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

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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;

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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