# Work Package 2 Task 7:

# Assessment of the long-term effects enhanced and reduced S and N deposition on UK forest ecosystems

Lead PI:

***Dr L Sheppard.***

Collaborating PIs:

***A Crossley***

***Dr N Cape***

INTERIM REPORT JULY 2002

# The effects of polluted cloud water on a Sitka spruce plantation (Deepsyke). Phase II: potential for recovery

**L. J. Sheppard, A. Crossley, J. N. Cape,**
**K Ingleby, V. Kennedy & D. Fowler**

## SUMMARY

- **Indicators of treatment change, soil solution chemistry and foliar chemistry, responded quickly, and significant trends were established within one year.**
- **Removing sulphuric acid from the treatments can be detected in the soil solution, foliar chemistry and foliar N uptake. Increased phosphate concentrations were measured both in the soil solution and foliage, indicating their close coupling. Foliar K was also increased. Soil solution acidity and sulphate also fell, while base cation levels decreased. Soil water nitrate concentrations increased, probably reflecting the improved conditions for nitrification. Increased nitrate was measured in throughfall, in response to the lower acidity concentration on the needle surface restricting needle uptake of nitrate ions, which may also contribute to the increase in nitrate.**
- **On this acid peat the removal of sulphuric acid appeared to improve conditions for nitrification. Such an effect may lead to greater nitrate leaching from similar peat sites in response to N deposition in the absence of acidified S inputs.**
- **Decreasing levels of acidified S in the atmosphere will reduce foliar N uptake and the immobilisation of N as ammonium in peat soils.**
- **Removing N or S from the treatments impacted on N and S in the soil solution but not the base cations. The removal of N reduced nitrate concentrations but barely affected ammonium. The removal of S reduced sulphate by a similar proportion to that seen for sulphuric acid removal.**
- **The removal of sulphuric acid and S produced similar changes in soil solution chemistry to those observed over the winter period, when there was no treatment. This indicates the changes are occurring in response to current rather than stored S and acidity inputs on this peat soil.**
- **The removal of S may reduce the attractiveness of the spruce foliage to the spruce aphid, since a reduction in aphid density was observed with the removal of sulphuric acid.**
- **Ectomycorrhizal fruiting body numbers have yet to respond to the removal of N, S or sulphuric acid.**
- **Growth responses are too early to report with confidence.**
- **Changes in foliar chemistry were observed, and were quite large *eg.* increases in foliar P and K in response to sulphuric acid removal (+20%) but were also quite heterogeneous ($p = 0.25$)**

## BACKGROUND

In the first phase of this experiment, a Sitka spruce plantation (P 1986) on peat in southern Scotland (Deepsyke, near West Linton, Borders Region) was treated with simulated cloud water for 5 years, to study the effects on tree growth, understorey vegetation and forest soil. There were 24 plots, each containing 10 trees, which were treated with one of 6 different simulated cloud treatments:

| | |
|---|---|
| NSAcid | sulphuric acid + ammonium nitrate<br>1.6 mM, 'dose' 50 kg N,S yr$^{-1}$ |
| 2NSAcid | 'double dose' 100 kg N,S yr$^{-1}$ |

| | | |
|---|---|---|
| S only | sodium sulphate | 1.6 mM |
| N only | ammonium nitrate | 1.6 mM |
| Control | rainwater + NSAcid | 0.1 mM |
| | | |
| No spray | no treatment | |

**Results from Phase I were reported in 2001, and may be summarised**:

- Tree growth (stem area increment) was increased by N in treatment

- NSAcid: increased litter fall, fine root mortality and aphid attack
  - killed understorey mosses
  - the acidity was neutralized in the canopy, but only a small proportion by ion exchange
- 2NSAcid: as for NSAcid, but also reduced foliar P, K, Ca, Mg;
  - increased foliar N, soil solution acidity, Al, N;
  - emitted $N_2O$
- N only reduced ectomycorrhizal diversity
  - doubled fine root production
  - increased foliar cytokinin concentrations
- S only no significant effects

## PHASE II

In the second phase, the treatment regime has been changed, in order to investigate:

1. The potential for and rate of recovery of trees from the first 5 years of treatment;
2. Continue the treatments to some of the plots for a further 3 years and
3. Identify indicators that respond quickly to change.

Originally, the 6 treatments were applied to 4 replicate blocks. Two of the blocks (selected at random) receive the original treatment, and the other two receive a different treatment, as shown in Table 1. The new treatment regime started in late spring 2001, and continued through to the end of November. Treatment in 2002 resumed in May. The results to date are presented below.

**Table 1. Changes to treatments after 2000: two plots per treatment**

| **Phase 1** | **Phase II** | |
|---|---|---|
| **NSAcid** | **NSAcid** | |
| | **N only** | ***removal of S and acidity*** |
| **2NSAcid** | **2NSAcid** | |
| | **2N only** | ***removal of S and acidity*** |
| **N only** | **N only** | |
| | **Control** | ***removal of N*** |
| **S only** | **S only** | |
| | **Control** | ***removal of S*** |
| **Control** | **Control** | ***no change*** |
| **No Spray** | **No Spray** | ***no change*** |

# RESULTS

## Soil water chemistry

Soil water from zero-tension lysimeters inserted into the rooting zone of the forest floor was sampled on 4 occasions over the spray period. Results are available and have been averaged for 3 occasions. Error bars on the figures show the standard deviations of the replicate plots. An asterisk or circle denotes a statistically significant difference between the 'new' treatment and the 'old' treatment for each of the sets of 4 plots.

For the plots originally treated with NSAcid, removal of the sulphuric acid from the treatment led to a marked reduction in soil sulphate concentrations, a significant decrease in base cation concentrations and an increase (doubling) of phosphate concentrations (Figure 1). Similar changes had been observed in the samples collected over the winter no treatment period.

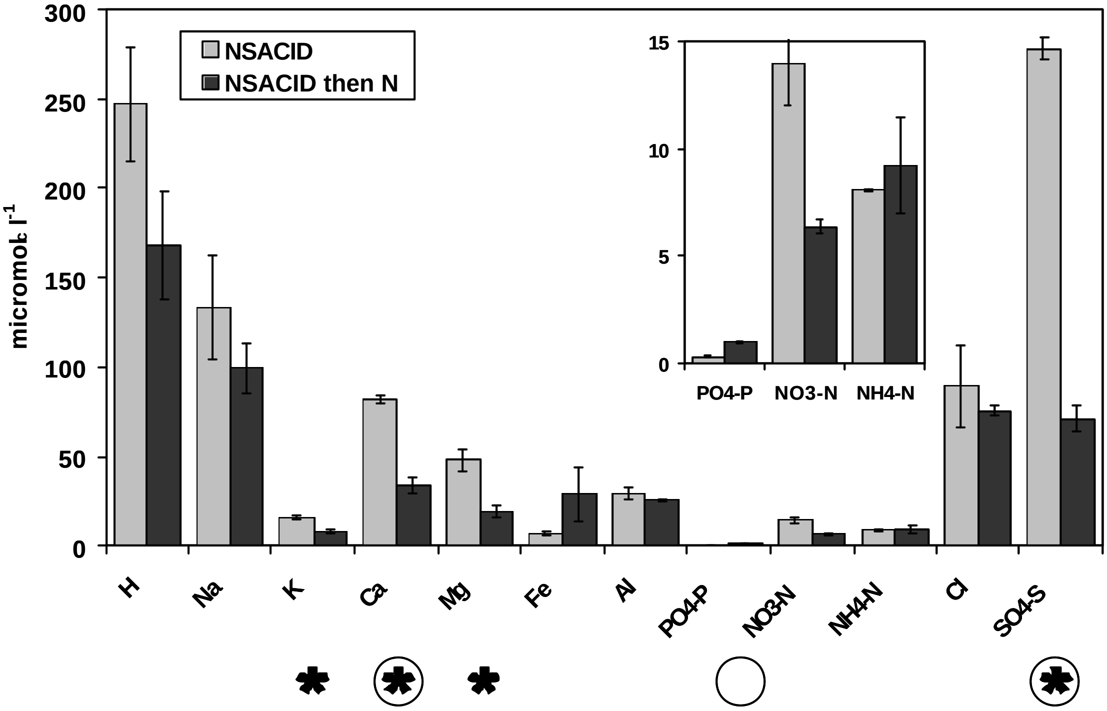

**Figure 1: Soil water chemistry: change from NSAcid to N only treatment**

For the plots originally treated with NSAcid at double the frequency (2NSAcid), removal of the sulphuric acid produced similar results, but in this case there was also a significant reduction (halving) of soil water acidity, and a doubling of soil nitrate concentrations. It seems likely that the reduction in acidity has improved conditions for nitrification, which would be consistent also with the fall in ammonium. It is also possible that removal of the sulphuric acid will alter the way in which the trees utilise nitrate, either through canopy uptake or by changes in the rooting zone. Canopy uptake of nitrate was shown (Phase I final report) to be much greater when ammonium nitrate was supplied to the canopy in the presence of acid (NSAcid) than when applied alone (N only treatment). This behaviour was repeated in 2001 (see below, Table 2), and may at least partly explain the increased soil solution nitrate concentration on removal of the sulphuric acid. The soil water nitrate concentration in these plots exceeded 50 µMol$_c$, which is considered indicative of N saturation.

The replacement of the ammonium nitrate (N only) treatment by the control treatment led to few changes in soil water chemistry, having minimal effects on ammonium and base cation concentrations. Nitrate concentrations, however, fell from around 25 µMol$_c$ to close to zero.

The removal of the sodium sulphate treatment (S only) led to a large decrease in soil water sulphate, as in the NSAcid plots, but no significant reduction in sodium concentrations. The ion balance was maintained by an increase in chloride ion concentrations. This result is surprising, and reflects the different timescales for both anion and cation retention in peat soils. There was also a small, but significant, increase in potassium concentrations (see below). There were no significant differences detected between the two pairs of plots that continued to receive the Control treatments.

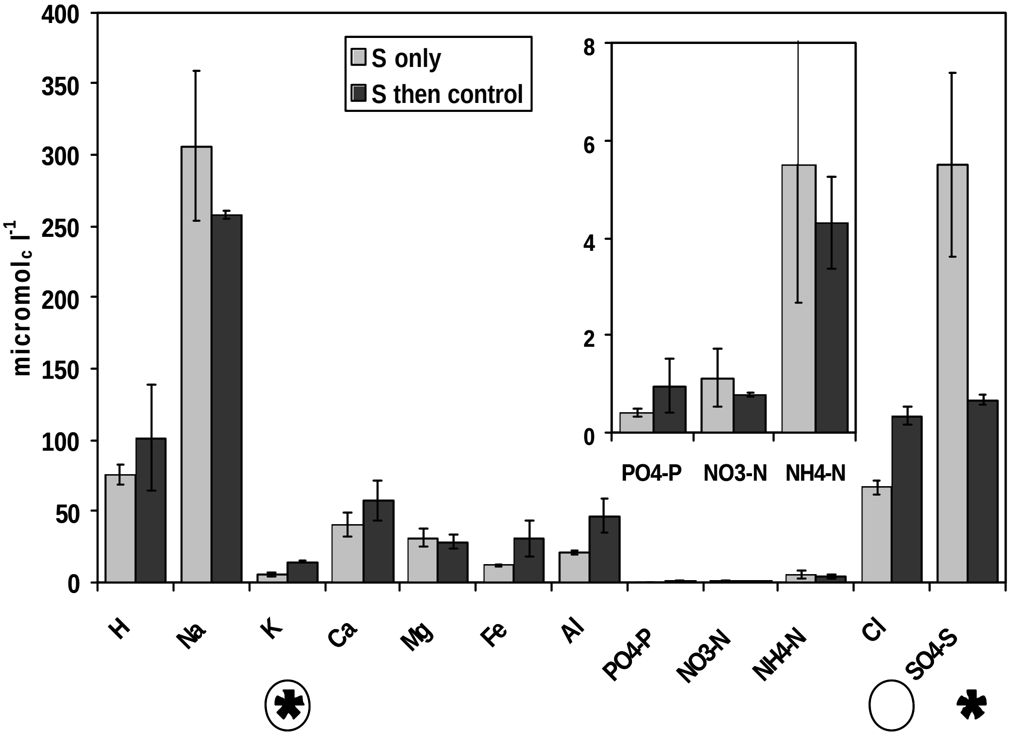

**Figure 2: Soil water chemistry: change from sodium sulphate (S only) to control treatment**

## Tree growth

Stem basal areas were measured using girth bands, read fortnightly from March to November, and the conventional DBH (diameter at breast height) was measured at the start and end of the treatment period. In order to look for effects of a change in growth behaviour in response to the change in treatment (*i.e.* evidence of recovery) the relative annual growth (stem area in autumn 2001 relative to stem area in autumn 2000) during the study period was compared, for each plot, with the relative annual growth in the previous year (i.e. stem area in autumn 2000 relative to stem area in autumn 1999). This method of analysis compensates for any between plot differences in growth rates caused by factors other than the treatments, such as differences in soil composition *eg*. texture and chemistry. Because the trees are approaching the end of their exponential growth regime, the relative growth rate decreases from one year to the next. For example, the relative annual stem area increment of all trees in the experiment in 1998-1999 (expressed as a %) was 32%, compared to 18% in 1999-2000, and 13% in 2000-2001 (Figure 3).

Before the treatment changes the difference in relative increment *ie*. from 1999 to 2000 was therefore (18%-32%) = **-14%**. This change in relative increment from 1999 to 2000 was similar in all plots and across all treatments (Figure 4), showing that for one year it is difficult to pick up treatment effects, they need to be consolidated over several years. In addition conifers exhibit predetermined growth whereby the needle compliment is set down the previous year *ie*. under the previous treatment regime. Changing the treatments will probably alter this relative growth increment between 2000 and 2001 but it is unlikely to cause a large detectable treatment effect.

As can be seen in figure 4b, where the scale has been amplified, treatment differences were small, <5%. Between the untreated plots, the annual difference was (13%-18%) = **-5%,** and this should be taken as the yardstick against which the other plots should be evaluated. The control plots showed a similar difference, between -4 and -5% (Figure 4b). The plots that continued to receive ammonium nitrate (N only), and the double dose of NSAcid, grew less well than expected (-8%), as did the plots from which the S only treatment was removed. The deteriorating growth in the 2NSAcid treatment supports the contention, based on the declining foliar P, K, Ca and Mg status seen over the last few years, that this treatment is reducing the availability of these nutrients which is having a negative effect on the growth rate of these trees.

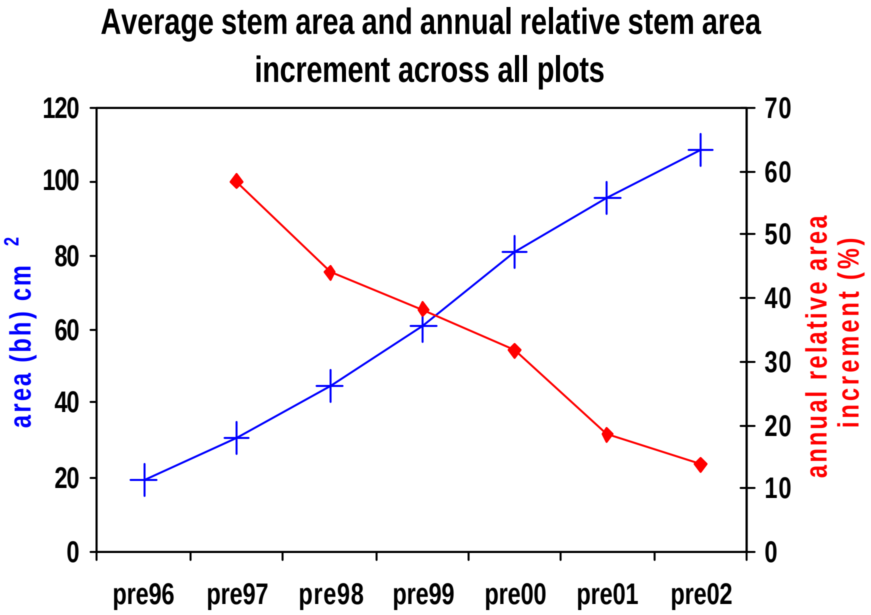

**Figure 3: Changes in growth rates of all 240 trees (absolute and relative) from 1996. "pre96" refers to size at the start of the 1996**

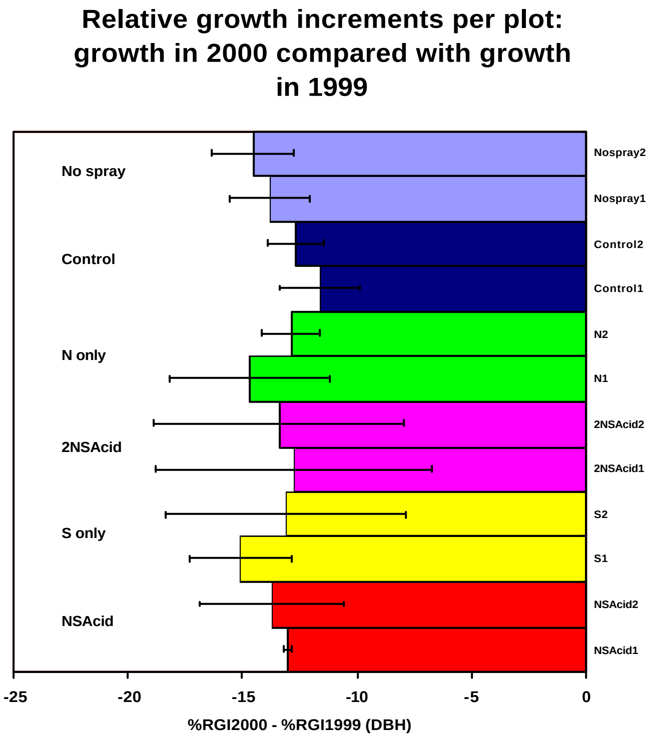

Figure 4a: Change in relative growth between 1999 and 2000, before treatments were changed

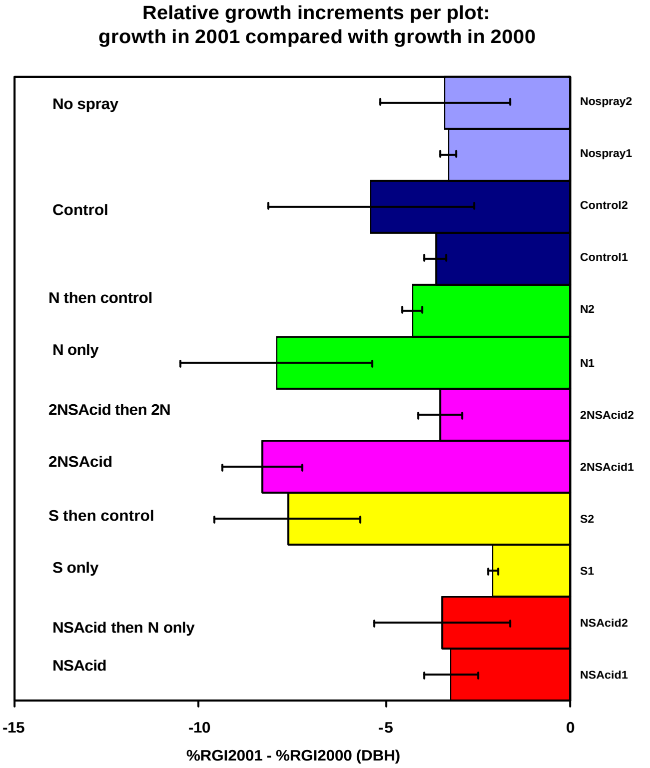

Figure 4b: Change in relative growth between 2000 and 2001, after treatments were changed

### Litter loss

The mass of litter collected from the throughfall gutters (1 $m^2$ per plot) is measured and totalled for each year. In all previous years there has been significantly greater, and in proportion to dose, litter fall from the NSAcid and 2NSAcid treatments than from the other treatment plots. However, in 2001, approximately the same quantity of litter (ca. 200 g dry wt. $m^{-2}$) was recovered from all plots, regardless of treatment. The large reduction in litter fall compared with 2000 (300 g $m^{-2}$ in most plots, up to 750 g $m^{-2}$ in 2NSAcid plots) and the lack of any treatment effect marks a change in the behaviour of the forest. It remains to be seen whether this was a uniform response to weather conditions during 2001, or whether it will be repeated in subsequent years.

### Throughfall chemistry

The overall patterns of throughfall chemistry in relation to experimental treatment were similar to earlier years, with throughfall reflecting the actual treatment during the year, rather than any historical treatment. For the first time, measurements were made of total N in precipitation and throughfall, so that the role of dissolved organic nitrogen (DON) could be quantified. The results are summarised in Table 2. Ammonium, nitrate and DON in rainfall were all retained by the forest canopy, but addition of ammonium and nitrate in the simulated cloud treatments led to greater uptake of inorganic ions, and net formation of DON in the canopy. The canopy transformation of deposited N changes the form in which N reaches the forest floor, and this may have implications for the eventual fate and effects of the deposited N in soil.

**Table 2: Nitrogen budget kg N $ha^{-1}$ of the forest canopy during summer 2001.**

| | **Treatment** | Applied to canopy | Measured in throughfall | Retained by canopy | **Percent retained** |
|---|---|---|---|---|---|
| **Nitrate** | Rain | 0.76 | 0.38 | 0.36 | **49** |
| | N only | 10.8 | 9.4 | 1.4 | **13** |
| | NSAcid | 10.8 | 6.4 | 4.3 | **40** |
| **Ammonium** | Rain | 1.8 | 0.38 | 1.4 | **80** |
| | N only | 11.9 | 8.3 | 3.6 | **31** |
| | NSAcid | 11.9 | 9.2 | 2.7 | **22** |
| **Dissolved organic N** | Rain | 0.29 | 0.25 | 0.04 | **14** |
| | N only | 0.39 | 0.97 | -0.57 | **-150** |
| | NSAcid | 0.39 | 0.85 | -0.46 | **-120** |

### Foliar Nutrient concentrations (Table 3) and needle weights

In the 2000 growing season needle weights were much higher, almost double, those in previous years. Current year needles ranged from 4.5 to 7.4 mg and one-year old needles from 5.4 to 7.6 mg. Plot to plot variation in needle weight tends to be high and no treatment effects were found. In 2001 needle weights were lower and more similar to those found previously, ranging from 2.5 to 5.1 mg for current and from 4.7 to 6.7 mg for one-year-old needles. Again no treatment effects were found.

Foliar K concentrations were as much as 50% higher for 2001, most probably reflecting the lower needle weights, and thus less growth dilution. K is a very mobile element, easily leached and thus closely coupled to environmental change. By contrast other elements *e.g* Ca tend to be 'fixed' in the plant in cell walls. Removing the sulphuric acid increased K in current year needles by comparison with the respective NSAcid treatments (p= 0.30,0.31). Foliar Ca concentrations were lower than in the previous year, in all treatments. There was a tendency for the removal of sulphuric acid (double dose) to exacerbate this reduction (p=0.26). Concentrations of P in current year needles increased (p=0.38) in response to the removal of sulphuric acid. Foliar N concentrations barely changed. Data for S is not yet available.

The effects of removing sulphuric acid, S, and N were similar but much less pronounced in one-year-old needles (data not shown).

Table 3 Current year nutrients – percent changes in foliage between the 2000 and 20 01 growing seasons.

| | **%K** | **% Ca** | **%Mg** | **%P** | **%N** |
|---|---|---|---|---|---|
| **N** | 47 | -12 | 1 | 20 | 5 |
| **NS Acid** | 8 | -14 | 3 | 3 | 0 |
| **Control** | 22 | -15 | 4 | 6 | 1 |
| **S** | 24 | -16 | 1 | 1 | -5 |
| **2NS Acid** | 9 | -7 | -9 | 11 | 1 |
| **2N** | 31 | -26 | -14 | 17 | 2 |
| **Control** | 18 | -13 | -1 | 14 | 0 |
| **N** | 17 | -11 | 6 | 10 | 7 |
| **Control 1** | 45 | -16 | 4 | 18 | 7 |
| **Control 2** | 37 | -23 | -2 | 23 | 7 |
| **No Spray 1** | 18 | -28 | 2 | 4 | 2 |
| **No Spray 2** | 34 | -21 | 4 | 27 | 10 |

### Fungal fruiting bodies

Two surveys were conducted in late summer/autumn 2001, where numbers and species of fungal fruiting bodies were recorded. No significant changes in response to the changed treatment regime could be detected because of large plot-to-plot variability. The survey is being undertaken more frequently this year and cores will be removed to assess the effects of sulphuric acid, N and S removal on mycorrhizal infection and fine root mortality.

## Collaboration

Throughfall measurements have stopped across the whole site, however, collaboration with the University of Bayreuth has led to a study, this summer, of aphid populations and their associated microflora and their effects on throughfall chemistry under individual trees in the original, single dose treatments. Preliminary results of surveys of the whole site confirm those from a previous survey indicating the aphids prefer to feed on needles treated with sulphuric acid and N.

## Conclusions

The changes in treatments applied to the forest at Deepsyke have already showed major changes in the chemistry of the soil solution, some of which appear in the foliage. Small changes in growth have also been observed, but their significance will only become clearer in the future. Large plot to plot variation means that the results are rarely significant at the 5% level but after 3 years of treatment we expect this to improve.