rate of peatland afforestation has decreased considerably during the past two decades (Black et al., 2009), many of the previously planted blanket bog forests are now reaching harvestable age and concerns have been raised about the potential for plant nutrient and sediment loss to receiving surface waters (Kortelainen and Saukkonen, 1998; Ahtiainen and Huttunen, 1999). This study has two main objectives: i) to determine whether catchment forestry operation yields a similar hydrochemical response in lakes as has been described for running waters, and ii) to determine whether or not this hydrochemical change is predominantly acidification or eutrophication driven. Small (typically <2.5 ha) replicate lakes were selected in homogenous blanket bog catchments, with catchment land use restricted to either unplanted blanket bog or conifer plantation forestry, to ensure that any change in water chemistry could be unambiguously attributed to plantation forestry, rather than from other concurrent catchment inputs, particularly those from agricultural activity. The potential mitigating impact of underlying geology was examined by selecting lakes in sedimentary (sandstone) and igneous (granite) catchments. To further investigate potential differences in the biochemical lability of TDOC emanating from afforested catchments, water samples were collected from three separate streams from a nearby recently clearfelled site: i) a stream draining from the clearfelled site; ii) a stream draining from the mature plantation; and iii) a stream draining from nearby undisturbed blanket bog.

2. Materials and methods

2.1. Site description

2.1.1. Study lakes

Potential study lakes in areas of upland and lowland blanket bog throughout the west of Ireland were identified using ArcGIS (ESRI ArcMap v.9.3). Lakes were selected on the basis of size (all lakes but one were <4 ha), geology, soil type and catchment land use. The three distinct catchment land uses selected were: i) blanket bog (B): unplanted blanket bog only present in the catchment, ii) mature plantation (M): catchment dominated by closed-canopy conifer plantation forest only and iii) clearfell (C): catchment containing closed-canopy conifer plantation forest and recently clearfelled areas (within previous 2–5 years). A forestry database was provided by Coillte Teoranta, the Irish semi-state forestry body. Conifer plantation forests surrounding the lakes were dominated by sitka spruce (*Picea sitchensis* Bongard) with some lodgepole pine (*Pinus contorta* Douglas ex Louden) also present. Forestry operations were carried out to current Irish forestry best management practices (Forest Service, 2000). The plant species surrounding the undisturbed blanket bog lakes were typical blanket bog species (Fossitt, 2000). These included: purple moor-grass *Molinia caerulea* (Linnaeus); cross-leaved heath *Erica tetralix* Linnaeus; deergrass *Scirpus cespitosus* Linnaeus; common cottongrass *Eriophorum angustifolium* Roth; bog asphodel *Narthecium ossifragum* (Linnaeus) Hudson and white beak-sedge *Rhynchospora alba* (Linnaeus) Vahl.

A total of 26 lakes were selected following site visits: 13 lakes had catchments of unplanted blanket bog, seven lakes had catchments dominated by mature conifer plantation forests and no clearfelling and six lakes had catchments containing mature (closed-canopy) conifer plantation forests with recently clearfelled areas (Table 1). Lakes were situated in three different regions in the west of Ireland (Fig. 1). The 12 lakes in the south- and mid-west were underlain by sandstone (S) geology, whereas the 14 lakes in the west were underlain by granite geology (G). Lake area ranged from 0.5 to 5.5 ha (mean = 1.8 ha), mean depth ranged from 1.4 to 3.5 m (mean = 2.2 m) and catchment area ranged from 2.3 to 72.6 ha (mean = 21.8 ha).

2.1.2. Clearfell site — Glennamong

The Glennamong catchment (total area 685 ha) is situated some 50 km north of the western lakes (Fig. 1). The catchment is dominated by blanket bog which is underlain by quartzite and schist of low buffering capacity. Lodgepole pine comprised 86% of the tree crop and sitka spruce 13%. Clearfelling of an 8 ha coupe commenced at the site on the 8th February 2011, following current Irish forestry best management practices. Water samples were collected from three separate

Table 1
Geographic location, physical characteristics and catchment land use of the non-forested lakes. Blanket bog classification is based on Fossitt (2000) habitat classification scheme (S = sandstone, G = granite, B = blanket bog, M = mature plantation and C = clearfell).

Lake code	Latitude/Longitude	Altitude (m)	Lake area (ha)	Mean depth (m)	Catchment area (ha)	% Blanket bog	% Mature plantation	% Clearfell	Underlying geology	Blanket bog classification
SB1	N 51°58.953′ W 009°11.188′	426	1.6	1.6	2.3	100.0	0.0	0.0	Green-grey sandstone & purple siltstone	Upland
SB2	N 51°58.960′ W 009°10.916′	429	2.2	2.2	17.6	100.0	0.0	0.0	Green-grey sandstone & purple siltstone	Upland
SB3	N 53°04.899′ W 008°40.568′	282	0.9	2.5	10.0	100.0	0.0	0.0	Mudstone, siltstone, conglomerate	Upland
SB4	N 53°03.747′ W 008°28.646′	183	1.2	1.5	10.0	100.0	0.0	0.0	Mudstone, siltstone, conglomerate	Upland
SB5	N 52°56.533′ W 008°43.845′	273	0.5	2.1	11.6	100.0	0.0	0.0	Mudstone, siltstone, conglomerate	Upland
SB6	N 52°56.770′ W 008°43.710′	262	1.4	1.6	11.5	100.0	0.0	0.0	Mudstone, siltstone, conglomerate	Upland
GB1	N 53°19.239′ W 009°25.840′	93	1.2	2.4	12.2	100.0	0.0	0.0	Aphyric fine grained granite	Lowland
GB2	N 53°18.354′ W 009°26.926′	108	1.0	1.4	5.3	100.0	0.0	0.0	Aphyric fine grained granite	Lowland
GB3	N 53°18.210′ W 009°26.981′	100	1.2	2.3	15.7	100.0	0.0	0.0	Aphyric fine grained granite	Lowland
GB4	N 53°18.511′ W 009°27.485′	80	1.2	3.1	52.7	100.0	0.0	0.0	Monzogranite, small megacrysts	Lowland
GB5	N 50°18.508′ W 009°27.379′	86	0.5	2.3	5.2	100.0	0.0	0.0	Monzogranite, small megacrysts	Lowland
GB6	N 50°17.207′ W 009°21.697′	73	4.0	2.5	72.6	100.0	0.0	0.0	Monzogranite, mafic, megacrystic	Lowland
GB7	N 50°17.232′ W 009°21.436′	77	1.4	1.8	6.8	100.0	0.0	0.0	Monzogranite, mafic, megacrystic	Lowland
SM1	N 51°59.242′ W 009°14.428′	366	1.2	2.2	13.8	6.9	93.1	0.0	Green sandstone & purple siltstone	Upland
SM2	N 51°58.982′ W 009°14.125′	373	0.9	1.6	20.2	0.8	99.2	0.0	Green sandstone & purple siltstone	Upland
SM3	N 51°58.591′ W 009°12.555′	383	2.1	1.9	29.1	12.3	87.7	0.0	Green sandstone & purple siltstone	Upland
GM1	N 53°19.340′ W 009°24.141′	114	3.5	2.8	33.2	3.0	97.0	0.0	Aphyric fine grained granite	Lowland
GM2	N 53°22.108′ W 009°23.130′	150	4.0	2.8	32.2	1.6	98.4	0.0	Monzogranite, mafic, megacrystic	Upland
GM3	N 53°22.740′ W 009°23.529′	233	1.0	2.3	9.3	2.2	97.8	0.0	Monzogranite, mafic, megacrystic	Upland
GM4	N 53°23.398′ W 009°23.165′	239	1.1	2.1	35.3	2.4	97.6	0.0	Monzogranite, mafic, megacrystic	Upland
SC1	N 53°02.562′ W 008°34.388′	185	2.5	1.6	25.0	0.0	67.1	32.9	Mudstone, siltstone, conglomerate	Upland
SC2	N 53°01.446′ W 008°37.110′	122	1.4	1.9	16.7	16.7	51.9	31.4	Mudstone, siltstone, conglomerate	Lowland
SC3	N 52°57.372′ W 008°44.332′	291	5.5	2.9	43.1	0.0	87.3	12.7	Mudstone, siltstone, conglomerate	Upland
GC1	N 53°20.912′ W 009°19.059′	75	2.7	1.7	42.5	0.0	85.0	15.0	Monzogranite, mafic, megacrystic	Lowland
GC2	N 53°20.064′ W 009°20.572′	85	2.2	1.8	30.0	2.2	65.0	32.9	Monzogranite, mafic, megacrystic	Lowland
GC3	N 53°20.020′ W 009°20.507′	86	1.1	3.5	3.7	9.4	12.1	78.6	Monzogranite, mafic, megacrystic	Lowland

streams on site: i) a stream draining from the clearfelled site; ii) a stream draining from the mature plantation; and iii) a stream draining from nearby undisturbed blanket bog.

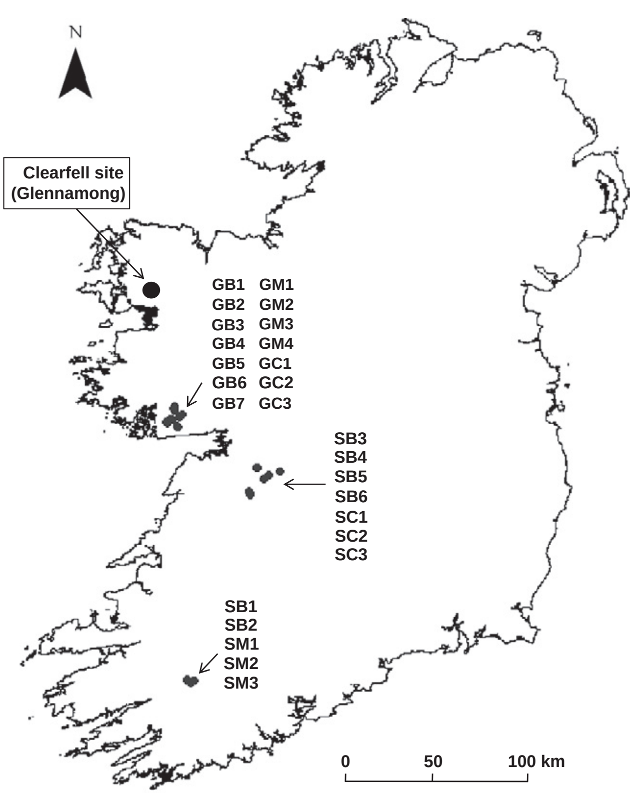

Fig. 1. Map of Ireland showing the location of the 26 study lakes and the clearfell study site — Glennamong (S = sandstone, G = granite, B = blanket bog, M = mature plantation and C = clearfell).

2.2. Water chemistry sampling

2.2.1. Lake samples

Water samples were taken from the littoral zone of each lake at a similar depth and distance from shore, bimonthly for 12 months, beginning in March 2009. Water samples were collected in acid-washed polypropylene bottles, stored at 4 °C in a cooler box and transported to the laboratory for analysis within 24 h after collection. Conductivity, dissolved oxygen and temperature were measured on site using WTW portable meters.

A total of 19 water chemistry parameters were analysed. pH was determined using a WTW pH meter (pH330i) following 2-point calibration with WTW technical buffer solutions (4.01 and 7.00). Alkalinity was measured by Gran titration (Mackereth et al., 1989). Colour was determined by the manual colorimetric method, using diluted HACH colour standards for calibration (Eaton et al., 2005). Total dissolved organic carbon (TDOC) was determined using Shimadzu Total Organic Carbon Analyzer. Ammonia was determined by automated Lachat Quik-Chem 8000 FIA on 0.45 μm-filtered samples (salicylate method QuikChem Method 10-107-06-3-D). Soluble reactive phosphorus (SRP) was determined using the automated Lachat Quik-Chem 8000 FIA on 0.45 μm-filtered samples (QuikChem Method 10-115-01-1-B), based on Murphy and Riley (1962). Total oxidised nitrogen (TON) was determined by automated Lachat Quik-Chem 8000 FIA with copper-amalgamated cadmium column for reduction to nitrite followed by colorimetric detection (QuikChem Method 10-107-04-1-C). Total phosphorus (TP) was determined using the molybdate-ascorbic acid method (Murphy and Riley, 1962), following digestion of the unfiltered sample with persulphate and sulphuric acid. Total nitrogen (TN) was determined using the automated Lachat Quik-Chem 8000 FIA method (QuikChem Method 10-107-04-1-C) following persulphate oxidation of unfiltered sample with potassium persulphate and boric acid (Grasshoff et al., 1983). Sodium (Na), magnesium (Mg), chloride (Cl) and sulphate (SO_4) were determined by Ion Chromatography (QuikChem Method 10-501-00-1-A/C). Potassium (K), calcium (Ca) and iron (Fe) were determined by the AA flame method. Manganese (Mn) and total monomeric aluminium (tot.Al) (i.e. filtered at 45 μm) were determined by the AA furnace method. Chlorophyll *a* was determined by the manual colorimetric method after extraction with methanol (HMSO, 1983).

2.2.2. Clearfell site samples — Glennamong

Dip samples were collected from the three streams from the Glennamong site on a single occasion on the 5th May 2011. Samples were taken and stored in the same manner as lake samples. Three parameters were analysed for streams from the Glennamong site. Biological oxygen demand (BOD) was measured using a standard five-day test method. Dissolved oxygen of thoroughly mixed samples was measured using a calibrated WTW dissolved oxygen metre before and after five days of incubation at 20 °C in the dark. BOD was calculated as the difference between the initial and final dissolved oxygen concentrations. Chemical oxygen demand (COD) was measured using closed reflux colourimetric method. Hach COD vials (0–150 mg O_2/l) and Reagcon COD vials (0–1500 mg O_2/l) were used. Calibration was carried out using potassium hydrogen phthalate standards. TDOC was analysed as per the lake samples.

2.3. Statistical analyses

Principal component analysis (PCA) analysis was performed, using PRIMER 6, to determine patterns in lake water chemistry. The ordinations were based on a Euclidean distance matrix derived from a normalised and log (x + y) transformed data set, y = smallest non-zero value in the data set, water chemistry data.

Analysis of variance (ANOVA) was performed, using PASW Statistic 17, to test for significant between-lake differences in chemical variables with respect to catchment land use (blanket bog, mature plantation and clearfell) and geology (sandstone and granite). Using a Bonferroni correction for multiple tests (Sokal and Rohlf, 1995), significance criteria were set at a conservative $p < (0.05/22)$. Prior to performing ANOVAs, normality and homogeneity of variances were tested using Kolmogorov–Smirnov and Levene's tests, respectively. The ANOVA models, with Bonferroni correction applied, were calculated on the basis of Type III sums of squares to take the unbalanced design into account. Significant results were tested for pair-wise comparisons using Bonferroni *post-hoc* tests. Dependent variables were transformed where necessary to fulfil the requirements of the parametric tests. Pearson correlation analyses were carried out, using PASW Statistic 17, to explore relationships within the water chemistry data from the lakes.

3. Results

3.1. Lake water chemistry

3.1.1. Principal component analysis — sandstone lakes

PCA revealed a strong effect of plantation forestry on sandstone lake water chemistry, with clearfell lakes, and to a lesser extent mature plantation lakes, being chemically distinct from the non-forested blanket bog lakes (Fig. 2). PC axis 1 accounted for 42.4% of the total variance in the water chemistry variables. PC axis 2 and PC axis 3 accounted for 16.2% and 11.2% of the total variance, respectively.

Clearfell lakes scored negatively on PC axis 1, and were associated with elevated concentrations of TP, SRP, TN, ammonia, chlorophyll *a*, TDOC, total monomeric Al, Fe, Mn and major ions, higher colour and conductivity, and lower dissolved oxygen concentrations (Fig. 2). PC axis 2 represented pH, alkalinity, temperature, SO_4, and K; however, this axis did not differentiate between lakes of contrasting catchment land use (Fig. 2).

3.1.2. Principal component analysis — granite lakes

As for the sandstone lakes, PCA of the granite lakes revealed a strong effect of plantation forestry on lake water chemistry (Fig. 3).

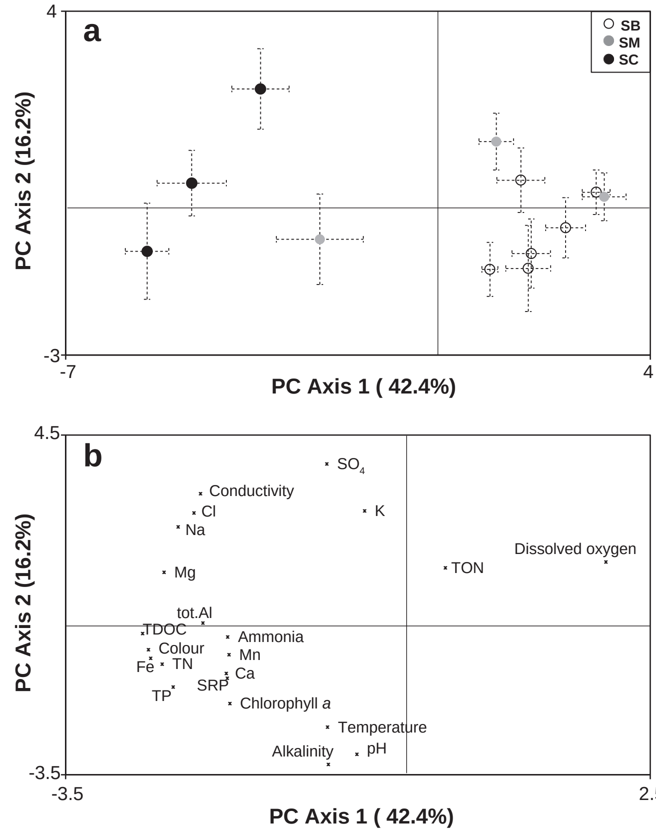

Fig. 2. Principal component analysis (PCA) ordinations indicating a) the variation in chemical status of the sandstone lakes and b) the variable loadings of the chemical variables on PC axis 1 and PC axis 2. Group centroids represent the mean lake scores (± 1 S.E.) over the over the 12 month sampling period (S = sandstone, B = blanket bog, M = mature plantation and C = clearfell).

PC axis 1 accounted for 30.3% of the total variance in the water chemistry variables. PC axis 2 and PC axis 3 accounted for 24.1% and 12.8% of the total variance, respectively.

Clearfell and mature plantation lakes tended to score negatively on PC axis 1, and were associated with elevated concentrations of TP, SRP, TN, ammonia, TDOC, total monomeric Al, Fe, Mn, higher colour and lower dissolved oxygen concentrations (Fig. 3). PC axis 2 largely represented major ions and conductivity. Unlike the hydrochemistry pattern for sandstone lakes, forestry operations in the granite catchments were much less associated with elevated major ions (Na, Cl, Mg and SO_4) and conductivity, which were more associated with non-forested blanket bog lakes (Fig. 3). As with the sandstone lakes, pH, alkalinity and TON did not separate the non-forested from the forestry-effected lakes.

3.2. Univariate analysis of lake water chemistry

Univariate analysis of water chemical parameters revealed significant differences between lakes with respect to catchment land use and geology (Fig. 4; Table 2). The forestry-effected lakes had significantly higher TDOC, TP, K, total monomeric Al and Fe concentrations, increased colour and lower dissolved oxygen concentrations in comparison to the unplanted blanket bog lakes (Fig. 4; Table 2). Clearfell lakes also had significantly higher concentrations of TDOC and Fe, increased colour and lower concentrations of dissolved oxygen than mature plantation lakes (Fig. 4; Table 2). K concentrations were significantly lower only in the mature plantation lakes (Fig. 4; Table 2). With

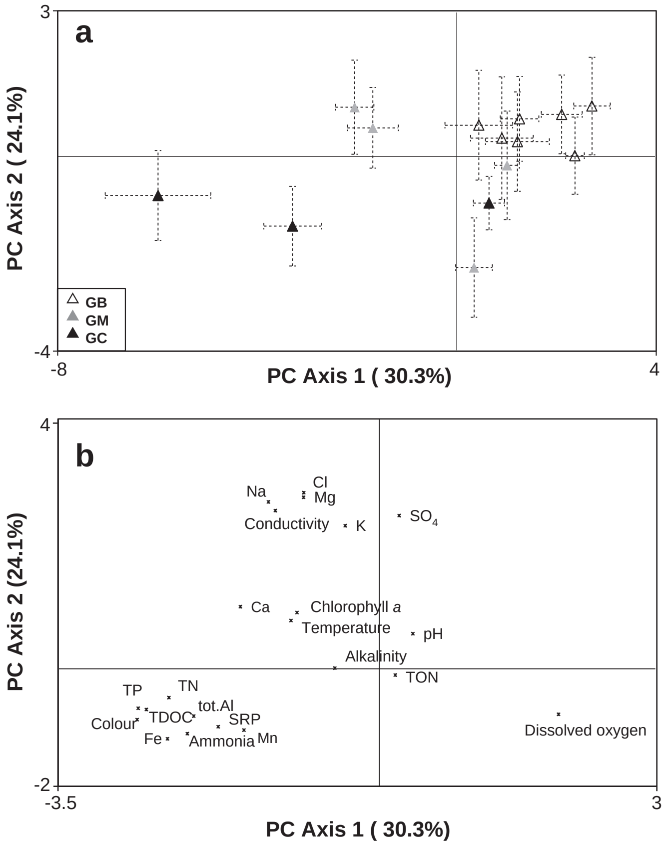

Fig. 3. Principal component analysis (PCA) ordinations indicating a) the variation in chemical status of the granite lakes and b) the variable loadings of the chemical variables on PC axis 1 and PC axis 2. Group centroids represent the mean lake scores (±1 S.E.) over the over the 12 month sampling period (G = granite, B = blanket bog, M = mature plantation and C = clearfell).

respect to geology, the lakes underlain by granite geology had significantly higher marine ion concentrations, as well as higher conductivity and temperature values (Fig. 4; Table 2). A significant interaction between catchment land use and geology occurred for SO_4, Cl and Mg, with higher concentrations in sandstone clearfelled lakes but lower concentrations in granite clearfelled lakes (Fig. 4; Table 2). The differences in lake pH, alkalinity, chlorophyll *a*, SRP, TN, TON, ammonia, Ca and Mn concentrations across catchment land use and geology were not significant (Fig. 4; Table 2).

Correlation analysis revealed strong linkages between individual hydrochemical parameters within lakes (Table 3). TDOC and colour were both strongly positively correlated with TP, SRP, TN, ammonia, total monomeric Al, Mn and Fe. TP was also strongly correlated with Fe and TDOC (Fig. 5; Table 3). The strong positive correlation of Cl with Na, Mg, SO_4, indicates that these ions were mainly of marine origin, assuming Cl is entirely marine-derived and unreactive within the catchment (Evans et al., 2001). Although strongly correlated with alkalinity, pH did not show any other significant correlations with SO_4, marine-derived ions, TDOC or TON (Table 3).

To assess trophic state of lakes in Ireland at present, the maximum chlorophyll *a* concentration recorded during the summer and autumn months is preferred to TP concentrations as there is no requirement for a minimum number of samples (McGarrigle et al., 2010). Under this modified Environmental Protection Agency (EPA) version of the Organisation for Economic Cooperation and Development (OECD) scheme for lake trophic classification, nine of the thirteen blanket bog lakes, four of the mature plantation and only one of the clearfell lakes were classified as oligotrophic. The two most trophically enriched lakes were both afforested: SC2 was hypereutrophic and SM2 was strongly eutrophic (Table 4).

3.3. Glennamong clearfell site water chemistry

TDOC concentrations were highest in runoff from the clearfelled site and lowest in runoff from the blanket bog (Fig. 6). The BOD and COD of runoff water from the clearfell catchment were also strongly elevated, the BOD exceeding guideline concentrations for good status under the European Communities Environmental Objectives (Surface Waters) Regulations 2009 (Fig. 6).

4. Discussion

Forestry impacts on receiving waters are complex and depend strongly on local and regional catchment and atmospheric factors (Tetzlaff et al., 2007). Much attention over the past decades has focused on the potential impact of forestry on the acidification of running waters (Ormerod et al., 1989; Puhr et al., 2000; Harriman et al., 2003; Ågren et al., 2010; Neal et al., 2010; Ågren and Löfgren, 2012). Recent reductions in acid episodes in streams draining forested catchments have been linked to reductions in atmospheric S emissions (Malcolm et al., in press). Others studies, however, have shown that forestry-associated acidification is still occurring despite these reductions (Kowalik and Ormerod, 2006; Ormerod and Durance, 2009). Nutrient loadings to receiving waters as a result of forestry operations have received less attention in comparison, although forestry practices, particularly clearfelling, have been shown to lead to enhanced levels of P, N and C leaching to receiving waters (Kortelainen and Saukkonen, 1998; Cummins and Farrell, 2003a, 2003b; Feller, 2005; Kortelainen et al., 2006; Kreutzweiser et al., 2008; Rodgers et al., 2010). The net chemical impact of forestry on receiving waters will be greatly influenced by catchment characteristics (slope, soil type, location, altitude and latitude), regional rainfall patterns and the nature of forestry operations themselves. The impacts of forestry on hydrochemistry will also tend to differ between streams and lakes: streams will be affected more by rainfall-driven effluxes of substances from forests, whereas lakes will tend to demonstrate a more temporally integrated pattern of water chemistry. The results of this study reveal several clear patterns of lake hydrochemistry with respect to forestry. Firstly, catchment forestry operations were associated with elevated concentrations of plant nutrients, heavy metals (Al, Fe and Mn) and TDOC. This effect was seen most strongly for clearfelling, but was also apparent for mature forest plantations. Secondly, despite the strong hydrochemical effect of forestry, particularly Al concentrations, there was little discernible effect on the pH of lakes. Thirdly, concentrations of marine-derived ions – Na, Cl and Mg – were elevated in forestry-impacted lakes in sandstone catchments but reduced in forestry-impacted lakes in coastal granite catchments. Finally, concentrations of dissolved oxygen were markedly reduced in forestry-impacted lakes, particularly those associated with clearfelling.

4.1. Plant nutrients

The potential source of the plantation-derived plant nutrients include: i) fertilisers applied to the forest crop during the forest cycle (Foy and Bailey-Watts, 1998), ii) decomposition/mineralization of the underlying peat soil and clearfell residues (Sundström et al., 2000; Piirainen et al., 2004) and iii) increased atmospheric deposition via enhanced scavenging (Miller et al., 1996). Different nutrients can come from distinct sources. For example, P in water draining afforested peat catchments is mainly derived from the application of fertilisers to the tree crop (Cummins and Farrell, 2003a), whilst the source of leached N is predominantly from the peat soil itself, through mineralization of soil organic matter (Nieminen, 1998, 2003).

In Ireland, P is the main nutrient fertiliser applied (as rock phosphate), with N (urea) and K (muriate of potash) occasionally applied as remedial fertilisers (Forest Service, 2000). Although current fertilisation rates are being reduced in Ireland, fertilisation rates of >50 kg P ha^{-1} have previously been applied (Dickson and Savill, 1974). Although this anthropogenic input is generally considered low in comparison to most agricultural systems, the potential impact to receiving waters on peatland are exacerbated due to blanket peats having a very low capacity to sorb P (Malcolm et al., 1977). Fertiliser-induced leaching of P from peatlands drained for plantation forestry has been the focus of a range of studies in Ireland and Scandinavia, in recognition of the potential environmental damage of excess plant nutrients on the ecological status of aquatic ecosystems (Nieminen and Ahti, 1993; Nieminen and Jarva, 1996; Cummins and Farrell, 2003a). Although the majority of applied P is assumed to be quickly sequestered by the trees, elevated P concentrations in runoff, associated with fertilisation, are evident for up to 10 years post-fertilisation (Kenttämies, 1981).

Application of P fertilisers has also been demonstrated to stimulate the release of N and K through enhanced decomposition of the peat soil (Malcolm et al., 1977). After N (urea) fertilisation, hydrolysis is rapid and this can lead to rapid runoff of ammonia to receiving waters. Oxidation of ammonia may also lead to the leaching of nitrate from the forest floor when conditions amenable to nitrification are present. For the study lakes however, given the saturated and acidic character of the peat soil, it seems likely that sub-optimal conditions for nitrification on the peat surface may have given rise to elevated concentrations of ammonia rather than TON being leached.

The loss of soil N from conifer plantations on peat soils to surface waters is strongly regulated by rates of soil N mineralization and immobilisation. Although peat soils are recognised as being nutrient-

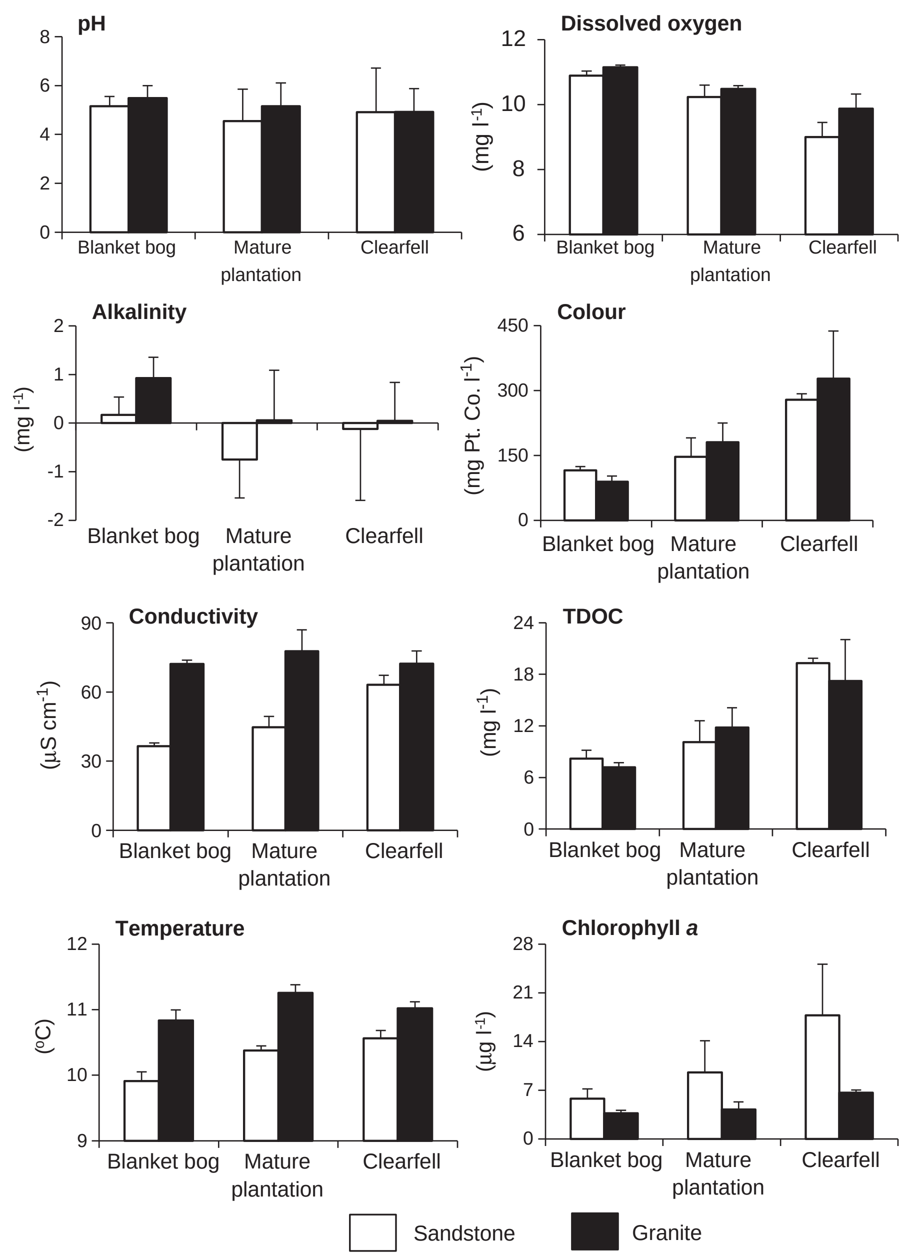

Fig. 4. Mean ± 1 S.E. (pH = median ± 95% C.I.) values/concentrations of hydrochemical parameters for lakes in *each* catchment land use across both geologies (n: *SB* = 6, *GB* = 7, *SM* = 3, *GM* = 4, *SC* = 3 and *GC* = 3). Mean ± 1 S.E. concentrations of hydrochemical parameters for lakes in *each* catchment land use across both geologies (n: *SB* = 6, *GB* = 7, *SM* = 3, *GM* = 4, *SC* = 3 and *GC* = 3). Mean ± 1 S.E. concentrations of hydrochemical parameters for lakes in *each* catchment land use across both geologies (n: *SB* = 6, *GB* = 7, *SM* = 3, *GM* = 4, *SC* = 3 and *GC* = 3).

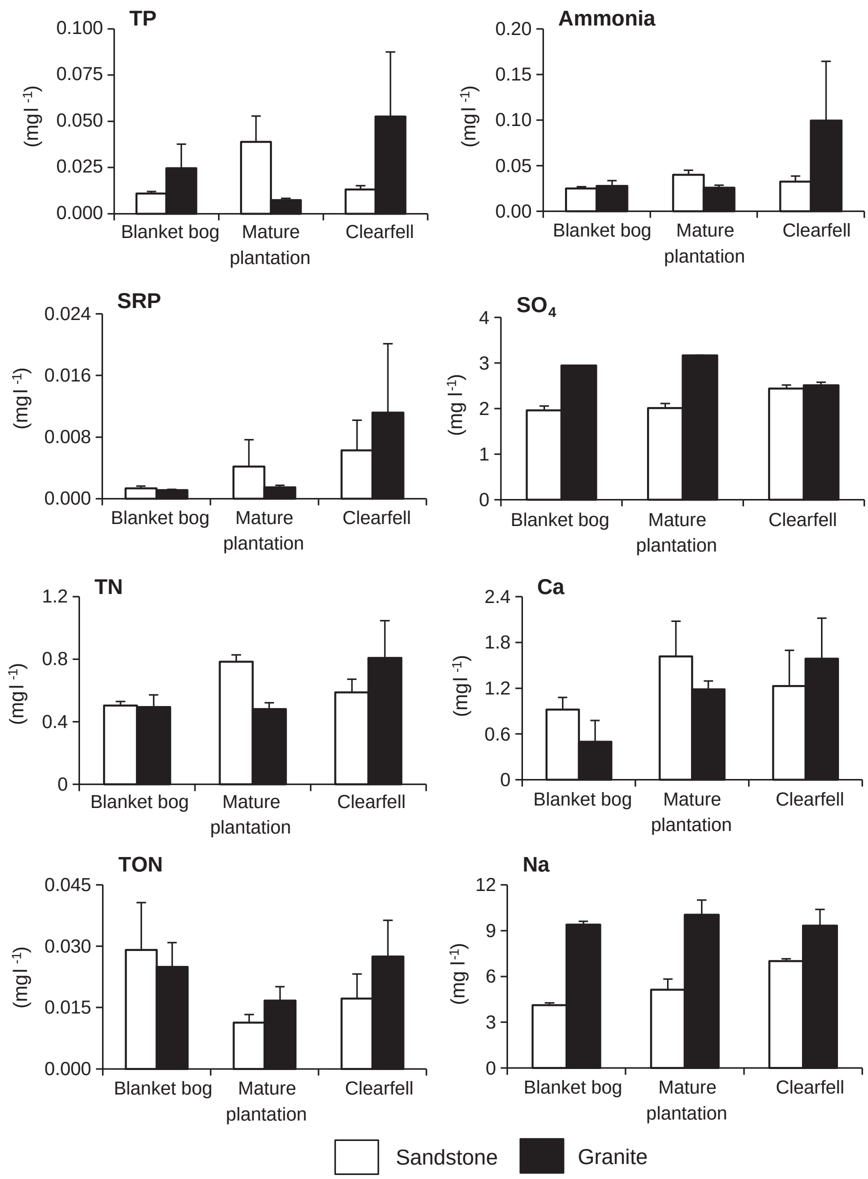

Fig. 4 (*continued*).

deficient, the top metre of deep organic soils can contain relatively large quantities of elements such as N, S, P and C (Miller et al., 1996). Mineralization–immobilisation responses of soil N are dependent upon environmental factors (temperature, redox potential and pH) and substrate factors (stage of decomposition, organic matter quality, nutrient content, chemistry of the soil solution and the presence of chemical and biological inhibitors to microbial activity), many of which are altered following forestry drainage and clearfell operations (Holden et al., 2004). The lowering of the water table during forest drainage of peat soils leads to an increase in the air-filled porosity of the peat which stimulates aerobic decomposition rates (Clymo, 1983). Subsequently, this enhances the mineralization of nutrients (Holden et al., 2004), resulting in the increased leaching of nutrients that were previously immobilised within partly decomposed plants (Laiho and Laine, 1994). This has been previously demonstrated in both Finland (Laiho et al., 1999) and Sweden (Sundström et al., 2000), where elevated P and N concentrations were recorded from the upper soil layers following forest drainage.

The decomposition of clearfell residues is another major source of leached plant nutrients, TDOC and major ions being received by the clearfell lakes (Laskowski et al., 1995; Qualls et al., 2000; Finér et al., 2003; Palviainen et al., 2004a, 2004b; Piirainen et al., 2004). Fine clearfell residues, such as foliage, fine roots and small branches, are the probable source of leached nutrients soon after clearfelling because they are the most nutrient-rich parts of the trees, and they decompose faster than coarse residues; stumps, coarse roots and branches (Hyvönen et al., 2000; Palviainen et al., 2004b). Consequently, it can take several years or even decades for nutrients to be released from coarse clearfell residues (Laiho and Prescott, 1999). Although our data is limited to lake water chemistry, it is likely that changes in soil temperature and moisture conditions, coupled with the increased mechanical disturbance from the harvesting machinery, led to an enhanced decomposition of these residues post-clearfell in the clearfell lake catchments.

K concentrations were significantly lower in the mature plantation lakes and were only slightly higher than undisturbed levels in the clearfell lakes. This suggests that a significant proportion of the potential K pool of a site may be bound in tree matter during the growing phase and subsequently released during the decomposition of clearfell residues and tree stumps post-clearfell. K release from clearfell residues can be considerable (Palviainen et al., 2004a; Piirainen et al., 2004).

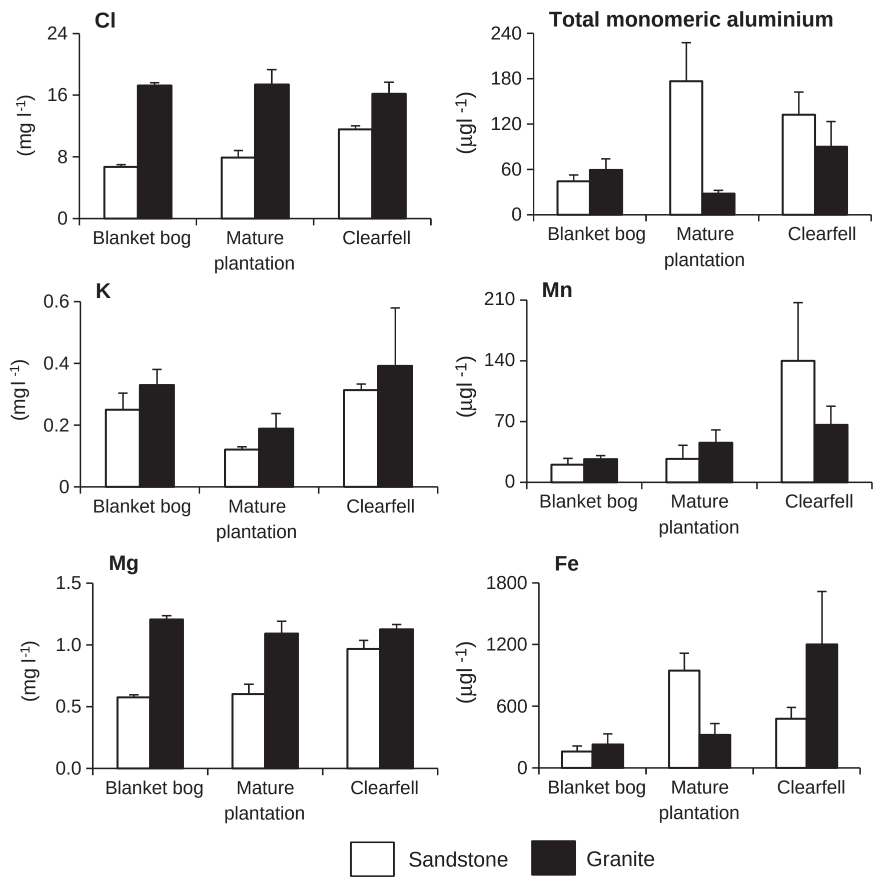

Fig. 4 (*continued*).

Given the location of all the study lakes in the west of Ireland, coupled with the fact that Ireland receives less atmospheric pollution than most other European countries (Aherne and Farrell, 2002), the potential input of plant nutrients from atmospheric deposition seems negligible.

4.2. TDOC

Concentrations of TDOC in the mature plantation and clearfell lakes were strongly associated with plant nutrients and heavy metals suggesting that the source and release mechanisms responsible are similar. Kortelainen et al. (2006) have demonstrated that TOC export accounted for as much as 95% of the variance in TON export, and 61–73% of the variance in ammonia, Fe and TP export from peatland catchments. Similarly, Kreutzweiser et al. (2008) suggested that the hydrological and biogeochemical processes that increase DOC fluxes from clearfelled catchments can increase the export of P. Previous studies have demonstrated similar results of increased DOC fluxes as a result of forestry operations, especially clearfelling, on peatlands (Nieminen, 2004; O'Driscoll et al., 2006; Piirainen et al., 2007; Saari et al., 2009).

There are three potential sources of the leached TDOC being received by the mature plantation and clearfell lakes: the decomposition of clearfell residues (Qualls et al., 2000); canopy leachate from living trees and litterfall during the mature forest stage (Qualls et al., 1991; Fröberg et al., 2007); and the decomposition of the organic matter within the Oe (moderately decomposed [hemic]) and Oa (highly decomposed [sapric]) horizons of the forest peat soil (Michalzik et al., 2001; Park and Matzner, 2003).

DOC in freshwaters is often categorised with respect to bacterial degradability into labile (L-DOC) and refractory (R-DOC) fractions. It is has been suggested that DOC leached from plant tissues is more labile in nature than that leached from forest soils (Qualls and Haines, 1992). Kalbitz et al. (2003), investigating the biodegradation of DOM of different origins, showed that 56.9% of the DOC present within a spruce forest litter layer was labile in nature, and that this L-DOC is rapidly mineralized, having a half-life of only about 3 days. In a similar study by Qualls and Haines (1992), the most biodegradable DOC was recorded from throughfall and from the Oi (litter layer) horizon, and that 33% of the litter DOC was degraded after 134 days. Although the TDOC within the study lakes was not categorised, the high BOD and COD of water draining from the clearfell site in Glennamong suggests that a considerable quantity of labile TDOC draining off the site is derived from clearfell residues.

4.3. Heavy metals

The source(s) of the elevated heavy metal concentrations within the mature plantation and clearfell lakes are likely to be somewhat similar to those of the elevated TDOC concentrations. Palviainen et al. (2004a) demonstrated that fine roots of logged trees can release large amounts of Fe and Al soon after clearfelling. Cummins and Farrell (2003b) similarly showed an increase in Al concentrations, in conjunction with elevated DOC, from a clearfelled area of a blanket peatland forest in Ireland. Forestry drainage of peatland can also release substantial quantities of Fe and Al (Joensuu et al., 2002).

The co-leaching of TDOC and heavy metals has been previously shown for peatland forestry operations in Finland (Kortelainen and Saukkonen, 1998; Joensuu et al., 2001), Canada (Dillon and Molot, 1997) and Scotland (Grieve and Marsden, 2001). It is widely recognised that the complexation between heavy metals and DOC controls the speciation, toxicity, bioavailability and ultimate fate of metals (Bidoglio and Stumm, 1994). The close association of TDOC, TP and Fe in our study

Table 2
Summary of 2-way Bonferroni corrected ANOVAs of water chemical parameters (mean annual values calculated over the 12 month sampling period), with catchment land use (blanket bog, mature plantation and clearfell) and geology (sandstone and granite) as main factors. Any two catchment land uses sharing a common letter are not significantly different.

	2-way ANOVA				*Post-hoc* Bonferroni tests		
		d.f.	*F*	*p*	Blanket bog	Mature plantation	Clearfell
pH	Land use	2, 20	2.045	0.156	–	–	–
	Geology	1, 20	2.034	0.169	–	–	–
	Interaction	2, 20	0.166	0.848	–	–	–
Alkalinity	Land use	2, 20	0.795	0.465	–	–	–
	Geology	1, 20	1.322	0.264	–	–	–
	Interaction	2, 20	0.009	0.991	–	–	–
Conductivity	Land use	2, 20	6.832	0.005	–	–	–
	Geology	1, 20	58.299	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	6.854	0.005	–	–	–
Temperature	Land use	2, 20	5.941	0.009	–	–	–
	Geology	1, 20	30.008	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	1.059	0.365	–	–	–
Dissolved oxygen	Land use	2, 20	23.575	<**0.001**	**a**	**b**	**c**
	Geology	1, 20	6.182	0.022	–	–	–
	Interaction	2, 20	1.004	0.384	–	–	–
Colour	Land use	2, 20	12.598	<**0.001**	**a**	**a**	**b**
	Geology	1, 20	0.046	0.832	–	–	–
	Interaction	2, 20	0.842	0.446	–	–	–
TDOC	Land use	2, 20	12.518	<**0.001**	**a**	**a**	**b**
	Geology	1, 20	0.155	0.698	–	–	–
	Interaction	2, 20	0.547	0.587	–	–	–
Chlorophyll *a*	Land use	2, 20	6.276	0.008	–	–	–
	Geology	1, 20	9.973	0.005	–	–	–
	Interaction	2, 20	0.681	0.517	–	–	–
TP	Land use	2, 20	8.983	**0.002**	**a**	**ab**	**b**
	Geology	1, 20	0.889	0.357	–	–	–
	Interaction	2, 20	0.237	0.792	–	–	–
SRP	Land use	2, 20	4.790	0.020	–	–	–
	Geology	1, 20	0.063	0.804	–	–	–
	Interaction	2, 20	0.155	0.858	–	–	–
TN	Land use	2, 20	7.030	0.005	–	–	–
	Geology	1, 20	0.131	0.722	–	–	–
	Interaction	2, 20	0.352	0.708	–	–	–
TON	Land use	2, 20	1.069	0.362	–	–	–
	Geology	1, 20	1.052	0.317	–	–	–
	Interaction	2, 20	0.206	0.815	–	–	–
Ammonia	Land use	2, 20	4.665	0.022	–	–	–
	Geology	1, 20	1.517	0.232	–	–	–
	Interaction	2, 20	0.705	0.506	–	–	–
SO_4	Land use	2, 20	0.461	0.637	–	–	–
	Geology	1, 20	47.783	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	8.286	**0.002**	–	–	–
Ca	Land use	2, 20	2.722	0.090	–	–	–
	Geology	1, 20	2.100	0.163	–	–	–
	Interaction	2, 20	0.892	0.426	–	–	–
Na	Land use	2, 20	6.193	0.008	–	–	–
	Geology	1, 20	106.076	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	6.947	0.005	–	–	–
Cl	Land use	2, 20	4.651	0.022	–	–	–
	Geology	1, 20	144.179	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	8.873	**0.002**	–	–	–
K	Land use	2, 20	15.074	<**0.001**	**a**	**b**	**a**
	Geology	1, 20	6.688	0.018	–	–	–
	Interaction	2, 20	0.035	0.965	–	–	–
Mg	Land use	2, 20	7.877	0.003	–	–	–
	Geology	1, 20	89.622	<**0.001**	**Granite > sandstone**		
	Interaction	2, 20	10.904	**0.001**	–	–	–
Total monomeric Al	Land use	2, 20	13.807	<**0.001**	**a**	**b**	**b**
	Geology	1, 20	0.429	0.520	–	–	–
	Interaction	2, 20	4.165	0.031	–	–	–
Mn	Land use	2, 20	4.046	0.033	–	–	–
	Geology	1, 20	0.810	0.379	–	–	–
	Interaction	2, 20	0.541	0.590	–	–	–
Fe	Land use	2, 20	9.539	**0.001**	**a**	**a**	**b**
	Geology	1, 20	1.882	0.185	–	–	–
	Interaction	2, 20	0.376	0.691	–	–	–

Significant terms are emboldened.

highlights the importance of humic complexes for P and Fe mobilisation to surface waters (Kortelainen and Saukkonen, 1998; Kortelainen et al., 2006).

Interestingly, lake Al and Fe concentrations, as well as P and N, revealed dissimilar responses to catchment forestry between the two geologies. Concentrations of P, N, Al and Fe from the mature plantation

Table 3
Summary statistics from the correlation analysis for all chemical variables from the 26 study lakes.

Variable	pH	Cond.	Temp.	DO	Colour	Alkalinity	Chl. *a*	TDOC	TP	SRP	TN	Ammonia	SO_4	tot.Al	Ca	Na	Cl	K	Mg	Mn
Conductivity																				
Temperature		0.710**																		
Dissolved oxygen																				
Colour				−.758**																
Alkalinity	0.927**																			
Chlorophyll *a*				−.754**																
TDOC		0.389*		−.864**	0.949**		0.482*													
TP				−.589**	0.814**		0.414*	0.683**												
SRP				−.446*	0.780**			0.616**	0.972**											
TN		0.418*		−.657*	0.905**		0.395*	0.876**	0.810**	0.763**										
TON																				
Ammonia					0.773**			0.604**	0.883**	0.904**	0.803**									
SO_4		0.865**	0.639**																	
tot.Al		0.416*		−.686**	0.639**		0.410*	0.740**			0.643**									
Ca	0.621**			−.509**	0.528**	0.780**		0.567**	0.498**	0.446*	0.543**	0.447*								
Na		0.978**	0.752**										0.869**		0.408*					
Cl		0.970**	0.733**										0.885**			0.992**				
K		0.398*							0.464*	0.514**	0.494*	0.611**			0.457*	0.430*	0.448*			
Mg		0.922**	0.720**										0.843**		0.505**	0.942**	0.953**	0.511**		
Mn				−.664**	0.512**		0.606**	0.554**	0.523**	0.430*	0.443*				0.485*					
Fe		0.429*		−.673**	0.889**			0.797**	0.849**	0.798**	0.815**	0.800**		0.478*	0.619**	0.436*		0.556**	0.408*	0.597**

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

lakes were higher than those recorded from the clearfell lakes underlain by sandstone geology, whereas the opposite trend was recorded for the forestry-effected granite lakes. Site-specific responses of receiving water hydrochemistry to catchment forestry have been previously noted (Tetzlaff et al., 2007; Kreutzweiser et al., 2008). This variation in response may be due to differences in catchment characteristics, lake morphology or forestry operations. For example, the drainage of peatland for forestry can release substantial quantities of Fe and Al, with the concentrations of Al in runoff displaying high spatial variation between sites (Joensuu et al., 2002). Similarly, slope of peatland catchments has a major influence on catchment export of N, DOC and Fe (Kortelainen et al., 2006). Further research is needed to elucidate the exact process(es) responsible for the observed differences between catchment geologies and individual lakes.

4.4. Dissolved oxygen

The lower dissolved oxygen concentration recorded in the mature and clearfell lakes is consistent with other studies on the impact of forestry on lake oxygen levels (Rask et al., 1993; Evans et al., 1996). In general, lake oxygen concentrations are dependent upon seasonal temperature variation, depth, wind and trophic status (Wetzel, 2001). Increased loadings of TDOC, leading to dark, peat-stained water can increase the absorption of incoming solar radiation which is subsequently transferred into heat in a thinner layer of water, thereby reducing the solubility of dissolved oxygen within the water column. Increasing TDOC concentrations can also reduce dissolved oxygen via enhanced aerobic bacterial decomposition, predominantly at the sediment–water interface where bacterial decomposition is higher (Wetzel, 2001). Although necessarily limited in scope, the small-scale investigation into the biological and chemical reactivity of the TDOC in runoff from a single clearfell site indicated that clearfelling can input considerable quantities of L-DOC into receiving waters, potentially accounting for the reduced concentrations of dissolved oxygen in clearfell lakes.

4.5. Conductivity, marine ions, temperature and acidity

Conductivity, temperature and concentrations of Na, Cl, Mg and SO_4 ions were all significantly higher in the lakes underlain by granite geology. These lakes are nearer to the coast than the sandstone lakes, and are at a somewhat lower elevation, such that marine deposition (via sea spray, occult deposition) is likely to be greater in the former lakes, potentially accounting for the higher conductivity. Aherne et al. (2002) have previously shown that the deposition of marine-derived ions in Irish lakes decreases with increasing distance inland from the coast. The significantly lower temperature of the upland lakes is most likely explained by their location at higher altitude.

Interestingly, our findings revealed that conifer plantations had no significant effect on the pH of naturally acidic blanket bog lakes. This has previously been shown for streams draining clearfelled areas (Neal et al., 2004b). The atmospheric deposition of acidifying S and N compounds has dramatically reduced in both Britain and Ireland during the previous two decades (Aherne and Farrell, 2002; Fowler et al., 2005; Malcolm et al., in press). However, this alone cannot explain the lack of a pH effect in our study lakes, as forestry is still responsible for low pH receiving waters in many poorly-buffered European catchments (Ågren et al., 2010; Ågren and Löfgren, 2012; Malcolm et al., in press). Sea salt deposition within a catchment has also been shown to lead to lower pH in surface waters (Hindar, 2005; Larssen and Holme, 2006). The lakes in coastal granite catchments unsurprisingly, had considerably higher marine-derived ion concentrations than the more inland sandstone catchments, yet had a somewhat higher pH than sandstone lakes. The lack of a pH response to catchment afforestation may potentially be due to the increased loadings of TDOC, TDOC is known to be the principal buffer in highly humic acid (pH 4–5) surface waters (Kullberg et al., 1993).

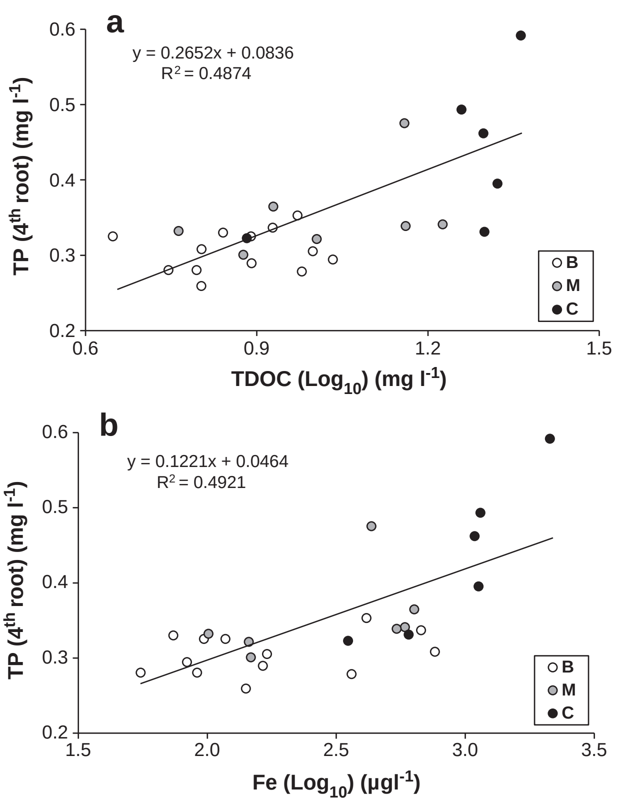

Fig. 5. Correlation between a) TP and TDOC and b) TP and Fe for all study lakes (B = blanket bog, M = mature plantation and C = clearfell).

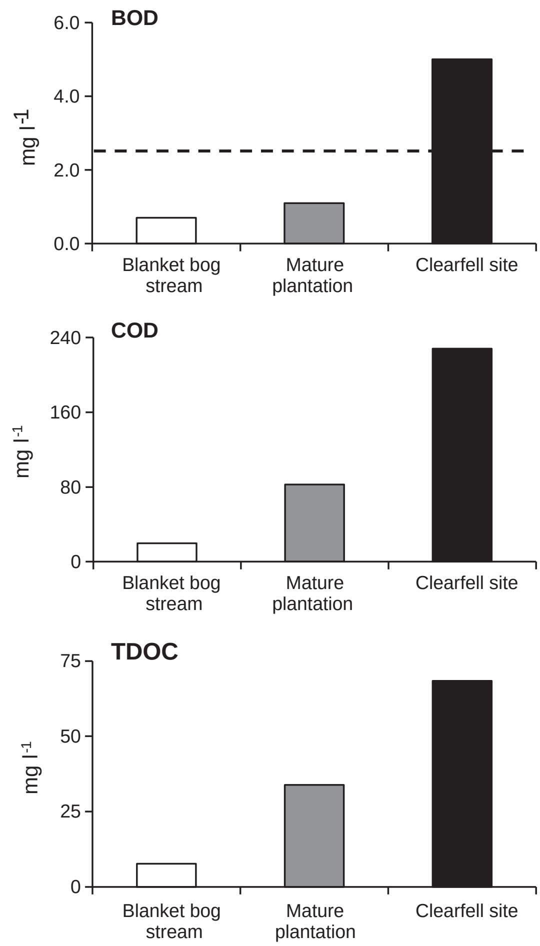

Fig. 6. The concentrations of chemical parameters sampled from the Glennamong clearfell site. The dashed line indicates the guideline for annual mean concentrations for 'good water status' listed in the European Communities Environmental Objectives (Surface Waters) Regulations (2009).

4.6. Chlorophyll a

The increase in chlorophyll *a* concentrations in the mature and clearfell lakes, especially in the lakes underlain by sandstone, is consistent with other studies demonstrating the potential eutrophication effects of forestry on lakes (Kortelainen and Saukkonen, 1998; Bredesen et al., 2002). The increase in primary production is most likely attributable to the increase in plant nutrient concentrations, primarily P. Arvola and Tulonen (1998) also demonstrated the effects of allochthonous DOM on the growth of bacteria and algae from a highly humic lake by showing that algal production increased with increasing DOM concentrations. The difference in chlorophyll *a* concentrations between the two separate geologies, also not significant, is likely explained by the greater concentration of ambient plant nutrients available in the lakes underlain by sandstone in comparison to the lakes underlain by granite.

Table 4
Trophic classification of all 26 study lakes with respect to catchment land use. Maximum chlorophyll *a* concentrations were calculated from samples taken during May to September.

Catchment land use	Lake	Max chlorophyll *a* (μg l^{-1})	Trophic classification
Blanket bog	SB1	9.6	Mesotrophic
	SB2	12.6	Mesotrophic
	SB3	3.9	Oligotrophic
	SB4	16.7	Mesotrophic
	SB5	3.6	Oligotrophic
	SB6	7.7	Oligotrophic
	GB1	4.3	Oligotrophic
	GB2	2.8	Oligotrophic
	GB3	9.6	Mesotrophic
	GB4	3.1	Oligotrophic
	GB5	7.2	Oligotrophic
	GB6	3.7	Oligotrophic
	GB7	2.7	Oligotrophic
Mature plantation	SM1	5.1	Oligotrophic
	SM2	52.7	Strong Eutrophic
	SM3	5.8	Oligotrophic
	GM1	9.5	Mesotrophic
	GM2	3.1	Oligotrophic
	GM3	16.8	Mesotrophic
	GM4	2.5	Oligotrophic
	SC1	21.8	Mesotrophic
	SC2	88.0	Hypereutrophic
	SC3	15.2	Mesotrophic
	GC1	5.8	Oligotrophic
	GC2	9.8	Mesotrophic
	GC3	11.8	Mesotrophic

5. Conclusions

Our findings demonstrate that plantation forestry has a major impact on the hydrochemistry of blanket bog lakes in Ireland, this effect being most apparent post-clearfell. Previous attempts to quantify the catchment export of chemicals associated with conifer plantation forestry were usually confounded by co-occurring (and usually overriding) catchment land uses such as agriculture. Previously, it was suggested that nutrient release from plantation forestry was negligible and would unlikely amount to any change in the chemical or ecological state of receiving surface waters (Nisbet, 2001). However, this study provides empirical evidence that plantation forestry present in lake catchments does lead to significant changes in lake water chemistry. Previous work by our group has also demonstrated that such catchment effluxes associated with peatland conifer forestry has a major impact on the biological communities of receiving waters, the biological response being consistent with a trophic rather than an acidic effect (Drinan et al., in press).

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