
Stevens, P. A.; Emmett, B. A.; Reynolds, B.; Norris, D. A.. 1993 Critical loads of nitrogen for upland forests in Wales - effects of plantation age. In: Hornung, M.; Skeffington, R. A., (eds.) *Critical loads: concept and applications.* London, HMSO, 90-93. (ITE Symposium, 28).

Critical loads of nitrogen for upland forests in Wales – effects of plantation age

P A Stevens, B A Emmett, B Reynolds & D A Norris

Institute of Terrestrial Ecology, Bangor Research Unit, Orton Building, University College of North Wales, Deiniol Road, Bangor, Gwynedd LL57 2UP

For ten years or more, staff at ITE Bangor have studied the effects of upland land use change on the biogeochemical cycling of nutrients. Using the small catchment approach, a primary objective has been to assess the effects of afforestation with exotic conifers, mainly Sitka spruce (*Picea sitchensis*) on soils, soil waters and streamwaters. Analysis of streamwater from a small number of agriculturally unimproved moorland and young forest stands at Llyn Brianne and Plynlimon reveals low concentrations of nitrate (Figure 1). These observations are, therefore, in line with the traditional view that these systems are nitrogen-limited and are unlikely to lose nitrogen through the process of nitrate leaching. Figure 1 also shows that the mature, 50-year-old spruce plantation at Beddgelert has a considerably higher streamwater nitrate concentration. In fact, the inorganic nitrogen budget for the Beddgelert catchment reveals a state approaching nitrogen saturation. Streamwater inorganic nitrogen outputs (entirely as nitrate) have averaged 14.6 kg N ha^{-1} yr^{-1} since 1982, whereas wet deposition inputs, which admittedly underestimate total inputs, have averaged 10.3 kg N ha^{-1} yr^{-1} (Stevens *et al.* 1993). It is clear that the trees, forest floor litter or soil microbial biomass of the Beddgelert system are unable to immobilise the available nitrogen, unlike the moorland and younger tree crops.

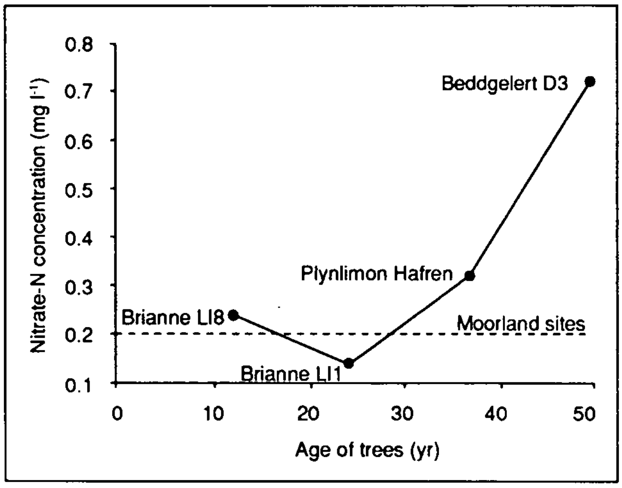

Figure 1. Streamwater nitrate concentrations at ITE forest and moorland sites in Wales

Because of the comparatively large nitrate leaching losses (for an upland ecosystem) at Beddgelert, there is concern that acidification of soils will be occurring at a faster rate than that attributable to acid deposition and biomass uptake of base cations. This concern is based upon the acidifying effect of nitrification. Nitrification is the conversion to nitrate-N of ammonium-N derived from mineralisation of soil organic matter or entering the system as atmospheric deposition. For each nitrate ion generated by nitrification, two hydrogen ions are released. If the nitrate is taken up by plants, the hydrogen ions are re-immobilised in the vegetation and there is no overall increase or decrease in hydrogen ion concentration in the system (Reuss & Johnson 1986). If the nitrate is in excess of plant or soil microbial demand, it may be leached. In this case, the hydrogen ions may:

- leach from the soil, resulting in stream acidification;
- exchange for Al or base cations on the soil exchange complex, leading to enhanced Al concentrations in streams or a reduction in soil base saturation;
- lead to enhanced weathering rates and the generation of Al minerals, which in turn will increase the extent of Al saturation on the soil exchange complex.

Acidification of soils by atmospheric deposition of nitrogen compounds will be mainly through nitrification of ammonium-N inputs, coupled with leaching of the nitrate-N generated. Acidification resulting from wet deposition of nitrate-N and dry deposition of NO_x will depend upon the relative proportions of acidic and basic cations accompanying the incoming and outgoing nitrate.

Acidification due to the nitrogen transformations in soil may be estimated using the method proposed by van Breemen, Driscoll and Mulder (1984) and applied by Berdén *et al.* (1987):

$$\text{Acidification} = (NH_4^+{}_{in} - NH_4^+{}_{out}) + (NO_3^-{}_{out} - NO_3^-{}_{in})$$

At Beddgelert, the average rate of acidification from this process for the period 1982-90 is 1.00 keq H^+ ha^{-1}

yr^{-1}. This figure compares with acid deposition (wet only) inputs of 0.94 keq H^{+} ha^{-1} yr^{-1} and a critical load for acidity of 0.2 keq H^{+} ha^{-1} yr^{-1} for the soil at Beddgelert (K R Bull, pers. comm.), although a degree of 'double accounting' of the nitrogen inputs is included in these calculations. In Britain, the maps of critical load exceedance of soils have been prepared using acid deposition inputs as the only acidifying influence. Nitrogen transformations have so far been excluded from these exercises, but it is clear that, in sites such as Beddgelert, this source of acidification may have a substantial impact.

It would be easy to dismiss the Beddgelert site as 'unusual'. However, there are a number of plausible and undoubtedly interlinked explanations why this and other mature spruce plantations may be unable to utilise available nitrogen, resulting in it being lost as nitrate.

i. Inputs of inorganic-N, primarily as dry deposition and cloud water deposition, may be greater to taller, older crops.
ii. Rates of mineralisation and nitrification of forest floor and pre-existing soil organic matter may be greater in older crops, either as a result of improved microclimatic conditions or increased N concentrations in throughfall (see i).
iii. Mature crops have a reduced demand for nitrogen, which results in greater rates of leakage of the N made available in throughfall and mineralisation. Reduced demand for N may be the result of smaller growth increments (because of the physiological age of the trees or deficiencies of other nutrients such as P and K), or increased internal retranslocation of N. Inputs of nitrogen in wet deposition over most of Wales are significantly greater than at pristine sites, and these inputs may be greater than the trees' requirement in the later stages of the crop cycle.

In order to test the hypothesis that there is a relationship between nitrate leaching rates and spruce crop age, the Forest Nitrogen Survey was established. In 25 upland catchments in mid- and north Wales, wet deposition inputs, throughfall, soil water and stream solute concentrations were measured every four weeks for one year until November 1991. Five of these catchments were agriculturally unimproved moorland or grassland, and there were five catchments in each of four forest age categories; 0-15, 16-30, 31-45, and greater than 45 years. Data from the first six months of this study indicate a very clear relationship between streamwater nitrate concentration and forest age (Figure 2), and a similar trend to that in Figure 1. Only in forests older than 30 years are stream nitrate concentrations higher than 0.2 mg N l^{-1}, but in the oldest sites nitrate concentrations reach 1.0 mg N l^{-1}. Initial data analysis indicates that throughfall inorganic-N fluxes increase linearly with age, but the increase is insufficient to explain the trend in streamwater nitrate concentrations. Also, rates of mineralisation and nitrification in the soil increase with crop age, and particularly in crops older than 30 years. A combination of (i) and (ii) above, and probably (iii) are, therefore, the likely causes of the observed leaching losses.

It may be concluded that soils of crops older than 30 years will be acidifying through the influence of nitrogen transformations, especially as more than half of the inorganic-N entering the system in rain or throughfall is in the ammonium form. In much of Wales, where the critical load for acidity of soils is exceeded by wet deposition inputs alone, total exceedance of the critical load for acidity will be substantially more than currently recognised.

The critical load for nitrogen *as a nutrient* is clearly exceeded in crops older than 30 years. In much of upland Wales, wet deposition inputs of inorganic-N are around 10 kg N ha^{-1} yr^{-1}, and evidence from Beddgelert indicates that total inputs are nearer 20 kg N ha^{-1} yr^{-1} if throughfall fluxes are used as a surrogate (Stevens *et al.* 1990). For there to be no leaching losses of nitrogen, immobilisation within the tree biomass or soil must occur. However, immobilisation within the soil microbial population or soil organic matter only delays the losses until a phase of increased mineralisation occurs, such as following clearfelling. It may therefore be argued that, to avoid acidification, rates of atmospheric N inputs should be balanced, in the long term, by the removal of nutrients in timber at harvest. The 50-year-old trees at Beddgelert contain 128 kg N ha^{-1} in harvestable timber and 428 kg N ha^{-1} in all above-ground biomass (Stevens *et al.* 1988), equivalent to rates of accumulation of 2.5 and 8.5 kg N ha^{-1} yr^{-1} respectively. Allowing for an acceptable (and arbitrarily defined) rate of acidification of, for example, 2.5 kg N ha^{-1} yr^{-1}, conventional (stem only) and whole-tree harvesting would require the target load for nitrogen to be set at 5 and 11 kg N ha^{-1} yr^{-1} respectively. Whole-tree harvesting is probably not a long-term solution, however, as losses of base

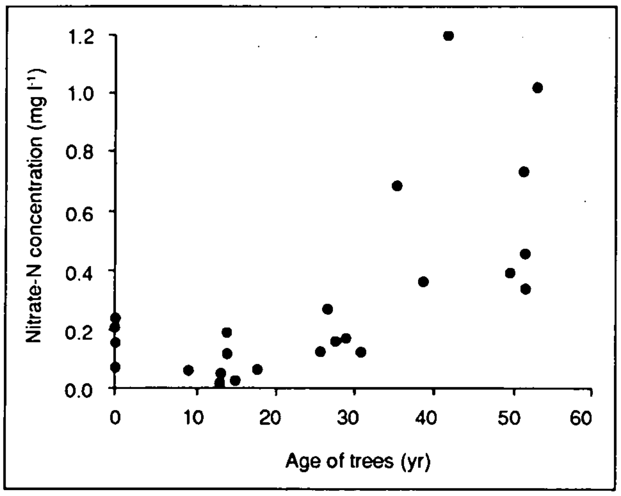

Figure 2. Streamwater nitrate concentrations at the 25 Forest Nitrogen Survey catchments. Plotted points are means of the first six months of the study. Moorland sites are plotted at age 0

cations in harvested material would also result in significant soil acidification. For example, at Beddgelert, 279 kg Ca ha^{-1} would be removed by whole-tree harvest at a site where the soil pool of extractable Ca is only 112 kg Ca ha^{-1} to the base of the rooting zone, and the total calcium content of the soil is 1390 kg ha^{-1} (Stevens *et al.* 1988). Unless this rate of removal is balanced by rain or dust inputs of Ca, significant soil base cation depletion will result.

Unless whole-tree harvesting is practised, in which case fertilization with base cations and P will be necessary, inputs of N from the atmosphere will need to be reduced substantially from around 20 kg N ha^{-1} yr^{-1} (total inputs) to 5 kg N ha^{-1} yr^{-1}. Ideally, there should be a greater reduction of ammonium-N inputs than nitrate-N. Ammonium-N is derived mainly from agricultural sources, and each mole of ammonium contributes two moles of hydrogen ion to the soil if nitrified and leached, even if this process occurs indirectly via the soil organic matter. At forest sites studied in the Forest Nitrogen Survey, results to date indicate that ammonium-N occurs in larger concentrations than nitrate-N in both incident rainfall and in throughfall, and it is therefore the more significant acidifying influence. Emissions of ammonia from intensive agriculture and the subsequent deposition in nearby woodland have been recognised as the major acidifying influence in woodlands in The Netherlands (van Breemen *et al.* 1982). It is something of a surprise, then, that the substantially less intensive animal production in upland Wales can also be the source of significant acidification of forests.

In the Forest Nitrogen Survey, it has been concluded that a substantial reduction in nitrogen inputs to forests is necessary to reduce acidification rates. However, emissions of nitrogen pollutants from industry, transport and agriculture are stable or increasing (Skeffington & Wilson 1988). We have shown that forest systems younger than 30 years immobilise incoming nitrogen, but the implications of increasing nitrogen deposition raise a number of questions regarding the future ability of these systems to continue acting in this way.

- What is the role of nitrogen on ecosystem acidification and what are the effects on other nutrients?
- What is the maximum, or critical, load for nitrogen which can be immobilised by a young Sitka spruce stand?
- What are the comparative effects of inputs of nitrate- or ammonium-N on soil and plant processes and pools?

These questions will hopefully be answered by an experiment in the hills near Aber, some 9 km east of Bangor, in which ammonium-N and/or nitrate-N is being added in a water spray to the forest floor of a 30-year-old Sitka spruce plantation at present leaching 4.2 kg N ha^{-1} yr^{-1} as nitrate and receiving inputs of 17 kg N ha^{-1} yr^{-1}. It is a randomised block experiment (Figure 3) containing three replicate

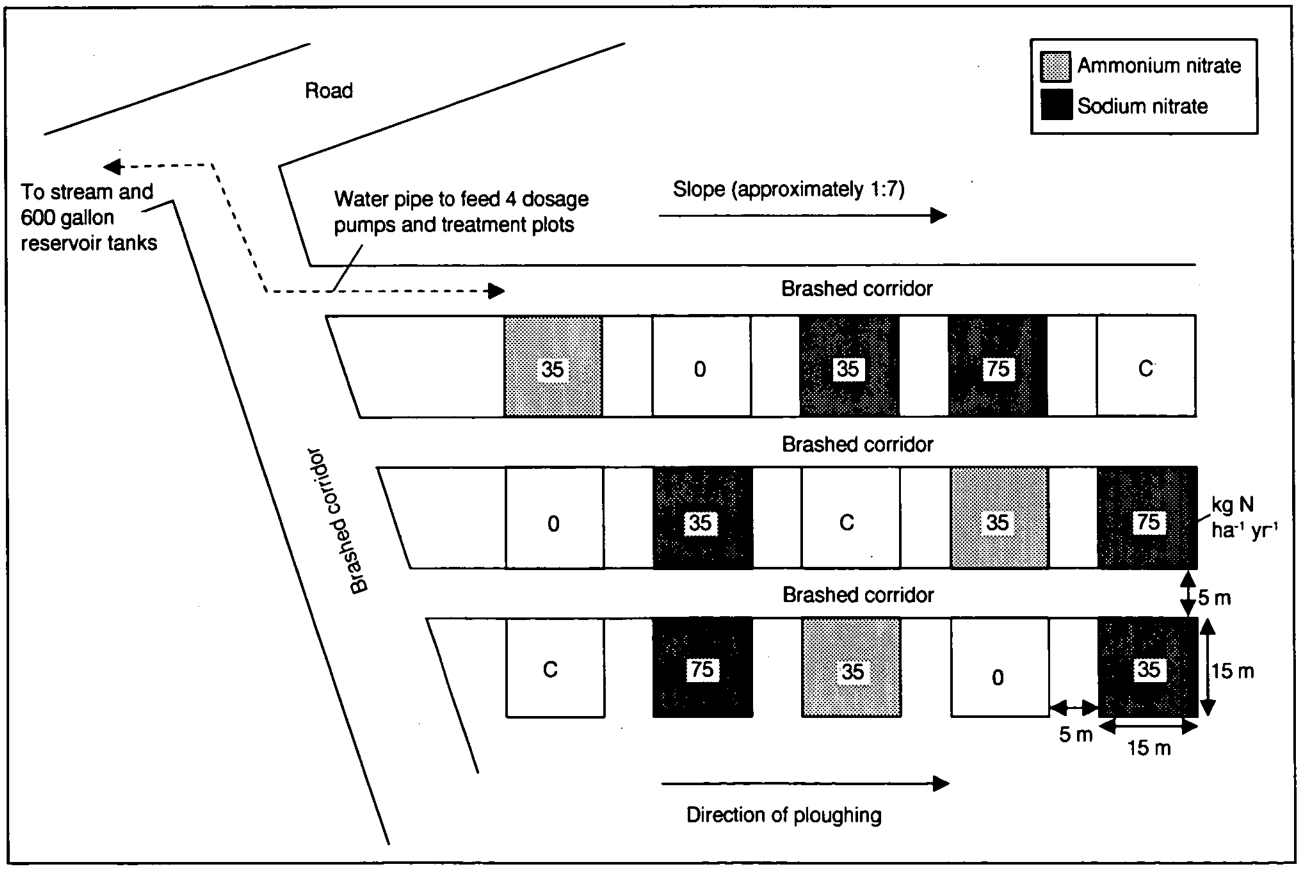

Figure 3. Layout of the Aber nitrogen critical load experiment. Each plot contains seven rows of spray tubing running parallel to plough furrows

plots of each of five treatments:

- control, no additional N, unsprayed
- zero N, sprayed with water only
- 35 kg N ha^{-1} yr^{-1} as sodium nitrate
- 35 kg N ha^{-1} yr^{-1} as ammonium nitrate
- 75 kg N ha^{-1} yr^{-1} as sodium nitrate

The additions represent extra nitrogen applied to the forest floor, and the total inputs, including throughfall and stemflow, are around 50 kg N ha^{-1} yr^{-1} in the 35 kg N spray plots. Spraying takes place approximately weekly, except in extended periods of dry or freezing weather. As a result, the additional nitrogen is applied at moderate concentration and avoids shock effects.

In each of the 15 plots, throughfall and soil water are collected and analysed every two weeks. Application of these treatments is intended to take place for 3-4 years. The first year was completed in October 1991, and ^{15}N is now being added to the N in the spray as an aid to identifying the sinks for the additional N. Results to date indicate that there is a significant sink for N in this forest; 100% of the ammonium nitrate and >75% of the nitrate in the sodium nitrate has been retained after one year of spraying. Sampling of soils, forest floor, tree biomass and litterfall, together with estimation of denitrification and soil water leaching losses, mineralisation and nitrification rates, will provide the basis for modification and development of models describing the effects of enhanced rates of nitrogen inputs to spruce plantations, and for the determination of a critical load.

Results from the Aber experiment will be integrated into an international network of Nitrogen Saturation Experiments (NITREX), comprising six European countries and funded by the CEC Science and Technology for Environmental Protection (STEP) programme. The network consists of either N addition or removal experiments across a nitrogen input pollution gradient from 5 kg N ha^{-1} yr^{-1} in Norway to 50 kg N ha^{-1} yr^{-1} in The Netherlands. The overall objectives of NITREX are to determine:

- the threshold for nitrogen saturation in coniferous forest ecosystems;
- when and how recovery occurs following removal or reduction of N inputs (forest roof experiments);
- the critical load for N in coniferous forests in Europe;
- the role of N in ecosystem acidification and forest decline.

ACKNOWLEDGEMENTS

We thank the National Power/PowerGen Joint Environmental Programme, Vattenfall, Department of the Environment, CEC and NERC for funding this work. The Forestry Commission, Economic Forestry Group and various other landowners kindly allowed access to their land.

REFERENCES

Berdén, M., Nilsson, S.I., Rosén, K. & Tyler, G. 1987. *Soil acidification: extent, causes and consequences.* (Report no. 3292.) Solna: National Swedish Environmental Protection Board.

Reuss, J.O. & Johnson, D.W. 1986. *Acid deposition and the acidification of soils and waters.* New York: Springer-Verlag.

Skeffington, R.A. & Wilson E.J. 1988. Excess nitrogen deposition: issues for consideration. *Environmental Pollution,* **54,** 159-184.

Stevens, P.A., Adamson, J.K., Anderson, M.A. & Hornung, M. 1988. Effects of clearfelling on surface water quality and site nutrient status. In: *Ecological change in the uplands,* edited by M.B. Usher & D.B.A.Thompson, 289-293. (British Ecological Society Special Publication no. 7.) Oxford: Blackwell Scientific.

Stevens, P.A., Adamson, J.K., Reynolds, B. & Hornung, M. 1990. Dissolved inorganic nitrogen concentrations and fluxes in three British Sitka spruce plantations. *Plant and Soil,* **128,** 103-108.

Stevens, P.A., Williams, T.G., Norris, D.A. & Rowland, A.P. 1993. Dissolved inorganic nitrogen budget for a forested catchment at Beddgelert, north Wales. *Environmental Pollution,* **80,** 1-8.

van Breemen, N., Driscoll, C.T. & Mulder, J. 1984. Acidic deposition and internal proton sources in acidification of soils and waters. *Nature, London,* **307,** 599-604.

van Breemen, N., Burrough, P.A., Velthorst, E.J., van Dobben, H.F., Toke de Wit, Ridder, T.B. & Reynders, H.F.R. 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. *Nature, London,* **299,** 548-550.