Hydrological impact of broadleaved forestry in the British uplands: implications for water use and water quality

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Abstract The impact of oak woodland on the quantity and quality of drainage waters were examined in upland Wales and compared to the effects of commercial conifer (spruce) forestry and unafforested moorland. Interception losses from broadleaved woodland are lower than those from coniferous forestry but higher than losses from moorland vegetation. This may lead to reduced water yields if extensive broadleaved planting occurs in headwater catchments. Soil water chemistry also differed between the three land uses; primarily due to the enhanced deposition of atmospherically-derived ions on to tree canopies. The concentration and flux of the mobile anions $\text{SO}_4^{2-}$ and $\text{Cl}^-$ increased in the order bulk precipitation < oak throughfall < spruce throughfall. The enhanced anion loading results in the acidification of soil waters and the mobilization of $\text{Al}$ in the two forest soils with the effect being most marked at the conifer site. Whilst broadleaved planting is unlikely to result in the same acidification problems associated with coniferous forestry in upland Britain, care should be taken when planting in acid-sensitive environments.

INTRODUCTION

A long history of forest clearance dictates that only 10% of the UK is currently afforested making it one of the least wooded countries in Europe (Atherden, 1992). An intensive programme of reafforestation over the last 75 years has mainly involved planting upland areas with commercial conifers, primarily Sitka spruce (Picea sitchensis). This major land use change has had a marked impact on the hydrology of upland catchments with both the quantity and quality of surface waters being affected. Thus, reduced water yields have been recorded as a result of increased interception losses from tall, dense conifer canopies (Kirby et al., 1991). Moreover, enhanced atmospheric deposition of acidic pollutants on conifer canopies has resulted in surface water acidification and the degradation of freshwater ecosystems in areas where the geology and soils have a low buffering capacity (Edwards et al., 1990) Such adverse environmental impacts of commercial forestry have recently contributed to increased pressure for a more diverse UK forestry policy. Consequently, there has been a major
initiative to increase the planting of native broadleaved trees; thus whilst broadleaves accounted for less than 2% of all new planting in 1972, this figure had increased to 27% by 1992. Much of this new planting has been concentrated in upland areas, with oak (Quercus spp.) being amongst the most favoured trees. Although planting rates are still relatively modest there is a clear strategic need for water managers to evaluate the likely impact of increased broadleaf cover on the freshwater environment (Harding et al., 1992).

This paper reports the results of a study carried out in upland Wales which examined the influence of broadleaved (oak) woodland on the quantity and quality of drainage water in comparison to traditional commercial conifer forestry and unplanted moorland. The implications for catchment management in the UK uplands are discussed.

STUDY AREA AND METHODOLOGY

The investigation was carried out at Llyn Brianne in the headwaters of the Afon Tywi in upland Mid-Wales (Fig. 1). The area has a mean annual precipitation total of 2000 mm and the underlying geology is dominated by Lower Palaeozoic mudstones and shales. There are three primary types of land use in the area: Molinia dominated moorland that is used for sheep grazing; large commercial forest plantations (established in the 1950s and 1960s) of Sitka spruce (Picea sitchensis); and small areas of semi-natural oak (Quercus petraea) woodland on steeply sloping sites.

Experimental plots were established under each of the three dominant land use types

Fig. 1 The location of the Llyn Brianne experimental catchment and the three study plots.
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Each plot was instrumented to evaluate the quantity and quality of drainage waters. The field investigation period commenced in January 1986 and ended in December 1988. All plots were established on steeply sloping areas (10-15°) and the underlying soil was a brown podzolic soil (Orthods) of the Manod series. These soils are acidic and freely draining and are favoured locations for new planting of broadleaved trees. The semi-natural oak woodland site had a 10-15 m high canopy dominated by *Quercus petraea* and an understorey of bracken (*Pteridium aquilinum*), grasses and mosses. A semi-natural stand was selected for the study as newly planted areas still immature (5-10 years old). The Sitka spruce site was planted in 1959 and had a height of around 17 m at the time of the study. A mixed grass community dominated by *Festuca ovina* and *Agrostis capillaris* characterized the moorland site.

The brown podzolic soil at each site had the same general characteristics: a dark brown A horizon (10-20 cm deep) overlying an ochreous B<sub>s</sub> horizon which merged into the little altered C horizon at a depth of 40-60 cm. The parent material at each plot was characterized by shattered colluvium derived from the underlying mudstone bedrock. The vegetation had clearly influenced the detailed profile characteristics at each plot. A thin, well-decomposed litter layer covered the surface of the oak woodland soil. Fine roots were abundant in this and the underlying A horizon, though course roots penetrated into the subsoil. A 2-3 cm deep litter layer of spruce needles covered the soil surface at the spruce plot where no ground vegetation was present. The podzolization process appeared to be most advanced at this site as the lower A horizon showed signs of eluviation with bleached grains and peds evident. A thin, well-humified O horizon had formed at the surface of the moorland plot and grass roots were generally restricted to this and the underlying A horizon.

Full details of the field methodology and laboratory analyses are given by Soulsby & Reynolds (in press) and only a brief summary follows. The volume and chemistry of bulk precipitation was recorded at the Llyn Brianne Automatic Weather Station on a weekly basis. The quantity and quality of throughfall and stemflow was measured fortnightly beneath the oak woodland and spruce forest canopy using a network of throughfall collectors and stemflow collars of the type described by Reynolds & Stevens (1987). At each site soil water was collected every two weeks from the major soil horizons (A, B<sub>s</sub>, and C) using porous ceramic cup samplers. The full chemical composition of water samples and the soil properties at each plot were analysed using standard methods (Allen, 1989).

**RESULTS AND DISCUSSION**

**Water Use**

**Canopy water balance** Canopy water balances for the study period were computed for the oak stand using precipitation, throughfall and stemflow data. Interception losses were just over 13% of incident precipitation with throughfall and stemflow accounting for 78% and 8% respectively. Malfunction of the stemflow recorders have prevented an accurate assessment of interception losses from the spruce canopy, though the precipitation and throughfall data suggest that it is 25-30%; a figure close to that recorded in other spruce stands in upland Wales (Calder, 1990). This lower loss from the oak stand...
is consistent with the relatively low density of the seasonal oak foliage compared to spruce. Given likely similarities in forest transpiration rates (Roberts, 1983), it would therefore be expected that increased planting of oak woodland would have a less marked impact on catchment water yields than a species like Sitka spruce. Nevertheless, given the low interception losses from moorland areas in upland Wales (<5% cf. Kirby et al., 1991) this increase may be significant in catchments used for water supply, particularly during summer low flows.

**Water Quality**

**Canopy-water interactions** The mean acidity of throughfall beneath the oak stand (pH = 4.73) is slightly greater than bulk precipitation (pH = 4.80) but lower that beneath Sitka spruce (pH = 4.56). In general all major ions except NO₃ exhibit increased concentrations (relative to bulk precipitation) beneath the two forest canopies in the order bulk precipitation < oak throughfall < Sitka spruce throughfall (Fig. 2). For atmospherically-derived ions this primarily reflects the enhanced dry and occult deposition of marine solutes (Na and Cl) and pollutants (SO₄), which is greater on the tall, dense, evergreen spruce canopy compared to the more open, seasonal oak canopy (Harding et al., 1992). For ions with an important nutrient cycling component (K, Ca and Mg), increased concentrations in throughfall may also reflect nutrient release from the tree canopy, whilst the retention of NO₃ in the oak canopy probably reflects efficient uptake by the foliage and rich epiphyte communities present on the surface of the tree bark.

The increased solute concentrations in the throughfall at the oak woodland plot result in an increased flux of all ions (except NO₃) compared to bulk precipitation (Fig. 3). The flux from the oak canopy is however lower than that in throughfall at the spruce site with flux of the mobile anions Cl and SO₄ increasing by approximately 40% and 150% respectively.

**Soil water chemistry** The soil at each study site is acidic; the base saturation is low and Al is the dominant exchangeable cation (Table 1). Soil acidity is highest in the A horizon at each site due to the presence of organic acidity which is neutralized with depth. The cation exchange capacity is also highest in the upper profile where exchange sites are available on weathered minerals and humic substances. The oak woodland soil is least acidic, with the pH of each horizon being 0.5 units higher than beneath spruce, which is the most acidic. The conifer site also has the lowest quantity of base cations in the upper profile indicating that the new plantation is acidifying the soil by increased nutrient uptake and accelerated leaching (Hornung, 1985). The moorland site exhibits intermediate soil acidity, presumably the reflecting the acidifying effect of forest clearance.

In contrast, the acidity of soil waters beneath the oak woodland (pH 4.2-4.8) are intermediate between those of the spruce site (pH 4.8-5.0) and the moorland soil waters (pH 4.8-5.0). Solute of atmospheric origin dominate both the anionic (SO₄ and Cl) and cationic (Na) composition of soil water at each site (Fig. 2). The increased concentration and flux of inorganic anions beneath the oak canopy is reflected in soil water concentrations that are higher than the moorland site but lower than the in the spruce stand. The
Fig. 2 The chemical composition (μeq l⁻¹) of (a) throughfall (TF) and soil water (A, B and C horizons) at the oak site; (b) throughfall (TF) and soil water (A, B and C horizons) at the Sitka spruce site; and (c) bulk precipitation (BP) and soil water (A, B and C horizons) at the moorland site.

distribution of ions such as NO₃, K, Ca, and Mg tend to exhibit reflect patterns of nutrient release and uptake with concentrations being highest in the upper profile and decreasing with depth.

The increased acidity and Al content of soil waters at the two forest sites is consis-
tent with the elevated concentration of mobile anions promoting cation exchange reactions (Soulsby & Reynolds, 1992, in press). Much higher Al concentrations beneath spruce indicate, however, that the process is more marked at that site, presumably due to the higher concentration and flux of mobile anions. A sub-set of soil waters samples from the two forest sites were fractionated into inorganic Al species and organically complexed Al (Fig. 4). The speciation is markedly different; at the oak site organically complexed Al is dominant in the upper profile, and only in C horizon soil waters are inorganic species dominant. In contrast, organically complexed species constitute only a minor fraction of the higher dissolved Al concentrations in the spruce soil water. This

Table 1 Soil pH, exchangeable base cations (BC), Al, H, cation exchange capacity (CEC) and percentage base saturation (%BS) at the three study sites (exchangeable cation data in meq/100 g).

<table>
<thead>
<tr>
<th>Site</th>
<th>Horizon</th>
<th>pH</th>
<th>BC</th>
<th>Al</th>
<th>H</th>
<th>CEC</th>
<th>%BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak woodland</td>
<td>A</td>
<td>4.36</td>
<td>1.24</td>
<td>5.41</td>
<td>0.05</td>
<td>6.7</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4.59</td>
<td>0.77</td>
<td>4.06</td>
<td>0.03</td>
<td>4.86</td>
<td>15.8</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>4.87</td>
<td>0.59</td>
<td>1.56</td>
<td>0.02</td>
<td>2.17</td>
<td>27.1</td>
</tr>
<tr>
<td>Sitka spruce forest</td>
<td>A</td>
<td>3.85</td>
<td>0.96</td>
<td>6.58</td>
<td>0.05</td>
<td>7.59</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4.00</td>
<td>0.76</td>
<td>3.96</td>
<td>0.03</td>
<td>4.75</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>4.26</td>
<td>0.78</td>
<td>2.25</td>
<td>0.02</td>
<td>3.05</td>
<td>25.6</td>
</tr>
<tr>
<td>Moorland</td>
<td>A</td>
<td>4.05</td>
<td>1.31</td>
<td>3.07</td>
<td>0.06</td>
<td>4.44</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>4.25</td>
<td>0.82</td>
<td>2.76</td>
<td>0.04</td>
<td>3.62</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>4.43</td>
<td>0.63</td>
<td>1.81</td>
<td>0.03</td>
<td>2.47</td>
<td>25.5</td>
</tr>
</tbody>
</table>
indicates that accelerated Al leaching resulting from enhanced acid deposition is most marked beneath sitka spruce, whilst podzolization processes involving the chelation of Al are still dominant beneath the oak woodland. The presence of inorganic Al species in acidic soil drainage waters is significant as it is inorganic species such as Al$^{3+}$ which are toxic to salmonids (Ormerod & Jenkins, 1994). Thus, whilst Al concentrations in drainage waters from the oak site are elevated compared to the moorland, they are significantly lower than those beneath the conifer stand. This suggests that the water quality impact of planting broadleaf species such as oak is unlikely to replicate the damage to freshwater ecosystems that was caused by surface water acidification problems resulting from commercial conifer forestry.

**MANAGEMENT IMPLICATIONS**

Current rates of broadleaf planting in the UK are modest and the average plantation size is small (7 ha). This will result in a much less marked effect on catchment hydrology than many of the large commercial conifer forests planted earlier this century. These were often several thousand hectares in area and often covered whole drainage basins. Nevertheless, the results of this study indicate that planting broadleaves on upland moorland in Wales could contribute to reduced water yields and may increase the acidity and Al concentrations of drainage waters. Thus, water managers will need to carefully monitor the extent and location of new planting in catchments that are used for water

![Diagram of Al concentrations in soil waters beneath oak woodland and Sitka spruce plantation.](image)
supply or are acid-sensitive. Recent guidelines for forest managers in the UK have advocated the creation of riparian buffer strips in new conifer plantations and to rehabilitate streams in existing ones (Forestry Commission, 1993). It is recommended that broadleaved species are used both to improve the freshwater and riparian habitat and enhance visual amenity. However, caution must be exercised when adopting this approach in acid-sensitive upland areas which are often favoured locations for forestry. The results of this study have demonstrated that acidification of drainage waters may result, which may be undesirable as riparian soils can exert a strong influence on stream water quality (Billet & Cresser, 1992). In such areas it may therefore be preferable to avoid planting altogether or to plant at low densities to minimize the increase in atmospheric deposition. The results of this investigation refer specifically to the impact of oak on brown podzolic soils in the Welsh uplands. Very little hydrological research has been executed in UK broadleaved stands and there is clearly a strategic need to increase the range of species, soil types and locations studied in order to aid catchment management strategies in upland areas where planting rates are increasing.

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**REFERENCES**


