Forests and Water Guidelines: broadleaf woodlands and the protection of freshwaters in acid-sensitive catchments

Z.Gagkas, K.Heal, N.Stuart and T.R. Nisbet

Introduction

Increased acidity of surface waters caused by pollutant deposition is a problem in certain acid-sensitive areas of the UK. Acidification in Scotland has been identified as the main cause of pollution in 17% (504 km) of polluted rivers, with 400 km of acidified rivers being in western Scotland, while in Wales 12 000 out of 24 000 km of river are estimated to be impacted by acidification (Jenkins and Ferrier, 2000). The adverse effects of acidified waters on freshwater biota include loss of acid-sensitive invertebrate species, reductions in the population density of brown trout and riparian birds or even extinction of sensitive species from lakes and streams in highly impacted areas. The loss of the conservational value of surface water environments also has serious financial impacts on many local economies which depend on income generated by the use of freshwaters for recreational fishery (e.g. from fishing licences and visitors).

The areas worst affected by acidification are dominated by soils with small base cation pools which are rapidly depleted in response to acidic deposition, resulting in the acidification of soils and freshwaters (Jenkins and Ferrier, 2000). Thus, reducing emissions of acid pollutants is the principal way of solving the problem of acidification. In the UK, there have been reductions in sulphur (S) emissions and deposition since the late 1960s, while nitrogen (N) emissions have declined since the late 1980s (NEGTAP, 2001). The European Union has agreed to further S and N pollutant reductions by 2010 to facilitate the recovery of acidified terrestrial and aquatic ecosystems.

However, increasing forest cover could delay the recovery of acidified waters, or even lead to further acidification in the most sensitive areas, with high deposition inputs and low buffering soils due to the capture of acidic pollutants by forest canopies ('the scavenging effect'). By the early 1970s, studies of land use effects on water quality suggested a link between the presence of conifer forests and higher streamwater acidity and/or higher aluminium concentrations (Nisbet *et al.*, 1995). Although pollutant deposition is smaller on broadleaf woodland than in more aerodynamically rough conifer canopies (Neal, 2002), the impact of larger broadleaf planting schemes needs to be taken into consideration. The expansion of native broadleaf woodlands plays an important part in the UK Government's strategy for sustainable development and great effort is being made through initiatives to restore native woodlands and improve the conservation status and habitat value of forested ecosystems (Rollison, 2000). Since 1978 there has been a gradual increase in the planting of broadleaf trees, with more than 11 000 ha planted in the UK in 2005. At the same time, the implementation of the Water Framework Directive requires the control of diffuse pollution from all sources, including forestry. Thus, the contribution of broadleaf woodland cover to freshwater acidification needs to be investigated.

Forests and Water Guidelines

The Forests and Water Guidelines were developed to protect the UK's freshwater environment from forestry activities (Forestry Commission, 2003). The latest edition of the guidelines takes into account the scavenging effect when considering new woodland planting or restocking plans in acid-sensitive areas. Freshwaters at risk of acidification are identified using the steady-state-water-chemistry (SSWC) model (Henriksen *et al.*, 1986) to calculate the critical load, the maximum pollutant load at which an acid-neutralising capacity (ANC) can be maintained above zero (equating with a pH>5.3) in order to protect salmonid fish.

The Forests and Water Guidelines use the provisional critical loads exceedance map for UK freshwaters to determine which areas are at risk from a forest scavenging effect (Figure 1). This map was derived from analysis of water samples from the most sensitive water body (on the basis of available soil and geological information) within each 10 × 10 km grid square and by comparing the calculated critical loads with the 1995–1997 total atmospheric deposition of S and N. According to the guidelines, within a critical load exceedance square or contiguous square, a critical load assessment is necessary when more than 10% of the catchment area is to be planted with conifers or more than 30% with broadleaves. One to three water samples are collected from the catchment outlet during high flow, preferably in January to March (when conditions tend to be more acidic) and the results of the chemical analysis are used to calculate the water's critical load, which is then compared with the pollutant deposition estimates. Where the critical load calculated is exceeded by the pollutant deposition estimate, approval of a planting grant is unlikely until pollutant emissions are reduced.

This study assessed the suitability of the Forests and Water Guidelines methodology for ensuring that new broadleaf woodland cover does not exacerbate water

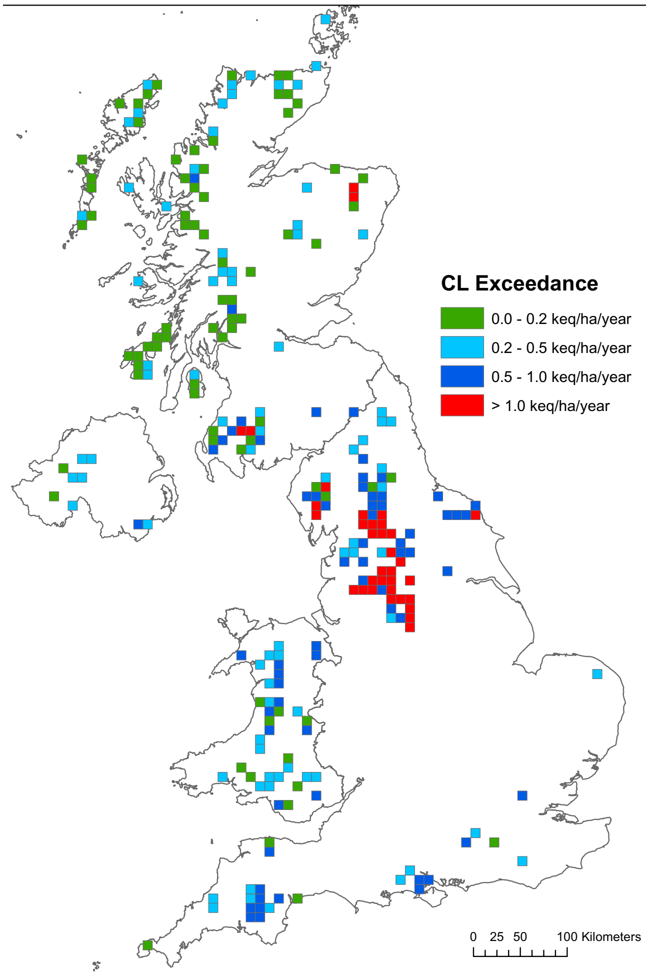

Figure 1 *Critical load exceedance squares of acidity for freshwaters in the UK by non-marine S and N deposition for 1995–97 (Forestry Commission, 2003)*

acidification in the UK. It aimed to:

(1) determine if there is evidence of an association between the proportion of broadleaf woodland cover within vulnerable catchments and various indicators of water acidification; and,
(2) assess freshwater critical loads in acid-sensitive catchments with broadleaf woodland cover.

Study catchments

Study catchments in the UK were identified and characterised using digital spatial datasets held in Arc (ESRI, California, USA) Geographical Information System (GIS). The main datasets were the critical loads exceedance dataset (Forestry Commission, 10 km grid) and the National Inventory of Woodlands and Trees (Forestry Commission, 1:25 000). Broadleaf woodland polygons were selected that lay within or immediately adjacent to a critical load exceedance square. Conifer and mixed forests were excluded from the analysis in order to identify catchments with solely broadleaf woodland cover. Catchment areas were delineated from digital elevation models (EDINA Digimap, PROFILE, 1:10 000) and percentages of broadleaf woodland cover were calculated. Solid geology digital data (BGS, 1:625 000) were used to ensure that the catchments were underlain by an acidic geology. Following field visits, ten catchments were selected with broadleaf woodland covers ranging from 10% to 79% of the catchment area (Table 1) in north-west Scotland (Glen Arnisdale, three catchments), the Trossachs (Loch Katrine, four catchments), Cumbria (Ullswater, two catchments) and Devon (Yarner Wood catchment) (Figure 2). Only catchments with no known influence from other confounding land uses and management practices such as liming and agricultural runoff were included. The dominant woodland types were upland birchwoods in the Scottish catchments, wet alderwood in the Ullswater

Table 1 *Characteristics of the study catchments Glen Arnisdale (GA), Loch Katrine (LK), Ullswater (UL), Yarner Wood (YAR) and Narrator Brook (NAR)). The control catchments are GACON, LKCON, ULCON and NAR (see text for explanation). Critical load exceedance is from the provisional map for UK freshwaters.*

Catchments	Broadleaf woodland cover (%)	Catchment area (ha)	Critical loads exceedance (keq^{-1} ha^{-1} yr^{-1})
GA1	27.3	66.0	0.0–0.2
GA2	24.9	16.9	0.0–0.2
GA3	20.3	53.5	0.0–0.2
GACON	0.0	35.6	0.0–0.2
LK1	29.0	103	0.5–1.0
LK2	16.3	132	0.5–1.0
LK3	19.7	20.9	0.5–1.0
LK4	10.3	39.6	0.5–1.0
UL1	53.4	8.56	Not exceeded-adjacent square
UL2	78.7	17.0	Not exceeded-adjacent square
ULCON	0.0	9.0	Not exceeded-adjacent square
YAR	49.9	134	0.2–0.5
NAR	2.0	240	0.2–0.5

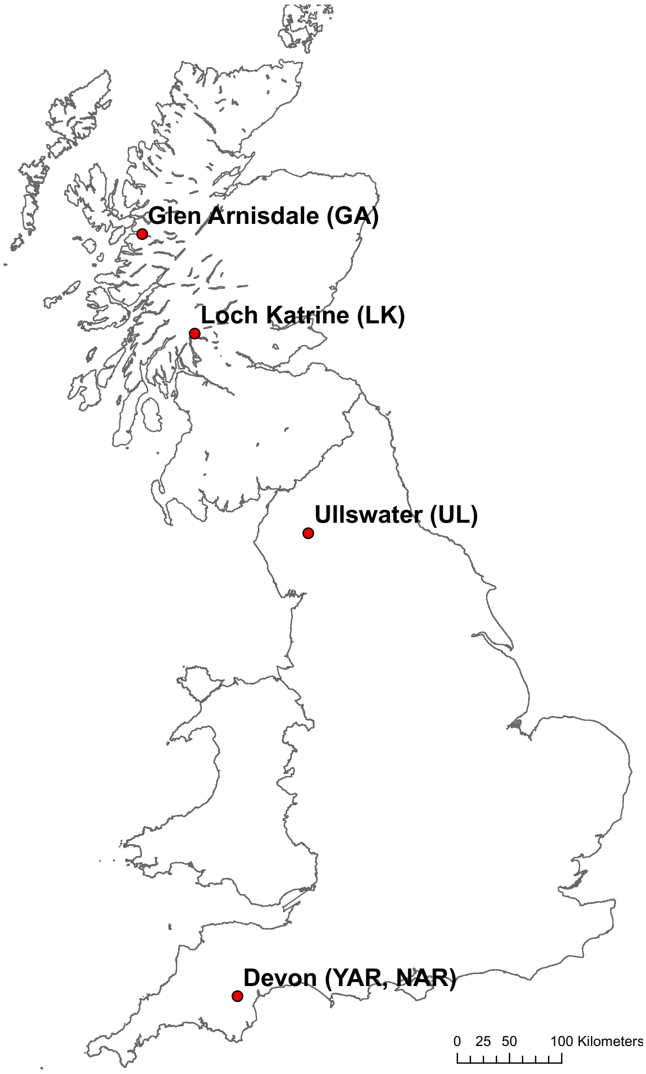

Figure 2 *Location of study catchments in Scotland and England*

catchments and acid oakwood in the Yarner Wood catchment. Three 'control' catchments with no woodland cover were selected adjacent to the catchments in Glen Arnisdale, Loch Katrine and Ullswater in squares of the same critical load exceedance class with similar topographic characteristics as the forested ones. For the Yarner Wood catchment, the control was the nearby (20 km) Narrator Brook catchment, part of the Acid Waters Monitoring Network (AWMN) with monthly streamwater chemistry data available since 1988.

Catchment soils were dominated by podsols and peaty gleys. The catchments in Glen Arnisdale and Loch Katrine have a clear upland character with maximum altitudes ranging from 600 to 700 m and mean slopes from 40 to 50%, while the English catchments have a gentler relief (mean slopes 15–20%) and maximum altitudes in the range of 400–500 m.

Two to ten streamwater samples were collected from the catchment outlets in January to April 2005 and November to March 2006 during high flow. The water samples were analysed for alkalinity, base cations, major anions (chloride, sulphate and nitrate) and aluminium, manganese and iron. Standard analytical methods were used and a selected subset of water samples was analysed by Forest Research in an interlaboratory comparison for quality control. In the case of Narrator Brook, chemistry results from monthly streamwater samples for January to March 2005 were used to coincide with the samples collected from Yarner Wood.

Results

Selected streamwater chemistry results are shown in Table 2. The Glen Arnisdale catchments are strongly influenced by the local marine climate resulting in the highest measured streamwater chloride (Cl) concentrations, but low concentrations of non-marine sulphate (xSO_4) and nitrate (NO_3). The highest concentrations of acidifying anions (both xSO_4 and NO_3) were in the Ullswater catchments. Relatively high streamwater sulphate concentrations occurred in the Yarner Wood and Narrator

Table 2. Mean concentrations of alkalinity (μeq l^{-1}), chloride, marine and non-marine sulphate (xSO_4) and nitrate (all mg l^{-1}) and aluminium (μg l^{-1}) in streamwater sampled at high flow.

Catchments	*No. samples*	*Alkalinity*	*Cl*	*SO_4*	*xSO_4*	*NO_3*	*Al*
GA1	2	33.9	18.9	2.76	0.81	0.23	48
GA2	2	20.1	20.0	2.82	0.77	0.21	51
GA3	2	0.0	23.0	3.10	0.74	0.22	53
GACON	2	54.0	24.9	3.40	0.83	0.21	46
LK1	10	35.4	4.80	1.97	1.47	0.53	61
LK2	10	1.55	4.27	1.86	1.21	0.41	49
LK3	10	8.04	4.76	1.86	1.37	0.33	38
LK4	10	32.8	4.44	1.99	1.53	0.71	29
LKCON	10	29.5	4.18	1.90	1.47	0.43	21
UL1	5	0.00	9.96	4.70	3.67	6.66	88
UL2	5	278	9.86	4.85	3.83	6.57	39
ULCON	5	141	5.52	4.03	3.46	0.31	15
YAR	8	20.0	11.9	3.84	2.62	2.57	66
NAR	3	15.1	8.87	4.00	3.09	0.49	50

Brook catchments and also relatively high nitrate concentrations in Yarner Wood. The Loch Katrine catchments are the most inland of the study catchments and had low chloride concentrations, with sulphate and nitrate concentrations intermediate between the English and the remote Scottish catchments.

Most catchments had a similar degree of acid sensitivity, with mean streamwater alkalinity ranging from 0 to 141 μeq l^{-1}, and only the UL2 catchment appeared to be well buffered to acidic inputs with alkalinity values above the acid sensitivity threshold value of 200 μeq l^{-1}. Mean concentrations of Al were highest in catchment UL1 (88 μg l^{-1}) while all catchments with woodland covers below 30% had Al concentrations less than 61 μg l^{-1}, with the lowest concentrations occurring in streamwater from the non-forested Loch Katrine and Ullswater catchments.

Spearman's rank correlation was used to investigate the associations between catchment percentage broadleaf woodland cover and streamwater chemical indicators of acidification. Significant positive correlations were found between percentage broadleaf woodland cover and mean

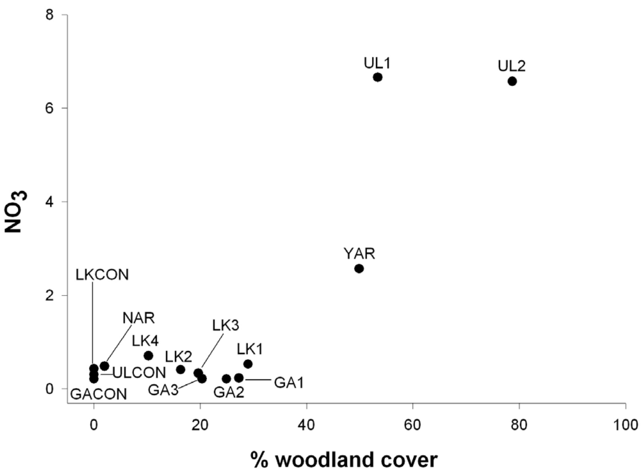

Figure 3 *Association between mean streamwater nitrate concentrations at high flow and % broadleaf woodland cover. Catchment acronyms are given in Table 1.*

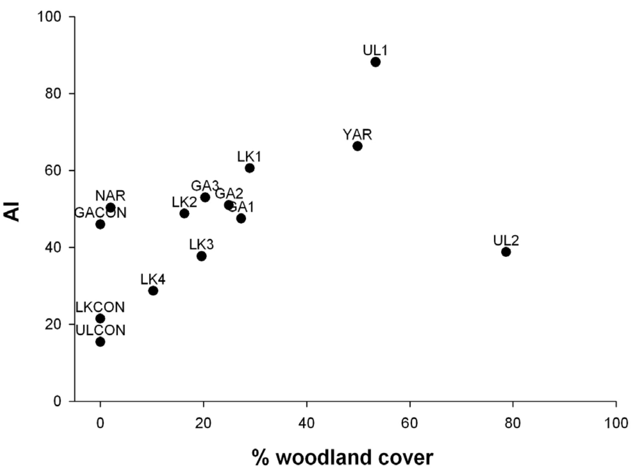

Figure 4 *Association between mean streamwater aluminium concentrations at high flow and % broadleaf woodland cover. Catchment acronyms are given in Table 1.*

streamwater NO_3 concentrations ($r_s = 0.51$, $p = 0.031$) (Figure 3) and also for Al concentrations ($r_s = 0.64$, $p = 0.007$) (Figure 4). Percentage woodland cover was also weakly correlated with mean SO_4 and xSO_4 concentrations (r_s = 0.28 and 0.29 respectively).

Mean streamwater concentrations for each catchment were used to calculate critical loads (CL) with the SSWC model. The CL values ranged from 0.40 to 2.64 keq H ha^{-1} yr^{-1}, showing moderate to high catchment susceptibility to acidification. Even though CL values for NAR are published by the Centre of Ecology and Hydrology (CEH) and calculated using a slightly different methodology, the CL values presented here for NAR were derived using the same methodology as the other catchments for consistency.

Comparison of the CL values with the 1995–97 modelled deposition data and nitrogen leaching in runoff found that critical loads were exceeded in only three of the 14 catchments (catchments NAR, YAR and UL1 at 0.45, 0.85 and 1.74 keq H ha^{-1} yr^{-1} respectively). NAR remained in the same CL exceedance class as its grid square, while YAR fell into a higher exceedance class (Table 1). UL1 fell into the highest exceedance class (>1 keq H $ha^{-1}yr^{-1}$), despite lying in a not exceeded square (Table 1). The CL are no longer exceeded in the Glen Arnisdale and Loch Katrine catchments while non-exceedance remained in catchments UL2 and ULCON (CL not exceeded by 0.15 to 1.21 keq H $ha^{-1}yr^{-1}$).

CL exceedance was recalculated using more recent modelled deposition data for 2002 generated by the FRAME model (Singles *et al*., 1998). Again, CL were only exceeded in catchments NAR, YAR and UL1 by 0.05, 0.36 and 1.02 keq H ha^{-1} yr^{-1} respectively. NAR is marginally acid-sensitive, categorised in the lowest CL exceedance class, while YAR and UL1 had lower CL exceedance than that calculated with the 1995–97 deposition data (Figure 5). CL was not exceeded in the remaining study catchments by 0.90 to 1.96 keq H ha^{-1} yr^{-1}.

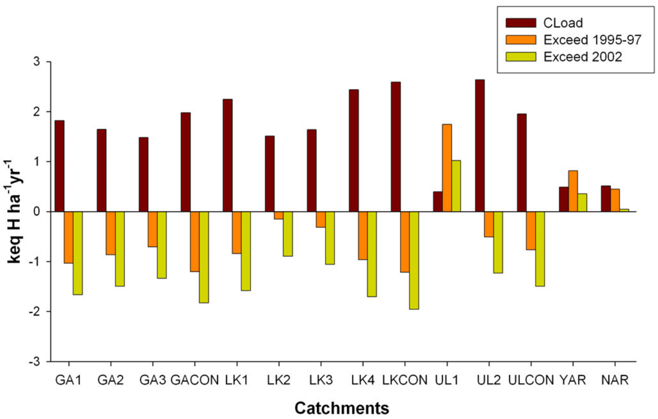

Figure 5 *CL values and CL exceedances calculated using the 1995–97 deposition data and the 2002 modelled deposition with FRAME. Negative values indicate non-exceedance.*

Discussion

Local variability in acidic pollutant deposition masked the influence of the woodland scavenging effect in the study catchments. For example, catchments with no or low percentage woodland cover (ULCON and NAR) had high SO_4 and xSO_4 streamwater concentrations, probably due to high past and present S deposition in north-west and south-west England (NEGTAP, 2001). These high concentrations meant that the expected strong relationship between streamwater SO_4 and xSO_4 and the percentage of woodland cover was not found in the study catchments.

The significant positive association between streamwater nitrate concentrations and percentage woodland cover was shaped by the high nitrate values of the high percentage woodland cover catchments (YAR, UL1 and UL2) with concentrations up to 6.7 mg l^{-1}, while all catchments with woodland coverage below 30% had similar low nitrate concentrations (all < 1 mg l^{-1}) (Figure 3). The high nitrate concentrations in Yarner Wood and the two Ullswater catchments were probably a result of the local N inputs and the type and extent of broadleaf woodland present. These catchments receive the highest N deposition inputs of all the study catchments (FRAME dataset), due mainly to their proximity to major pollution sources (e.g. nitrous oxides from vehicles, ammonia emissions from agricultural activities). Scavenging of pollutants by woodland canopies is strongly influenced by the height and structure of the vegetation layer, especially for dry and occult deposition (Nisbet *et al.*, 1995). Thus, the dense woodland communities of oak and alder in the Yarner Wood and Ullswater catchments respectively have a greater scavenging potential than the sparse vegetation of the upland birchwoods covering the Glen Arnisdale and Loch Katrine catchments. Furthermore, mature woodlands, as in the Yarner Wood and Ullswater catchments, tend to release more nitrate with age, while alder is an N-fixing species and has been reported to leach nitrate to water at high rates (Verburg *et al*., 2001). Therefore, the type of broadleaf woodland (i.e. tree species composition and woodland structure) appeared to have a large influence on streamwater nitrate concentrations in the study catchments.

The measured streamwater alkalinity values showed that most of the study catchments had a low to moderate capacity for neutralising acidic inputs, mainly because they lie on acidic, base-poor or slowly weathering geology. Only catchment UL2 had a high buffering capacity, probably due to past application of lime. Therefore, the observed strong positive association between streamwater aluminium concentration and percentage catchment woodland cover can be attributed to woodland pollutant scavenging along with nitrate leaching from woodland stands, resulting in high inputs of acidity that trigger the mobilisation and leaching of aluminium to streamwater. Aluminium mobilised at low streamwater pH during high acidic inputs can be highly toxic to freshwater biota (Stutter *et al.*, 2001).

The finding that most of the study catchments seem to be protected from further acidification (from comparison of CL values with the recent 2002 deposition data) can be attributed to the marked reductions in S emissions due to international agreements and the subsequent reductions in S deposition. Recent estimates indicate that deposition of non-marine S in the UK declined by 60% between 1986 and 2001 (Fowler *et al*., 2005). As levels of atmospherically deposited S decrease, surface water concentrations of xSO_4 have fallen accordingly. For example, most sites in the AWMN show a significant downward trend in xSO_4 concentrations (Davies *et al*., 2005). However, total N deposition (oxidised and reduced) has remained fairly constant in the UK, while small increases have been reported in coastal areas of western Britain. In addition, despite the decline of inland sources of SO_2, S emissions from shipping have increased and have become a significant contributor to S deposition in western areas, such as south-west England (Fowler *et al*., 2005). This could explain the high xSO_4 streamwater concentrations in the Yarner Wood and Narrator Brook catchments that led to the exceedance of their CL values. The high CL exceedance in catchment UL1 is caused by high streamwater xSO_4 and NO_3 concentrations, with nitrate being the major acidifying anion. Low S and N deposition levels in north-west Scotland and the Trossachs result in non-exceedance of CL values in the Glen Arnisdale and Loch Katrine catchments.

Conclusions

Broadleaf woodland appears to exert a significant influence on streamwater chemistry in acid-sensitive catchments, mainly due to pollutant scavenging and nitrate leaching, but only when it covers a large proportion of the catchment area. The finding that almost all study catchments with woodland covers of <30% are well protected from acidification suggests that the 30% woodland cover value is a sensible threshold for use within the Forests & Water Guidelines framework. The guidelines should ensure the minimisation of diffuse pollution from acidification in catchments in which broadleaf woodland is expanding. However, since recent emission reductions, especially for S, have led to most of the study catchments being protected from further acidification, the guidelines would much benefit from adopting more recent and improved modelled deposition estimates when determining the susceptibility of freshwaters to acidification.

Acknowledgments

Zisis Gagkas was funded by the Greek State Scholarships Foundation (IKY). The authors are grateful to the landowners for access to the sites, the staff from Forest Research and Eden Rivers Trust for collecting water samples, Forest Research for additional funding, ENSIS Ltd for data from Narrator Brook, BADC for rainfall data and Dr. Vieno for access to the FRAME deposition data.

References

Davies, J.J.L., Jenkins, A., Monteith, D.T., Evans, C.D. and Cooper, D.M., 2005. Trends in surface water chemistry of acidified UK Freshwaters, 1988-2002. *Environ. Pollut.*, **137**, 27–39.

Forestry Commission, 2003. *Forests and Water Guidelines: Fourth Edition*. Forestry Commission, Edinburgh, 66pp.

Fowler, D., Smith, R.I., Muller, J.B., Hayman, G. and Vincent, K.J., 2005. Changes in the atmospheric deposition of acidifying compounds in the UK between 1986 and 2001. *Environ. Pollut.*, **137**, 15–25.

Henriksen, A., Dickson, W. and Brakke, D.F., 1986. *Critical loads for Sulphur and Nitrogen,* Nordic Council of Ministers, Copenhagen, Denmark.

Jenkins, A. and Ferrier, R.C., 2000. Acidifying Atmospheric Pollutants. In: *Diffuse Pollution Impacts-The Environmental and Economic Impacts of Diffuse Pollution in the U.K,* B.J. D'Arcy, J.B. Ellis, R.C. Ferrier, A. Jenkins and R. Dils (Eds.), Terence Dalton Publishers. 105–111.

Neal, C., 2002. Interception and attenuation of atmospheric pollution in a lowland afforested site, Old Pond Close, Northamptonshire, UK. *Sci. Total Environ.*, **282-283**, 99–119.

NEGTAP, 2001. *Transboundary air pollution: acidification, eutrophication and ground-level ozone.* Prepared for the UK Department of the Environment, Food and Rural Affairs, Scottish Executive, The National Assembly for Wales/Cynulliad Cenedlaethol Cymru, Department of the Environment for Northern Ireland, National Expert Group on Transboundary Air Pollution (NEGTAP), CEH, Edinburgh.

Nisbet, T.R., Fowler, D. and Smith, R.I., 1995. An investigation of the impact of afforestation on stream-water chemistry in the Loch Dee catchment, SW Scotland. *Environ. Pollut.*, **90**, 111–120.

Rollison, T., 2000. The UK policy context. In: *The Restoration of Wooded Landscapes,* J. Humphrey (Ed.), Forestry Commission, Heriot Watt University, Edinburgh.

Singles, R., Sutton, M.A. and Weston, K.J., 1998. A multi-layer model to describe the atmospheric transport and deposition of ammonia in Great Britain. *Atmos. Environ.*, **32**, 393–399.

Stutter, M., Smart, R., Cresser, M.S. and Langan, S., 2001. Catchment characteristics controlling the mobilization and potential toxicity of aluminium fractions in the catchment of the River Dee, northeast Scotland. *Sci. Total Environ.*, **281**, 121–139.

Verburg, P.S.J., Johnson, D.W. and Harrison, R., 2001. Long-term nutrient cycling patterns in Douglas-fir and red alder stands: a simulation study. *Forest. Ecol. Manag.*, **145**, 203–217.