The nitrogen composition of streams draining grassland and forested catchments: influence of afforestation on the nitrogen cycle in upland ecosystems

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Abstract The nitrogen (N) composition of streams draining three moorland and three plantation forest catchments in mid-Wales was investigated and compared. Samples of stream water were collected every four weeks over one year and analysed for total dissolved nitrogen (TDN), nitrate (NO₃), ammonium (NH₄), dissolved organic nitrogen (DON) and dissolved organic carbon (DOC). There was no significant difference in TDN concentrations between forested and moorland streams. However, NO₃ concentrations were significantly larger in the forested streams and DON and DOC concentrations were significantly larger in the moorland streams. Nitrate and DON also displayed contrasting seasonal patterns: NO₃ concentrations were largest in the winter, while the opposite was observed for DON and DOC. The results confirm conclusions from other studies that afforestation of upland semi-natural vegetation can promote nitrification within the soil system, which is reflected in a change in the TDN composition of stream water. The results also emphasize the need to consider both inorganic and organic forms of N in studies that assess the impact of land management strategies on N cycling in terrestrial and aquatic ecosystems.

INTRODUCTION

Over the last sixty years, the major land use change in upland areas of Britain has been the conversion of semi-natural moorland to plantation forest dominated by Sitka spruce (Picea sitchensis). Upland rivers, which provide 40% of the public water supply, are often used for recreational fishing. Consequently, there has been much concern about the possible impacts of afforestation on both water resources and water quality. Studies carried out in the 1980s reported increased acidity and aluminium in streams draining forested catchments compared with those draining moorland catchments (e.g. Reynolds et al., 1989). These changes in chemistry were implicated in the deterioration of freshwater invertebrate communities and fish stocks in forested catchments (e.g. Ormerod et al., 1987).
More recently, a number of studies have observed that streams draining mature conifer plantations have larger nitrate (NO$_3$) concentrations than those draining adjacent moorland catchments (Reynolds & Edwards, 1995). However, as the majority of these studies only analysed for NO$_3$, and in some case ammonium (NH$_4$), there are few data describing either organic or total N concentrations. Therefore it is difficult to elucidate whether the larger NO$_3$ concentrations are the result of an absolute increase in the concentration of NO$_3$ in forest streams or a relative change in the proportions of the various N forms present as a result of changes in the soil N cycle. The study reported in this paper was undertaken to investigate and compare the N composition of streams draining adjacent moorland and forested catchments.

SITE DESCRIPTION

The catchments of the Cyff and Gwy lie within the headwaters of the River Wye, and the catchments of the Hafren and Hore lie within the adjacent headwaters of the River Severn (Fig. 1). Both headwaters drain the eastern slopes of the Plynlimon massif in mid-Wales, approximately 24 km from the west coast of Wales. The characteristics of these catchments are shown in Table 1 and described in more detail by Reynolds et al. (1989). Base-poor Silurian shales, mudstones and grits underlie the area. A mosaic of

![Location map of the Plynlimon catchments showing stream water sampling points.](image)
upland soils occurs throughout the catchments, consisting of peats, stagnopodzols and stagnogleys (Table 1). These soils are generally acidic, organic rich and contain small amounts of available nutrients.

The vegetation of the Wye catchment is acid grassland dominated by *Nardus* and *Festuca* species on the well-drained slopes with podzolic soils. The hilltop peats support *Eriphorium*, *Calluna* and *Vaccinium* communities, in contrast to the valley bottom peats and stagnogleys that are dominated by *Molinia* and *Juncus*. The Wye catchment forms part of a large hill-farm and supports low density sheep grazing (1–2 ewes ha⁻¹) for most of the year. Over the last 60 years, 25% of the Wye catchment has been agriculturally improved by a variety of methods, such as the periodic addition of lime and compound fertilizers (Reynolds et al., 1997). Within the Severn catchment, afforestation predominantly with Sitka spruce (*Picea sitchensis*) occurred in three phases between 1937 and 1964. Thus large areas are now mature forests (Table 1), although between 1985 and 1989, 29% of the Hore catchment was clear-felled and replanted with a second rotation crop. The vegetation also influences the atmospheric inputs of N to the catchments. The forest vegetation has a much greater ability to capture inputs of occult and dry deposition than moorland vegetation (Reynolds et al., 1997) and thus the forested catchments receive larger inputs of atmospheric N (Table 1).

**METHODS**

Streamflow from all the catchments except the Wye is monitored using steep stream flumes. Streamflow from the Wye is recorded using a weir. Samples of stream water from the Cyff, Gwy, Wye, Hafren, Hore and Severn were collected every four weeks between March 1997 and March 1998 from a point upstream of the gauging structures (Fig. 1). On return to the laboratory, the water samples were filtered through pre-washed 0.45 μm membrane filters. Nitrate-N and NH₄-N were determined colorimetrically using a Technicon TRAACS auto-analyser. Total dissolved N (TDN) was determined as NO₃-N after oxidation with alkaline potassium persulphate (Williams et al., 1995). Dissolved organic N (DON) was calculated as the difference

**Table 1** Characteristics of the Plynlimon catchments.

<table>
<thead>
<tr>
<th>Catchment area (ha)</th>
<th>Cyff</th>
<th>Gwy</th>
<th>Wye</th>
<th>Hafren</th>
<th>Hore</th>
<th>Severn</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>390</td>
<td>1055</td>
<td>347</td>
<td>335</td>
<td>870</td>
<td></td>
</tr>
<tr>
<td>Slope (m km⁻¹)</td>
<td>27.6</td>
<td>20.3</td>
<td>37.2</td>
<td>59.4</td>
<td>70.5</td>
<td>63.5</td>
</tr>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>2552</td>
<td>2667</td>
<td>2581</td>
<td>2609</td>
<td>2638</td>
<td>2425</td>
</tr>
<tr>
<td>Mean annual runoff (mm)</td>
<td>2055</td>
<td>2180</td>
<td>2051</td>
<td>1927</td>
<td>1833</td>
<td>1805</td>
</tr>
<tr>
<td>Total N deposition (kg ha⁻¹ year⁻¹)</td>
<td>22.6</td>
<td>23.6</td>
<td>23.1</td>
<td>33.0</td>
<td>39.0</td>
<td>37.2</td>
</tr>
<tr>
<td>Wet NO₃-N deposition (kg ha⁻¹ year⁻¹)</td>
<td>6.5</td>
<td>6.7</td>
<td>6.6</td>
<td>8.8</td>
<td>10.1</td>
<td>9.7</td>
</tr>
<tr>
<td>% Peat</td>
<td>14</td>
<td>37</td>
<td>26</td>
<td>52</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>% Stagnopodzols</td>
<td>70</td>
<td>43</td>
<td>45</td>
<td>47</td>
<td>50</td>
<td>43</td>
</tr>
<tr>
<td>% Stagnogleys</td>
<td>16</td>
<td>20</td>
<td>29</td>
<td>0</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>% Forest</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>48</td>
<td>77</td>
<td>68</td>
</tr>
</tbody>
</table>


*b* Reynolds et al. (1997).
between TDN and NO₃-N plus NH₄-N. All analysis was carried out less than one week after sample collection. A Total Organic Carbon analyser (OI analytical model 700) determined the dissolved organic carbon (DOC) content of the stream samples.

Statistical analysis

A one-way analysis of variance (ANOVA) was used to determine the effect of afforestation on N fractions and DOC in stream water. Box and whisker plots were used to show the range of N concentrations in stream water from the moorland and forested catchments. The middle horizontal line of the box represents the median value. Fifty percent of the data points lie within the box. The whiskers show the spread of data. A closed circle represents outliers.

RESULTS

Hydrologic conditions during the study period

The mean monthly flows and spot flows at time of sampling for the Rivers Wye and Severn are shown in Table 2. The mean monthly flow data during the study period do not display the typical seasonal flow pattern of smaller flows in the summer and larger flows in the winter. Lowest mean monthly flows were observed in April 1997 and February 1998 following extended periods of low rainfall. Exceptionally high rainfall in May and June 1997 produced rapid flow increases. After returning to lower flows in July 1997, mean monthly flows displayed a general increase until January 1998. In general, the flow at time of sampling was lower than the mean monthly flow and although water sampling was performed without consideration to rainfall events, only in May 1997 and January 1998 did sampling take place after a storm event.

### Table 2 Mean monthly flows (m³ s⁻¹) and spot flows (m³ s⁻¹) at time of sampling for the Rivers Wye and Severn.

<table>
<thead>
<tr>
<th></th>
<th>Wye: Monthly</th>
<th>Spot</th>
<th>Severn: Monthly</th>
<th>Spot</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1997</td>
<td>0.612</td>
<td>0.254</td>
<td>0.461</td>
<td>0.233</td>
</tr>
<tr>
<td>April</td>
<td>0.174</td>
<td>0.143</td>
<td>0.161</td>
<td>0.139</td>
</tr>
<tr>
<td>May</td>
<td>0.583</td>
<td>0.817</td>
<td>0.447</td>
<td>0.515</td>
</tr>
<tr>
<td>June</td>
<td>0.550</td>
<td>0.075</td>
<td>0.416</td>
<td>0.074</td>
</tr>
<tr>
<td>July</td>
<td>0.187</td>
<td>0.162</td>
<td>0.137</td>
<td>0.143</td>
</tr>
<tr>
<td>August</td>
<td>0.373</td>
<td>0.136</td>
<td>0.218</td>
<td>0.124</td>
</tr>
<tr>
<td>September</td>
<td>0.496</td>
<td>0.481</td>
<td>0.350</td>
<td>0.384</td>
</tr>
<tr>
<td>October</td>
<td>0.629</td>
<td>0.196</td>
<td>0.448</td>
<td>0.140</td>
</tr>
<tr>
<td>November</td>
<td>0.819</td>
<td>0.104</td>
<td>0.644</td>
<td>0.123</td>
</tr>
<tr>
<td>December</td>
<td>0.871</td>
<td>0.773</td>
<td>0.695</td>
<td>0.671</td>
</tr>
<tr>
<td>January 1998</td>
<td>1.267</td>
<td>1.732</td>
<td>1.110</td>
<td>1.422</td>
</tr>
<tr>
<td>February</td>
<td>0.313</td>
<td>0.128</td>
<td>0.240</td>
<td>0.120</td>
</tr>
<tr>
<td>March</td>
<td>0.711</td>
<td>0.772</td>
<td>1.340</td>
<td>0.578</td>
</tr>
</tbody>
</table>
Amount and composition of nitrogen in stream water

Figure 2 shows the range of TDN, NO$_3$-N and DON concentrations in stream samples collected from the moorland and forested catchments. The spread and range of TDN data was very similar for streams draining moorland and forested catchments. Although the median concentration was slightly larger for the forest streams (0.31 mg l$^{-1}$) than the moorland streams (0.27 mg l$^{-1}$), concentrations were not significantly different between the moorland and forested catchments. In contrast, NO$_3$-N concentrations were significantly ($P < 0.01$) larger in streams draining forested catchments, while DON concentrations were significantly ($P < 0.01$) larger in streams draining moorland catchments. Concentrations of NH$_4$-N were very small (<0.06 mg l$^{-1}$) and varied little between the streams draining the moorland and forested catchments.

The composition of TDN varied between the moorland and forest streams (Table 3). The NO$_3$ fraction dominated TDN in all streams, accounting for 86% of the annual mean TDN concentration in the forest streams compared with 72% in the moorland streams. The contribution of the NH$_4$ fraction was less than 6% of the TDN in all streams, the remaining being DON.

Fig. 2 Box and whisker plots summarizing concentrations of (a) TDN, (b) NO$_3$-N and (c) DON in stream samples collected from moorland and forested catchments at Plynlimon.
Table 3 The flow weighted mean NO$_3$-N, NH$_4$-N, DON and DOC concentrations and DOC:DON ratio in streams draining forested and moorland catchments during the year, summer and winter (values in brackets indicate the percentage contribution each N fraction makes to the flow weighted mean TDN concentration).

<table>
<thead>
<tr>
<th></th>
<th>NO$_3$-N</th>
<th>NH$_4$-N</th>
<th>DON</th>
<th>DOC</th>
<th>DOC:DON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forest streams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>0.373(86)</td>
<td>0.02(4)</td>
<td>0.043(10)</td>
<td>1.85</td>
<td>43</td>
</tr>
<tr>
<td>Summer$^a$</td>
<td>0.211(67)</td>
<td>0.01(2)</td>
<td>0.100(31)</td>
<td>2.39</td>
<td>24</td>
</tr>
<tr>
<td>Winter$^b$</td>
<td>0.446(92)</td>
<td>0.02(5)</td>
<td>0.017(3)</td>
<td>1.60</td>
<td>94</td>
</tr>
<tr>
<td><strong>Moorland streams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>0.278(72)</td>
<td>0.02(6)</td>
<td>0.086(22)</td>
<td>2.43</td>
<td>28</td>
</tr>
<tr>
<td>Summer$^a$</td>
<td>0.103(38)</td>
<td>0.01(3)</td>
<td>0.161(59)</td>
<td>3.50</td>
<td>22</td>
</tr>
<tr>
<td>Winter$^b$</td>
<td>0.372(83)</td>
<td>0.03(7)</td>
<td>0.046(10)</td>
<td>1.86</td>
<td>40</td>
</tr>
</tbody>
</table>

$^a$ May–October.
$^b$ November–April.

Temporal variation in NO$_3$ and DON concentrations

Figure 3 shows how the flow weighted mean NO$_3$-N concentrations varied monthly in the moorland and forest streams. In both the moorland and forest streams, NO$_3$ displayed a pronounced seasonal trend with smaller concentrations in the summer/autumn than the winter/spring. In both moorland and forest streams, minimum concentrations were observed in June and maximum concentrations in January. However, the maximum NO$_3$-N concentration was nearly 14 times greater than the minimum concentration in the moorland streams compared to only 4 times greater in the forest streams. Nitrate concentrations were larger in the forest streams than the moorland streams throughout the year. Between June and October, NO$_3$-N concentrations were, on average, 3.6 times greater in the forest streams than the moorland streams, whereas in the winter months, November to May, NO$_3$-N concentrations were only 1.4 times greater in the forest streams.
Figure 4 shows how the mean flow weighted concentrations of DON varied monthly in the moorland and forest streams. Dissolved organic N displayed similar trends through the year in both the moorland and forest streams. Concentrations displayed a general increase between March and October, although peaks occurred in May and June, before decreasing to a minimum in January. Thus, DON concentrations were larger in the summer (May–October) than the winter (November–April). In the moorland streams, DON was smallest in January and largest in October. In the forest streams, smallest concentrations were observed in March 1997 and January, while largest concentrations were observed in May. On average, DON concentrations were 1.6 times larger in the moorland streams than the forest streams, except in March and December 1997 when concentrations were over 12 and 6 times greater, respectively.

As DON and NO₃ concentrations displayed opposite seasonal patterns, the composition of TDN varied significantly ($P < 0.001$) between summer (May–October) and winter (November to April) (Table 3). In both the moorland and forest streams, the contribution of DON to TDN was larger in the summer, 59% and 31%, respectively, than in the winter, 10% and 3%, respectively.

![Fig. 4 Monthly flow weighted mean DON and DOC concentrations in streams draining (a) moorland and (b) forested catchments between March 1997 and March 1998.](image-url)
Relation between DON and DOC

There was a significant positive linear correlation ($r = 0.62$, $P < 0.001$) between DOC and DON concentrations in streams draining the moorland catchments. By contrast, no such relation was observed for DOC and DON ($r = 0.28$) in streams draining the forested catchments. However, the mean flow weighted concentrations of DOC displayed similar trends through the year in both the moorland and forest streams; concentrations increased between March and October before decreasing to a minimum in February (Fig. 4). Thus as observed for DON, DOC concentrations were larger in the summer than the winter (Table 3). However, the increase in mean concentration between the winter and summer was larger for DON than DOC. Thus the DOC:DON ratio was smaller in both moorland and forest streams in the summer than the winter (Table 3). Concentrations of DOC were also significantly ($P < 0.01$) larger in the moorland streams than the forest streams by, on average, a factor of 1.36.

DISCUSSION

Concentrations and forms of nitrogen in stream water

The NO$_3$-N and NH$_4$-N concentrations observed in the moorland and forested catchments in this study are comparable with those reported in other studies at Plynlimon (e.g. Reynolds et al., 1989). However, the magnitude of the NO$_3$ concentrations observed in the winter can be severely effected by periods of drought and extreme cold (Reynolds & Edwards, 1995). As few data for TDN and DON exists for upland streams in Britain, the monthly data obtained from this study provide information on the range, magnitude and temporal variability of TDN and DON concentrations in moorland and forest streams. Although there is much debate about the sampling frequency required to effectively characterize stream water chemistry, Brewin et al. (1996) showed that monthly sampling of stream water had no discernible effect on the apparent annual mean chemistry relative to the values derived from weekly data. In addition, they observed that relationships established between mean stream chemistry and land use were still strong at both weekly and monthly sampling frequencies. However, to investigate the relationship between NO$_3$ and DON concentrations with stream flow more intense sampling during storm events is necessary.

The seasonal trend observed in stream water NO$_3$-N in both the moorland and forested catchments is well established at Plynlimon and other upland catchments in the UK (Reynolds & Edwards, 1995) and is explained in terms of the seasonal availability of NO$_3$ within the soil for leaching. In summer, NO$_3$ derived from mineralization and atmospheric deposition is immobilized by plant and microbial uptake. In winter, mineralization and biological uptake is at a minimum. Therefore soils have a much lower ability to retain atmospheric inputs of NO$_3$ during the winter than the summer when it is more likely to enter the terrestrial N cycle. Wet deposition of NO$_3$-N to the Wye catchment is 6.6 kg ha$^{-1}$ year$^{-1}$ compared to 9.7 kg ha$^{-1}$ year$^{-1}$ in the Severn (Table 1). Thus the forested catchments receive 1.47 times more
The nitrogen composition of streams draining grassland and forest catchments

atmospheric NO₃-N than the moorland catchments which is very similar to the
difference observed between mean monthly NO₃-N concentrations in the moorland and
forest streams in the winter.

Concentrations of DON displayed a similar temporal pattern to those of DOC in
both the forest and moorland streams with larger concentrations in the summer than the
winter. Maximum DOC concentrations have been observed in soil solutions in the late
summer/early autumn (Hughes et al., 1990) due to increased microbial activity and
thus plant decomposition.

Influence of afforestation on the amount and form of nitrogen in stream water

The results of this study suggest that vegetation type influences the composition of
TDN in stream water, although the concentration of TDN varied little between streams
draining moorland and forested catchments. In the forest streams, the inorganic N
fraction accounted for 90% of the mean annual TDN concentration compared to 78%
in the moorland streams. The larger NO₃-N concentrations in the forest streams may
reflect a relative change in the proportions of the organic and inorganic N forms
leached from the soil rather than an absolute increase in total N leached.

Stevens & Wannop (1987) observed that the soil solution concentration of TDN
remained relatively constant down the soil profile of a stagnopodzol at Beddgelert
Forest, north Wales, and there was a transition from DON dominance to NO₃
dominance. They concluded that the transition to NO₃ dominance in the lower horizons
indicates that nitrification operates in the upper mineral horizons of these acid soils.
Other studies have reported an increase in net mineralization and nitrification rates in
forest soils from stands greater than 30 years old (Emmett et al., 1993) and along a N
deposition gradient (McNulty et al., 1990). Thus larger mineralization and nitrification
rates in the forest soils could account for the smaller DON concentrations and larger
NO₃ concentrations in streams draining the forested catchments.

The considerably larger NO₃ concentrations in the forest streams than the moorland
streams in the summer suggest that plant uptake and microbial immobilization of N in
the forested catchments is unable to contend with the quantities of available NO₃. En­
hanced concentrations of NO₃ in stream water during the summer is one of the suggest­
ed signs that a terrestrial system has become “nitrogen saturated” (Stoddard, 1994). This term is used to describe the declining ability of an ecosystem to retain added N.

The annual DOC:DON ratio was substantially higher for streams draining the
forested catchments than the moorland catchments. Harriman et al. (1997) observed
similar results for adjacent moorland and forested catchments in central Scotland. On a
seasonal basis, the DOC:DON ratio was wider over the winter period than the summer
period, particularly in the forest streams. Thus in the winter DOC was less N rich
compared to in the summer. This seasonal variation in the DOC:DON ratio may reflect
a change in the major source of DOC and DON between winter and summer.

This study has highlighted the potential effects of afforestation on the terrestrial N
cycle and thus the composition of N in stream water. The results also emphasize the
need to consider both inorganic and organic forms of N in studies that assess the effect
of land management strategies on the N cycle in terrestrial and aquatic ecosystems.
Acknowledgements This research was funded by the Natural Environment Research Council (grant GT5/96/2/FS) and the Scottish Office. The authors would like to thank Sue Hill and Sean Crane at the Institute of Hydrology, Plynlimon, for collecting the water samples and providing the flow data. Thanks also to Yvonne Cook for help with the chemical analysis.

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