Who Put the N in PristiNe

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Impacts of Nitrogen Enrichment in Fragile Mountain Environments

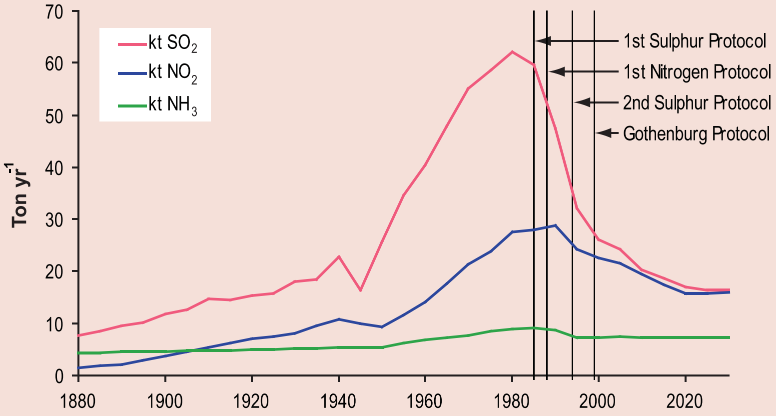
The last few decades have seen an exponential increase in the atmospheric concentration of reactive nitrogen. This has led to concerns from scientists, ecologists, and land managers regarding a cascade of ecosystem impacts, and the potential for elevated atmospheric inputs to significantly alter nutrient-poor systems. At particular risk are fragile mountain ecosystems, normally low in nutrients. Control of enhanced nitrogen deposition is required to prevent damage to terrestrial biodiversity and soil water quality, and decrease the release of excess nitrogen into headwaters to the detriment of aquatic ecology. To meet this challenge, control measures operate through legislation aimed at reducing emissions or by ecosystem management at a local level. Current legislation to reduce emissions is under review, whilst techniques aimed at managing nitrogen in lowland ecosystems are impractical in most remote mountain environments. Here we present research which shows the extent of ecosystem damage from enhanced nitrogen deposition and aims to inform future policy in support of national and international action to reduce nitrogen emissions.

Nitrogen: too much of a good thing

In the early 19th century, Fritz Haber and Carl Bosch freed the world from the chains of nitrogen limitation through a process that ‘fixes’ unreactive nitrogen from the atmosphere. The Haber-Bosch process gave farmers access to cheap nitrogenous fertilizers, enabling them to grow more crops at the expense of soil and water quality. At the same time the global atmosphere has experienced an exponential increase in reactive nitrogen (inorganic nitrate and ammonium) from combustion for industrial purposes, energy production, and transportation.

This has led to widespread concern over a cascade of impacts on human and environmental systems. Nitrogen is critical to plant nutrition and can regulate the structure of whole ecosystems. As a result, enhanced atmospheric deposition of reactive nitrogen has the potential for significant unintended detrimental impacts on nutrient-poor natural ecosystems. In large areas of Europe, chronic, long-term nitrogen deposition has led to nutrient enrichment in lowland and mountain ecosystems. In fragile mountain ecosystems, diffuse inputs of elevated nitrogen can significantly impact vegetation, soils, and surface waters, with further extensive adverse effects on terrestrial biodiversity and aquatic biota, including salmonid fish.

FIGURE 1 European emissions of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ammonia (NH_3) during the period 1880–2030, in metric tons per year.



There are two broad strategies to mitigate the impacts of diffuse pollution. The first—and perhaps most effective—is to reduce pollution at the emission source. The second is through local management strategies. Current research in the Scottish Highlands is unraveling the complex interplay between elevated nitrogen deposition, land management, and climate variability; it suggests that further national and international legislation to reduce nitrogen emission is required to avoid potentially catastrophic loss of pristine mountain ecosystems.

Here we outline the current legislative framework aimed at reducing atmospheric emissions and its relative effectiveness, and consider the potential for local mitigation options for managing the impacts of diffuse nitrogen. Finally, we present research showing the ecological and environmental effects of enhanced nitrogen deposition in a montane heathland that has high biodiversity value, under a scenario of unmanaged (escalating) nitrogen emissions.

Legislative framework to reduce atmospheric emissions

The United Nations Economic Commission for Europe (UNECE) has been largely responsible for legislation aimed at reducing diffuse pollutants at source through the Convention on Long-range Transboundary Air Pollution. The Convention is intended to protect the human environment against air pollution and to gradually reduce and prevent air pollution. Since 1979, the Convention has adopted 4 protocols to reduce emissions of sulfur and nitrogen gases to the atmosphere (Table 1). In parallel with these protocols, the European Union has established the National Emission Ceiling Directive. These protocols target water (and soil) quality specifically in headwater catchments that are sensitive to acidic deposition and nutrient enhancement. Negotiations are currently underway for the next protocol under the Convention, which are being partly guided by results from field experiments and model simulations described below.

During the past 2 decades, sulfur emissions (and subsequently deposition) have fallen dramatically across Europe (Figure 1), prompting recovery in acidified soils and surface waters. However, the efficacy of legislation has been less apparent for nitrogen emissions, particularly for the reduced form of nitrogen (NHy). Not only do these pollutants present a problem in themselves, but scientific evidence suggests that whilst NH_4 is readily removed from soil solution by plants and soil microbes, the long-term increases in soil and surface water nitrate (NO_3^-) concentrations (owing to nitrogen saturation in soils) might offset the expected recovery from acidification and lead to nutrient enrichment of vulnerable mountain ecosystems. The process of nitrogen "saturation" describes the decreased immobilization (retention) of deposited nitrogen in catchment soils as a result of increasing nitrogen (N) richness relative to carbon (C) (decreased C:N ratio) and subsequent NO_3^- breakthrough or leakage to surface waters.

TABLE 1 Protocols under the European Convention on Long-range Transboundary Air Pollution.

Year	Protocol	Emission control
1985	First Sulfur (Helsinki) Protocol	Reduce sulfur emissions by 30% by 1993 relative to 1980 levels.
1994	Second Sulfur (Oslo) Protocol	Reduce sulfur emissions by 80% of 1980 levels by 2010 (with different targets for each country).
1988	First Nitrogen (Sofia) Protocol	Stabilize nitrogen emissions at the 1987 level by 1994.
1999	Multi-Pollutant, Multi-Effect (Gothenburg) Protocol	By 2010 this would reduce sulfur emissions across Europe by at least 63%, nitrogen oxides by 41%, and reduced nitrogen by 17% relative to 1990 levels.

FIGURE 2 Altitude map of the United Kingdom and the Republic of Ireland showing the location of the Royal Society for the Protection of Birds (RSPB) reserve and the 2 experimental sites. (Map by M. Coull)

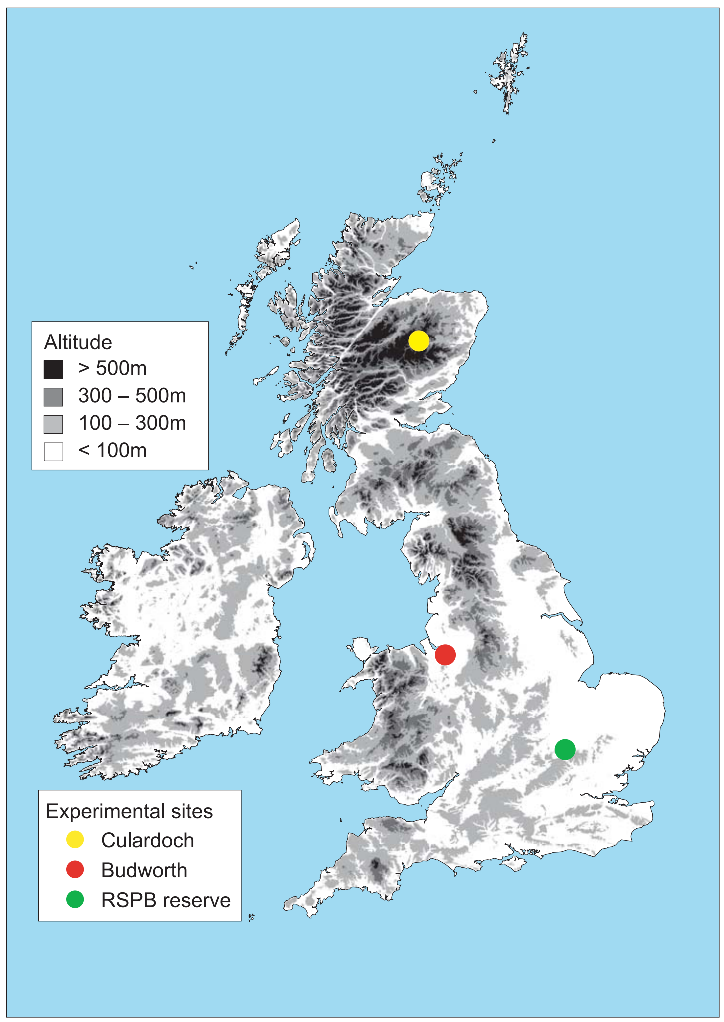


FIGURE 3 Vegetation cover in the area previously subject to turf-stripping (left) and an adjacent unmanaged area (right), August 2008. In the turf-stripped section, heather *Calluna vulgaris* (purple shrubs) can clearly be seen regenerating, whilst on the right, there is a fresh green growth of wavy hair-grass *Deschampsia flexuosa*. (Photo courtesy of M. Ausden)

Lowland management of nutrient enrichment

The nutrient status of lowland heaths can be maintained by management practices including burning, grazing, mowing, and turf-stripping. The local management of lowland heaths can result in effective remediation from nutrient enhancement; moreover, the restoration of vegetation communities and soil and water condition has been effectively demonstrated in a number of studies. Typical lowland heath, dominated by dwarf shrubs such as heather (*Calluna vulgaris* and *Erica* spp.), is a rare habitat in the United Kingdom (UK) and supports a distinctive fauna and flora. Research supported by the Royal Society for the Protection of Birds (RSPB) at their reserve (Figure 2; altitude 64 m) has shown that high rates of nitrogen deposition contributed to a replacement of heather-dominated heathlands by grasses, especially wavy hair-grass (*Deschampsia flexuosa*). For these habitats turf-stripping has been effectively used to reduce soil nutrients and encourage regeneration of heather (Figure 3).

Habitat management can also be used to counteract the effects of enhanced nitrogen deposition on ecosystem nutrient stores and soil and water quality. Here we draw on experimental evidence from Budworth, a lowland heath site located in Northwest England (see Figure 2; altitude 70 m) that receives around 800 mm of rainfall per year and has a background nitrogen deposition of 20 kg N ha^{-1} yr^{-1}. The site is dominated by *Calluna vulgaris*, with small amounts of *Deschampsia flexuosa*, and substantial moss cover. To assess the possible impact of a mowing treatment and 4 levels of nitrogen addition (0, 20, 60, 120 kg N $ha^{-1}yr^{-1}$), a hydrochemical model was applied to the Budworth site. The model forecasts suggest that intensive biomass removal had a significant effect on soil C:N ratio (used as an indicator of soil N status) and nitrogen leaching; however, when the biomass removal ceased on the control plots, this led to a predicted decrease in soil C:N (soil became more N-enriched relative to the soil carbon content) and a four-fold relative increase in nitrogen leaching by 2050, providing further evidence of the importance of continued management in these lowland ecosystems. Practical solutions to detrimental nutrient enhancement are therefore feasible and effective at a local scale.

However, in mountainous environments these options are impractical. The extensive spatial area receiving elevated nitrogen deposition makes intensive management both economically and practically impossible. Upland (sub-montane) environments account for 27–30% of the UK land area. In addition, most of the high-biodiversity upland ecosystems are protected by legislation (designated areas), significantly restricting the scope for intensive management strategies; moreover, even if management options were permitted, access issues due to their remote location and harsh climate would present a further challenge.

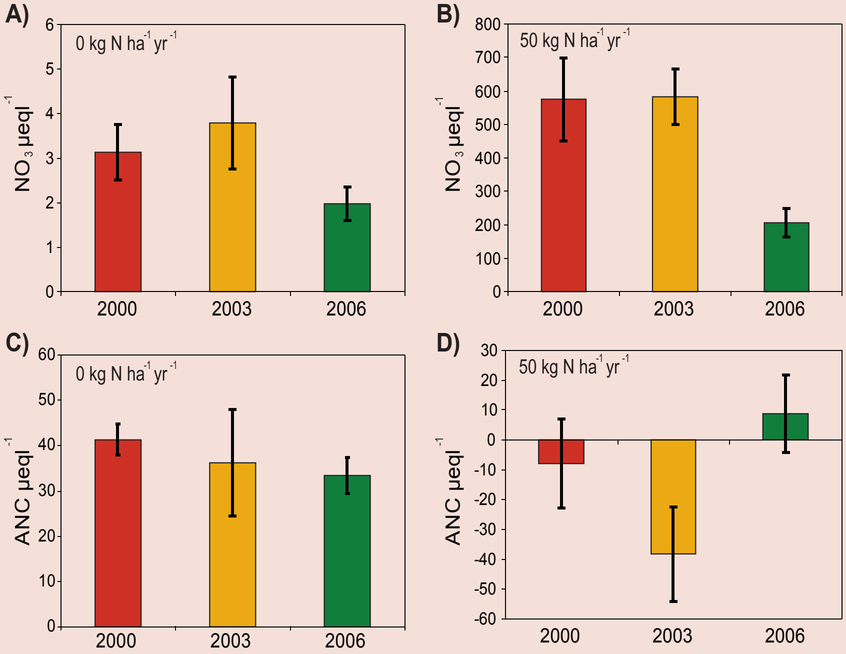
Research on the impact of nitrogen deposition on upland ecosystems

In order to inform and implement sustainable policy there must be a strong scientific basis to setting emission limits. The research presented here shows that unmanaged inputs of N into montane ecosystems can potentially result in significant damage to these fragile habitats, and aims at determining the critical thresholds for both acute (short-term effects) and chronic (long-term) impacts.

Evidence of the detrimental impacts of enhanced nitrogen deposition on montane ecosystems has been gathered at the Culardoch experimental site (see Figure 2) in the eastern Cairngorm mountains, Scottish Highlands. The Culardoch experimental site (Figure 4) is located on an area of prostrate *Calluna–Cladonia* heath on subalpine podzol at 750 m. We investigated how soil solution chemistry and vegetation communities respond to large nitrogen additions (50 kg $ha^{-1}yr^{-1}$), used to mirror long-term acute high-level N inputs, against a background deposition of 12 kg $ha^{-1}yr^{-1}$.

FIGURE 4 Sampling soil water in the midst of winter at the Culardoch experimental site. (Photo courtesy of Andrea Britton)

FIGURES 5A TO 5D Treatment effects on average soil water nitrate (NO_3^-): A) 0 kg N ha^{-1} yr^{-1}; B) 50 kg N ha^{-1} yr^{-1} and its impact on the capacity to neutralize acidity: Acid Neutralizing Capacity (ANC); C) 0 kg N ha^{-1} yr^{-1}; D) 50 kg N ha^{-1} yr^{-1}. (*Note different y-axes*)



Results show that nitrogen additions have a significant impact on soil water solution acidity. Soil water NO_3^- showed a highly significant and immediate response to nitrogen addition (Figures 5A, 5B) and this increase led to a decline in the soil C:N ratio over time as the soil became enriched with nitrogen following treatment. A 'flush' of base cations (calcium, magnesium, sodium, and potassium), which normally buffer the soil from the acid effects of deposited nitrogen, accompanied the excess nitrogen released from the soil, causing a decline in the acid neutralizing capacity and severe soil acidification (Figures 5C, 5D). This also shows that low-alpine heathlands, which occupy the headwaters of many rivers, have limited potential to retain atmospherically derived nitrogen and may rapidly become saturated, leaking higher concentrations of nitrogen to vegetation communities at lower elevations and enriching downstream waters. It is probable that very large, discrete nitrogen applications to this fragile ecosystem could either have a toxic impact on soil microbes—and overwhelm the rates at which the microbial population can immobilize nitrogen in the short term—or simply bypass the soil in water transported via soil cracks or macropores.

Variability in climate patterns during the study played an important role in determining temporal trends in soil water chemistry. Elevated soil water NO_3^- and ammonium concentrations followed the severe winter of 2000–2001 and the dry year of 2003. In addition, large peaks in soil water sulfate and base cation concentrations were observed in the spring of 2003.

Research at Culardoch has also shown that biodiversity of low-alpine *Calluna–Cladonia* heathlands is reduced by enhanced rates of nitrogen deposition. A significant decline in species richness was first detected after 2 seasons of nitrogen addition when compared with the control treatment. The deleterious effects of the high-nitrogen treatment were compounded when severe winter browning of *Calluna* was observed following early snowfall during the winter of 2003–2004 (Figure 6). This interaction affected only *Calluna* and appeared to have the potential to trigger species composition changes by reducing the dominance of this species. The critical load of nitrogen (amount above which deleterious impacts occur) for montane heaths lies within the current estimated range of 5–10 kg N ha^{-1} yr^{-1}. Effective conservation of biodiversity in low-alpine heathland will require action to reduce nitrogen deposition in the many areas that currently exceed this threshold.

The future of pristiNe environments

Nitrogen emissions throughout Europe are slowly declining but the effects of elevated nitrogen loading will not disappear overnight. Recovery of mountain biodiversity and soil and water quality from eutrophication is likely to be a slow process, but one which can be influenced by targeted management techniques employed at a local level, as well as by stringent legislation to reduce emissions at source.

Under current legislation nitrogen deposition exceeds the critical load of 5–10 kg N ha^{-1} yr^{-1}; furthermore, our research demonstrates that if deposition were to increase it would result in significant damage to vegetation communities, as well as in nutrient enrichment of soils and nitrogen leaching to surface waters.

FIGURES 6A AND 6B Nitrogen treatment effects on a low-alpine *Calluna–Cladonia* heath: A) No N addition (0 kg N ha^{-1} yr^{-1}); B) High N treatment (50 kg N ha^{-1} yr^{-1}).

Mountain ecosystems are extremely sensitive to environmental change and respond rapidly to perturbations in deposition and climate. Accordingly, it is important that future policy is focused on ecologically relevant thresholds.

The field experiments and model simulations presented here are being used to inform future policy; the output from these projects is very timely, given that the Gothenburg Protocol is currently under review.

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FURTHER READING

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