Forestry Commission
231 Corstorphine Road
Edinburgh
EH12 7AT
www.forestry.gov.uk

Ten Years of Intensive Environmental Monitoring in British Forests

INFORMATION NOTE

BY E. VANGUELOVA, N. BARSOUM, S. BENHAM, M. BROADMEADOW, A. MOFFAT, T. NISBET AND R. PITMAN OF FOREST RESEARCH

AUGUST 2007

SUMMARY

Twenty intensive monitoring sites have been established in British forests to gain a better understanding of the effects of air pollution and other environmental factors on forest ecosystem structure and function. Five tree species are represented across a broad range of pollution environments and climatic conditions. The sites form part of a European network (Level II Intensive Forest Monitoring Network) and were established in 1994. Measurements made over the past ten years have begun to reveal a number of important trends that help to explain some of the observed changes in forest condition. Chemical analysis of rainfall inputs indicates some reduction in the pollution experienced in the past, confirming the success of emissions control policies. However, concerns over the local effects of excess nitrogen deposition and ozone pollution remain, alongside those of climate change which is predicted to have both direct and indirect impacts on forest ecosystems. The intensive monitoring programme is a unique forest surveillance network, providing continuous, detailed information on the condition of forests and their interaction with the wider environment at both local and regional scales. The network also supports international reporting commitments concerning sustainable forest management.

INTRODUCTION

In the early 1980s, deterioration in the crown condition of trees across many regions of Europe raised concerns over the health of European forests, and many countries established surveys to monitor this. In Britain, the *Forest Condition Survey* was instigated in 1984 (Binns *et al*., 1985) with an annual assessment of tree crown density on between 300 and 400 plots of five widely planted forest tree species: oak, beech, Scots pine, Sitka spruce and Norway spruce (Hendry *et al*., 2005). In 1985, forest condition monitoring was co-ordinated across Europe under a United Nations initiative[1]. This is known as the 'Level I' programme.

In the 1990s, however, it became evident that detailed assessments of environmental factors were needed to identify the cause of observed changes in forest condition. In addition, there was a growing appreciation that 'forest health' should embrace all aspects of the forest ecosystem, not just crown condition. To achieve this, a second monitoring network, the Intensive Forest Monitoring Network or 'Level II' network, was established in 1994 under European legislation (see page 12). More than 800 Level II plots have been established across Europe, and the UK has operated up to 20 sites since 1995 (Figure 1).

[1]The programme was established by the United Nations Economic Commission for Europe, under its Convention on Long-range Transboundary Air Pollution, and implemented by the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests).

Figure 1

Location of the UK Level II plots. Original plots established in 1994 in upper case letters, additional plots established in 2002 in lower case.

Ten long-term Level II intensive monitoring plots were established in conventionally managed forests in 1995 (Durrant, 2000). The plots were located to ensure coverage of a broad range of climatic conditions and air pollution exposure levels. Three of the most widely planted tree species in Britain comprised the original network: oak (*Quercus petraea; Q. robur*), Sitka spruce (*Picea sitchensis*) and Scots pine (*Pinus sylvestris*). Ten further plots were established in 2002 to improve the spatial representation of oak and Scots pine and to introduce two further species, beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), which were thought likely to be the first species to be negatively affected by climate change. Plot establishment and instrumentation follow standardised protocols across Europe. Each plot covers an area of 0.25–0.3 ha and contains a permanent mensuration plot of 0.1 ha where five-yearly assessments of tree growth are made. In addition to tree growth, the main assessments include measurements of local air quality and meteorology, atmospheric deposition (volume and chemistry), litterfall (biomass and chemistry), soil and soil solution chemistry, foliar biomass and chemistry, crown density, phenology, and the composition of ground vegetation. The timing and frequency of all assessments are given in Table 1.

Table 1

Details of the timing and frequency of measurements made across the Level II network.

Measurement	Number of plots	Frequency
Tree growth	20	5 yearly
Crown density	20	annually
Foliar chemistry	20	annually
Soil (chemistry and description)	10	10 yearly
Litterfall	12	2–8 weekly
Deposition	10	2 weekly
Air quality	11	monthly
Soil solution	9	2 weekly
Meteorology	6 (5)	daily (hourly)
Phenology	10	2–4 weekly
Ground vegetation	20	3 yearly

Today, the assessment of forest condition under the UNECE and EU Level I and Level II long-term forest monitoring programmes constitutes one of the world's largest bio-monitoring networks. Forest decline in response to air pollution was, and still is, the driving force behind the ICP Forests programme, contributing to the development of clean air policies. It also contributes to policy formulation in areas such as nature conservation, biodiversity, sustainable forest management, the protection of freshwater resources and climate change.

At a national level, Level II data are used to support *UK Indicators of Sustainable Forestry* (Forestry Commission, 2002), *The UK Forestry Standard* (Forestry Commission, 2004) and *The UK Woodland Assurance Standard* (UKWAS, 2006). The data have been used to support UK obligations under the UNECE Convention on Long-range Transboundary Air Pollution, the EU Forest Focus Regulation, and UK submissions regarding Criteria and Indicators under the Ministerial Conference on the Protection of Forests in Europe (MCPFE, 2002).

This Information Note reviews the value of intensive monitoring and the light it has shed on important environmental and forestry policy issues. Examples are drawn from the range of Level II datasets to demonstrate the greater understanding that can be gained when evaluations consider how different environmental drivers and forest responses interact with one another, thus reflecting the complexity of forest ecosystems. In addition, the data also allow us to evaluate the health of British forests at the beginning of the 21st century and, looking forward, identify those environmental stresses that are likely to be of most concern in the future.

Figure 2

Litterfall and throughfall collectors at the Alice Holt Level II site.

ASSESSING ENVIRONMENTAL IMPACTS ON FOREST CONDITION AND FUNCTION

Tree crown density is often used as a measure of tree response to environmental change, and has been selected by the Ministerial Conference for the Protection of Forests in Europe as an indicator of the relative success (or failure) of sustainable forest management. Trends have been revealed at both national and European scales (UNECE, 2006). In the UK, oak and Norway spruce have shown small but statistically significant declines in crown density since the programme was established in 1987, while inter-annual fluctuations in the density of both beech and Sitka spruce have been related to specific episodes of masting and insect defoliation, respectively.

The Level II Network was established to identify those factors responsible for the observed variation, both spatial and temporal, in forest condition. Results from the past ten years are considered below, together with a wider evaluation of trends apparent in the datasets.

Tree crown density

A notable deterioration in mean tree crown density from 72% in 1995 to 45% in 2005 has been observed in the oak trees at the Grizedale Level II site. The decline in density is associated with severe defoliation by *Tortrix* caterpillars. This is indicated by a significant reduction in the biomass of leaf litter compared with a pest-free year, and the amount of frass and number of pupae recorded in litterfall analysis. There is evidence that nitrogen deposition can promote insect defoliation (NEGTAP, 2001), although other influences on population numbers, including climate, cannot be ruled out. A similar deterioration in crown density has been observed (from 75% in 1995 to 57% in 2005) at the Scots pine Level II site (Ladybower) in the historically polluted Pennines. Although acid deposition has fallen significantly at the site, indicators of the acidity and base status remain critical and could explain the trend. In contrast, a modest increase has been observed in crown density at another Scots pine plot, at Thetford (see Tree nutrition). Other sites show no significant trends in crown density, highlighting the importance of local factors rather than a widespread change in forest condition.

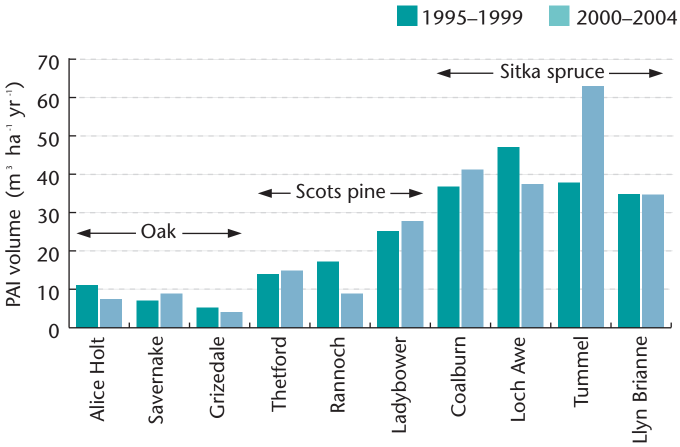
Tree growth

Tree growth is an indicator of how well matched the environmental requirements of a particular tree species (at a given stage in its life cycle) are with local environmental conditions as affected by management and biotic damage. Trees in the permanent mensuration sample plots at each Level II site are assessed every five years, and diameter at breast height (dbh) is measured annually on twenty four trees also assessed annually for crown density. These measurements enable the relative impacts of causal agents affecting tree growth over short or extended periods of time to be evaluated. For example, the largest inter-annual fluctuations in diameter growth are evident at the Grizedale oak site, where severe defoliation is a regular occurrence. In contrast, all four of the Sitka spruce plots also show a large degree of variation which is likely to be climate dependent.

More formal growth assessments from the Level II mensuration plots are presented in Figure 3, separately, for the first and second five-year periods of monitoring. Although clear growth trends cannot be identified from such a limited dataset, there is no evidence of a widespread downturn in productivity. Reductions at Rannoch and Loch Awe are probably due to increased exposure and wind damage. In contrast, some sites show an increase in volume, in some cases due to the effects of management intervention (thinning). Other explanations include rising CO_2 levels in the atmosphere, the fertilising effect of enhanced nitrogen deposition and global warming resulting in earlier flushing and longer growing seasons.

Figure 3

Periodic annual increment (PAI) of volume at the ten original Level II plots for the first and second five-year periods of monitoring. Volume includes both changes in standing volume and volume removed as thinnings.



Tree nutrition

Foliar chemistry provides an indication of the nutritional status of a tree. At ten of the Level II plots, tree foliar chemistry has been assessed annually since 1995. Changes in tree nutrients can thus be related to shifts in local environmental conditions at these sites. For example, foliar nitrogen concentrations in Scots pine at the Thetford Level II site have been in excess of 1.7% over the past ten years, rising to 2.2% in 2002 – a value indicating nutrient imbalance (Gundersen, 1999) and reflecting high levels of atmospheric pollution. However, a modest improvement has been observed in crown density and growth has not declined (Figure 3). Nevertheless, soil solution nitrate concentrations are high and impacts on the composition of the ground flora have been observed.

It is important to note that high levels of nitrogen deposition and critical load exceedance (see page 7) do not necessarily result in reduced tree growth. However, this situation may not hold in the long term and 'super-optimal' levels of foliar nitrogen remain a concern.

At the onset of monitoring at Ladybower, foliar nitrogen concentrations were also above 1.7%, but have since declined. This corresponds with a deterioration in crown density, suggesting that excess nitrogen deposition is not a causal factor in the deterioration.

There is a general downward trend in foliar sulphur levels at most sites, corresponding to a reduction in soil solution sulphate concentrations. Foliar sulphur levels at one Scots pine Level II site (Rannoch) are now classed as deficient according to Van den Burg (1985) and, if the downward trend continues, there is a real possibility that large areas of British woodland could become sulphur deficient in the foreseeable future.

Two out of the three oak sites have foliar phosphorus (P) concentrations classed as deficient, according to Taylor (1991), reflecting extremely low available P in the soil. Other essential nutrients such as magnesium, calcium and potassium are at optimal levels, but in the future they may decline, especially in infertile soils, as a result of emissions reductions. Base cation concentrations in rainfall have already fallen at most sites.

Future changes in climate, air quality and soil and water chemistry will result in altered tree nutrition. Monitoring at Level II sites can therefore give an early warning to forest managers of possible nutrient deficiency as well as inform policy makers of the timeframe and direction of forest responses to the implementation of pollutant emission control measures. Furthermore, the data identify that nutrient cycling and sustainability are important issues in the context of increased woodfuel utilisation from existing woodlands, and, in particular, the consequences of whole-tree harvesting on long-term nutrient sustainability.

Ground vegetation community structure and composition

Ground vegetation community structure and composition are good bio-indicators of site fertility and environmental change. A growing body of evidence indicates that the composition of ground flora in British woodland has been altered through the deposition of nitrogen compounds (Kirby *et al.,* 2005). Ground vegetation surveys are carried out at three-yearly intervals at Level II sites, and their environmental requirements assessed according to Ellenberg[2]. These assessments have been used to identify whether there have been any significant floristic changes in response to pollution or management. Analysis of the Alice Holt site reveals that the composition of understorey vegetation is highly resistant to short-term changes in climatic conditions (e.g. drought, frost). In contrast, the impacts of management are generally more dramatic and long-lasting, with increasing numbers of ruderal and light-requiring plants emerging following thinning. As an example, at the Thetford Level II site, the Ellenberg index of light requirement remained high for four years after stand thinning. At the same time, an increase in 'Ellenberg' indicators of nitrogen and pH at this site also indicate a response of the ground vegetation to increased nitrogen from atmospheric deposition or to canopy opening and release of nitrogen through the decomposition of brash left on site. This highlights the point that although tree growth appears to be currently unaffected, excess nitrogen is affecting the wider ecosystem, indicating an underlying pressure that may affect tree health and growth in the future.

Intensive monitoring sites are therefore helping to build up a picture of how biodiversity is affected by forest management and its interaction with the environment. This will be valuable in developing guidance for more informed conservation management of forests.

Forest soil dynamics

The soils of the Level II sites were extensively characterised when the network was established in 1995, and these data are proving valuable in a variety of ways. Several soil indicators suggest that infertile soils at some Level II sites (Grizedale, Sherwood, Rannoch and Coalburn) are vulnerable to loss of base cations as a result of acid deposition. These sites are mainly on podzolic soils, which are representative of a significant proportion of British forests. Other Level II sites, such as Thetford on a calcareous sandy soil over chalky drifts, are more resilient due to their high base status. Forest soils with a low organic matter content and surrounded by intensive agriculture, such as the Thetford site, are at risk from the effects of high nitrogen deposition (Pitcairn *et al.*, 1998). This is clearly demonstrated by a soil carbon to nitrogen ratio of less than 5, reflecting excess nitrogen mineralisation and leaching (Emmett, 2002), together with high nitrate concentrations in soil solution at this site. The Level II

[2] Ellenberg values are used to interpret plant distribution in terms of environmental factors. Ellenberg defined seven scales, each representing a particular environmental factor, but four scales used by Hill et al. (1999), i.e. Light, Moisture, Reaction (pH) and Nitrogen, have been adopted in forest ecological research in Britain.

data also highlight the variability in soil carbon stocks and provide a baseline for reporting future changes in soil carbon.

Soil solution is the primary source of nutrients to be taken up by trees, and is more responsive to changes in external factors than the soil itself. Soil solution chemistry is influenced by many external factors such as precipitation, temperature, microbial activity in the soil and chemical inputs from atmospheric sources and tree litterfall. Soil solution has been continuously monitored by tension lysimeters in nine Level II sites since 1995.

The concentration of sulphate (SO_4–S) in soil solution at most sites has decreased in recent years, consistent with the decline in atmospheric sulphur deposition (see Figure 4). Nitrate concentrations (NO_3–N) in soil solution vary greatly between sites, reflecting the range of atmospheric deposition (see Figure 5). For example, at the Scots pine sites, the nitrate concentration is negligible at Rannoch in highland Perthshire, relatively high at Ladybower in the Pennines, reflecting the site's historical pollution loading, and very high at Thetford (up to three times the UK drinking water limit). Nitrate concentrations in soil solution have also increased dramatically at two of the Sitka spruce sites, Tummel and Coalburn. At the first of these, the initial rise in concentration followed thinning in 1996. However, subsequent peaks appear to follow severe defoliation by the green spruce aphid, which is confirmed by litter-fall analysis. The high nitrate levels at Coalburn may be due to the reduced demand for nitrogen as the tree crop ages. Nitrate concentrations are also relatively high at Savernake, reflecting the proximity of agricultural activities, changing patterns of which may explain the large variability observed at the site.

A recovery of the highly acidified Ladybower site is evident with an increase in soil solution pH and decline in aluminium concentration. The soil solution calcium to aluminium molar ratio is very variable across the Level II sites, but ratios below the critical threshold of 1.0, which indicate a potential risk of aluminium toxicity to tree fine roots (Cronan and Grigal, 1995), have been observed at Grizedale, Ladybower and Llyn Brianne. These sites receive the highest atmospheric pollution inputs of acidity, sulphur and nitrogen and represent the most sensitive soils. Dissolved organic carbon in soil solution has also been monitored since 2002 and temporal trends provide an indication of the dynamics of soil carbon at these plots, of importance when evaluating changes in forest carbon stocks and stock changes.

Figure 4

Annual mean concentration of SO_4–S in (top) soil solution and (bottom) sulphur in foliage for Level II plots of oak (left) Scots pine (centre) and Sitka spruce (right), respectively. Black and grey dotted lines show limits of optimal and deficiency levels respectively.

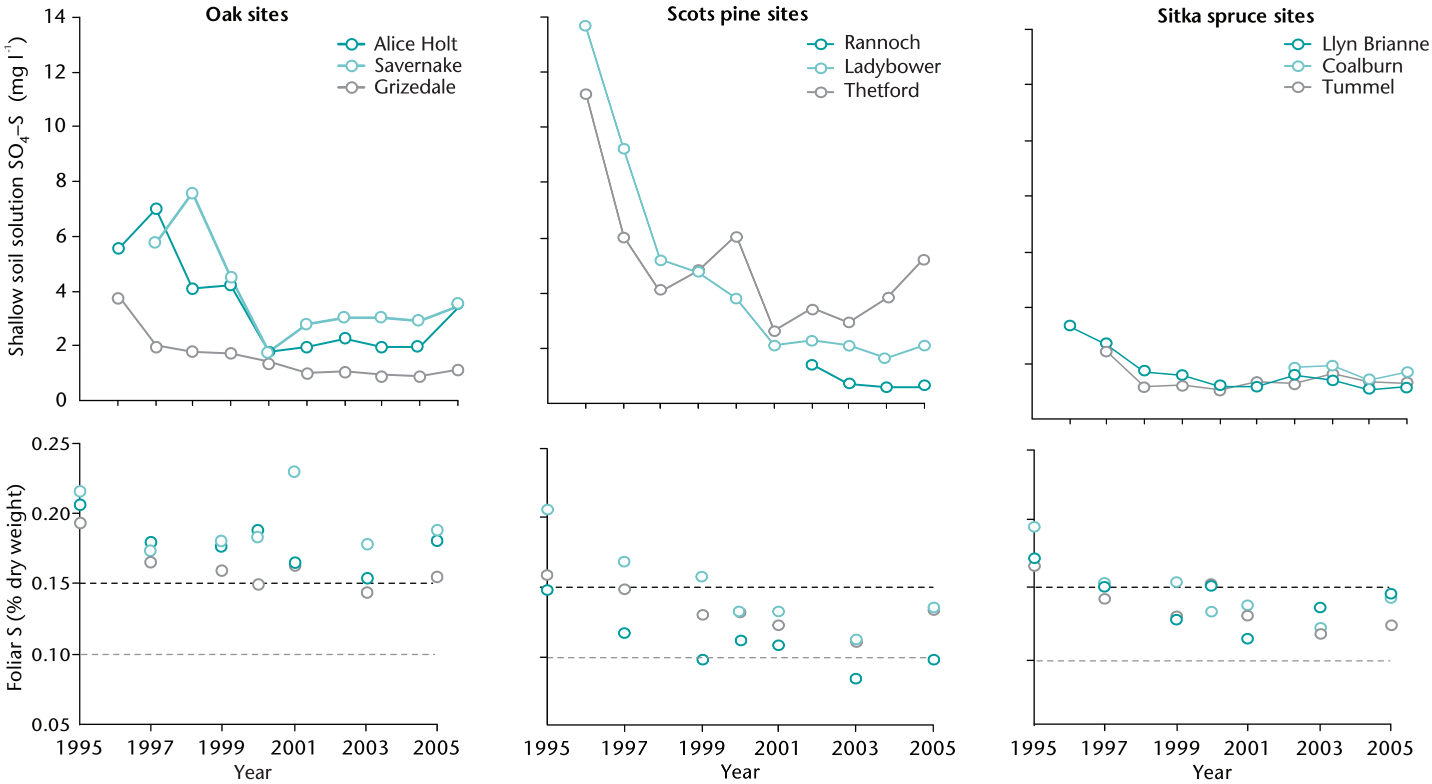
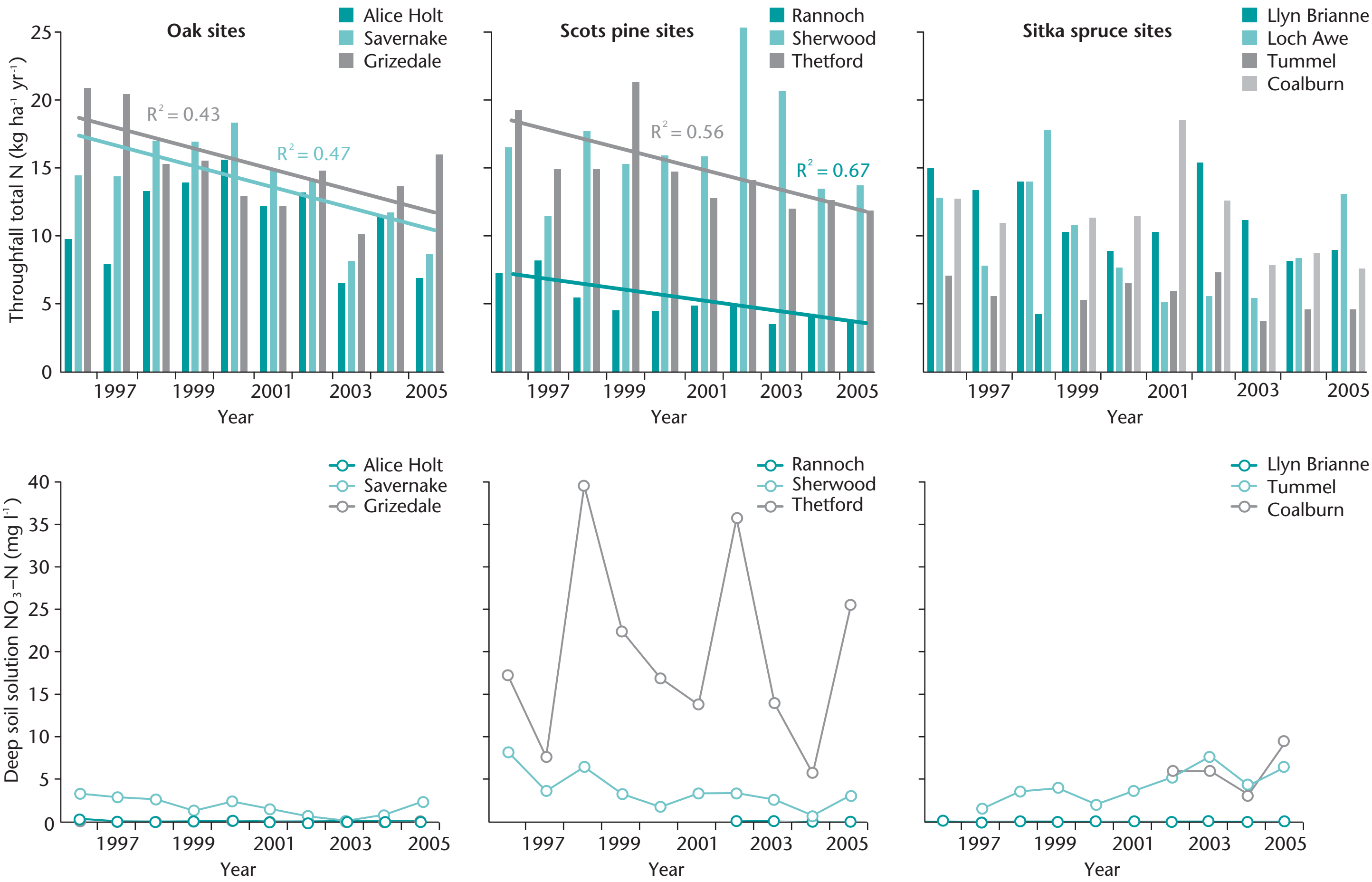


Figure 5

Annual deposition of total nitrogen, expressed as throughfall (top), and NO_3–N in soil solution (bottom), for oak (left), Scots pine (centre) and Sitka spruce (right) plots, respectively. Lines represent statistically significant trends.



FUTURE CHALLENGES FOR SUSTAINABLE FOREST MANAGEMENT

Sustainable forest management faces a number of key challenges, in particular climate change. The Level II network has a vital role to play in improving our knowledge and understanding of these challenges and in guiding the development of adaptation strategies.

Climate change

The British climate is predicted to become warmer and drier in the summer, with more frequent and severe droughts (Hulme *et al.*, 2002). Winters are expected to become milder and wetter, increasing the risk of flooding. The frequency and severity of storms may also increase. An understanding of how climate change will affect the growth potential and ecological suitability of individual tree species is essential for forest management, as is the need to evaluate the impacts on forest soils and water.

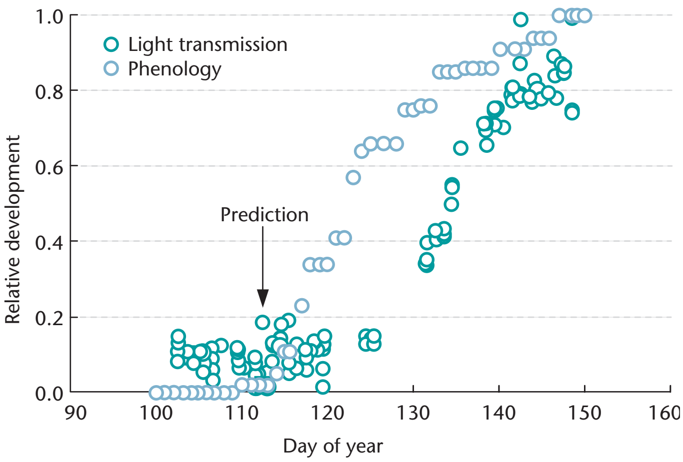
Climate change will affect forest soil function both directly and indirectly. Rising temperatures can accelerate mineralisation rates and soil nutrient availability, while nutrient leaching may be enhanced by heavier winter rainfall. Increasing soil moisture deficits in summer will decrease both nutrient uptake by trees and leaching losses. Physical soil disturbances may occur as a result of winter waterlogging and windthrow if the frequency of storm events increases. All of these effects will have implications for the nutrient and carbon balance of forest soils.

The Level II network is also contributing to our understanding of the impact of climate change on tree phenology. Certain phenological events are easily observed in trees, such as bud burst and leaf/needle emergence in spring and the timing of flower development and seed production. Fortnightly assessments of the developmental status in spring and autumn, together with litterfall collections, allow phenological changes to be compared between years and sites.

The timing of phenological events in trees is mainly determined by seasonal climatic variables such as temperature and photo-period. This has been clearly demonstrated for oak at the Alice Holt site where models supplied with data on these variables have returned accurate predictions (within 1–2 days) of the date of bud burst (Figure 6). So far it has not been possible to identify any trends due to the relatively short run of measurements and the large degree of inter-annual variation in the data, but there is now a good baseline for assessing future change.

Figure 6

Comparison of measures of canopy development in spring derived from measured light interception (dark blue) and assessment of bud development at the Level II oak plot at Alice Holt (pale blue). The predicted date of flushing (see Sparks and Gill, 2002) is also shown.



A modest increase in temperature can increase the length of time that a tree is photosynthesising, thus increasing forest productivity and carbon storage. It can also affect the soil nutrient regime and loss of nutrients by leaching. The network has an important role to play in monitoring these changes and assessing the consequences for sustainable forest management.

Predicting the future impacts of climate change and interactions with other environmental variables on forest productivity and ecosystem function requires the application of models. The most appropriate models for climate change research include a representation of physiological processes and are complex. The detailed characterisation of the Level II plots and availability of meteorological data means that they are suitable for developing and testing such models, as has been carried out for the Alice Holt and Coalburn plots (Evans *et al.*, 2005).

Air Pollution

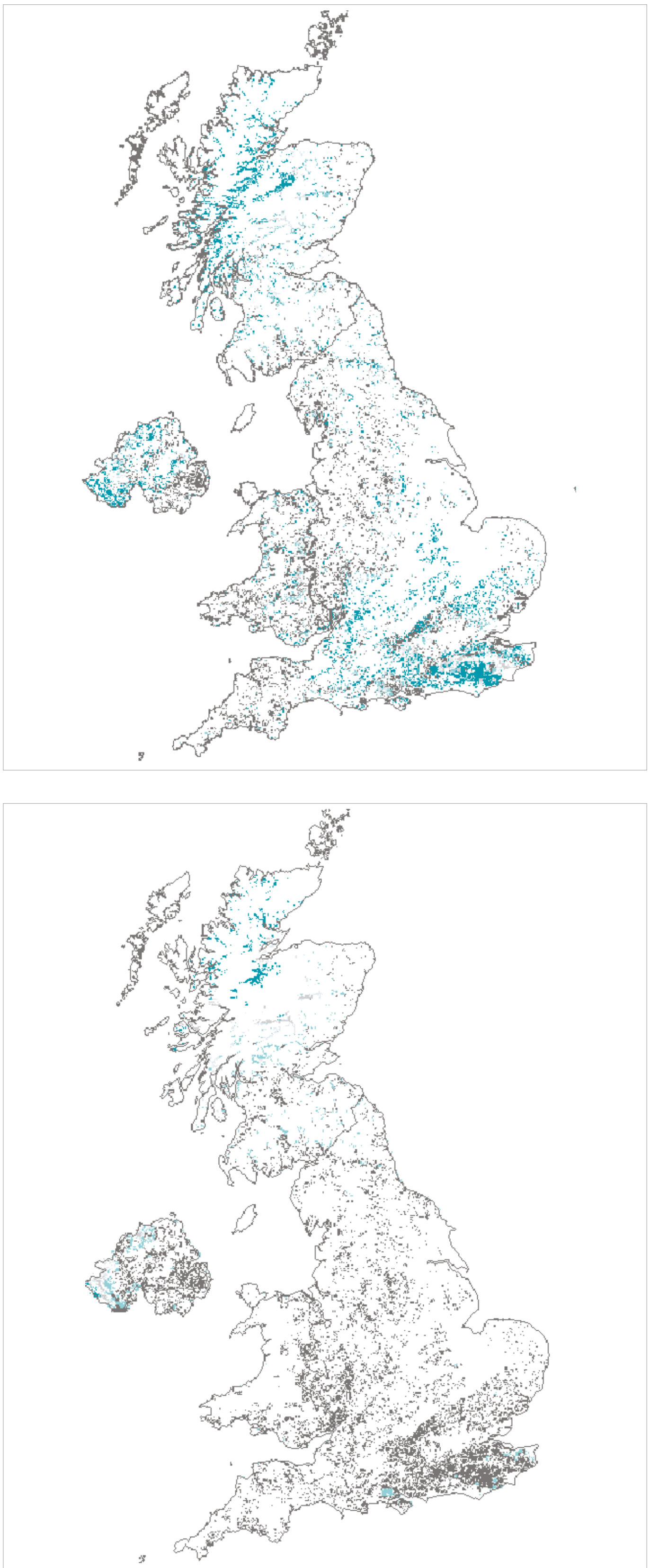
Air pollution has been a major source of disturbance to forest ecosystems in Europe over recent decades. This has contributed to the implementation of clean air policies and a decline in the concentrations of most air pollutants. Trends in concentrations of SO_2 and NO_2, and the deposition of sulphur and nitrogen (Figure 5) in rainfall and throughfall (rain water falling through the tree canopy) are falling in line with emission reductions (NEGTAP, 2001). However, concern remains over the impacts of other air pollutants such as ozone (O_3) and ammonia (NH_3). Emissions of NH_3 have changed little over the past decade, although Level II data indicate large spatial variation in NH_3 concentrations and in levels of nitrogen in deposition.

Ground-level ozone exposure in Britain regularly reaches the threshold values at which damage to trees can occur. High concentrations of ozone can cause visible injury to the leaves of trees, affect photosynthesis through changes in the internal leaf structure and make plants more susceptible to drought by limiting their ability to regulate water loss. It has been estimated that current levels of ozone exposure may be responsible for reducing forest productivity across Europe by about 10% (Semenov and Koukhta, 1996). Ozone exposure is being monitored at eleven Level II sites. Five ozone sensitive shrub/tree species are also assessed for ozone injury within the vicinity of these Level II plots at ‘light exposed sampling sites’. There is no evidence from the Level II data that ozone is causing a sustained decline in crown condition or growth, although ozone-like damage symptoms were observed in Kent and East Anglia in 2003. This indicates that the effects of ozone pollution are not limited to southern and central Europe.

Acid deposition continues to exert a major impact on forest soils and water. The amount of a pollutant that an ecosystem can withstand safely is known as a *Critical Load* (Nilsson and Grennfelt, 1988). When this is exceeded, ecosystem damage may occur. Critical load maps have been used to target national and international emissions reduction measures (Hall *et al.* 2003). The majority of forest soils in the UK are classified as exceeded for acidity and nutrient nitrogen, implying that they, together with sensitive elements of flora and fauna remain vulnerable to acidification (Figure 7). Intensive monitoring continues to play a major role in the development and testing of the critical loads approach and in monitoring the impact of acid deposition on the forest environment. The Level II data show no evidence of critical load exceedance having an effect on tree crown density or growth.

Figure 7

Critical load exceedances for acidity (top) and nutrient nitrogen (bottom) for broadleaved and semi-natural woodland (Hall *et al.*, 2003).



$keq\ ha^{-1}\ year^{-1}$

Not exceeded
0.0–0.2
0.2–0.5
0.5–1.0
>1.0

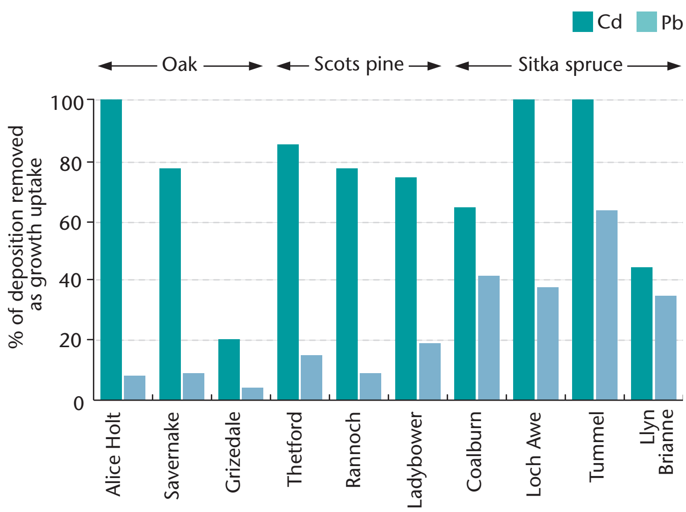
Further development of the critical load methodology is leading to improved dynamic models that are better able to forecast the long-term effects on forest ecosystems. These have been applied to the Level II sites and reveal the severity of past acidification and the slow response to recent emission control measures (Evans and Reynolds, 2003).

Nutrient removal during thinning and harvesting represents a significant loss of base cations (calcium, magnesium, potassium and sodium) and, in acid sensitive areas, it may enhance the acidification of forest soils and watercourses. At the same time, the removal of nitrogen in harvested wood limits the degree of acidification and nutrient enrichment in nitrogen saturated systems. Establishing the balance between these processes is clearly important to soil sustainability and is an issue that is expected to become increasingly important in the future with the desire to extract more biomass from forest stands for bioenergy. Data from the Level II network are being used to calculate base cation budgets for the main soil types to guide site suitability for the harvesting of brash residues.

Another example of the value of the monitoring network is in providing data for assessing heavy metal critical loads. Calculations show that forests are efficient at retaining some heavy metals such as cadmium, which helps to protect soils and water from contamination (Figure 8). However, on contaminated sites, consideration must be given to the end use of harvested products to ensure that the metals are not released into the environment at harmful levels.

Figure 8

Proportion of measured cadmium (Cd) and lead (Pb) deposition that is removed during growth and subsequent harvesting.



Carbon sequestration

The role played by woodland in removing carbon dioxide from the atmosphere is recognised in the UK Government's Climate Change Programme (Defra, 2006). It is important to be able to quantify both carbon stocks and rates of carbon exchange in order to provide estimates of net uptake and storage of carbon for any given planting and management scenario. This process of 'verification' is an important tenet of carbon stock and stock change reporting under the Kyoto Protocol and in the UK, and the Level II network is part of the process.

Although the carbon stored in harvestable timber (>7 cm diameter) can be estimated with relative simplicity using conventional mensuration approaches, the carbon stocks in other stand components are less certain. For example, the biomass and carbon stored in branches and stumps are estimated from stemwood volumes assuming that they represent a constant fraction of stemwood (approximately 20%). In a recent study of beech, carried out during routine thinning of the Level II plots, it was found that conventional methods underestimated total above-ground carbon stocks by up to 54%. Soil carbon stocks were highly variable, with values of between 47 tC ha^{-1} and 500 tC ha^{-1} for the top 1 m of soil.

Carbon stock changes for above-ground components are monitored across the network by repeated surveys. It is more difficult to measure change in below-ground carbon stocks because the magnitude of change is usually very small relative to the total carbon present. New methods are being evaluated at the Alice Holt site, including the use of a flux station to provide precise measurements of stand level carbon exchange at a high temporal resolution. Quantifying the loss of dissolved organic carbon in drainage waters is also part of routine Level II measurements.

Protecting biodiversity

Level II sites are located in managed forests, which are the most widely represented forest ecosystems in Britain. Long-term monitoring allows us to assess changes in biodiversity in relation to environmental factors and management. Regular measurements are made of stand structure, ground vegetation (cover and species composition), patterns of tree recruitment and deadwood (abundance and condition). The particular advantage of intensive and integrated monitoring is the availability of detailed physical and chemical data on atmospheric–vegetation–soil processes that can help to explain the cause of any recorded changes in habitat condition.

THE STATE OF BRITISH FORESTS AT THE BEGINNING OF THE 21st CENTURY

Ten years of intensive monitoring of forest ecosystems in Britain have not identified a consistent picture of deteriorating or improving forest condition. A recovery from high levels of acid deposition is evident at some sites, but continued impacts of point sources of nitrogen pollution are clear at others, e.g. Thetford. Data from the monitoring network suggest that forest planted on soils sensitive to acidification and nitrogen enrichment will take a considerable time (possibly decades) to recover. There is good evidence that atmospheric pollution affects not only soil solution and foliar chemistry, but also ground vegetation community structure.

There are downward trends in indicators of plant available sulphur at most Level II sites across Britain, and sulphur deficiency may become more widespread in British forests if this trend continues. Together with observations of pollution impacts and recovery, the monitoring of biotic damage to trees is revealing phenomena that may be related to climate change. A good example is the significant decline in crown condition of oaks associated with severe defoliation by *Tortrix* caterpillars. There is no convincing evidence to date that climate change has affected those forest types represented in the Level II network, but the sites are well placed to pick this up when it occurs.

Level II sites are deliberately located in managed forests, and they have revealed the importance of forest management on ground flora structure, composition and therefore on forest biodiversity. In general, biodiversity indices demonstrate a relative stable richness in lower plant groups (e.g. bryophytes) under coniferous tree species, and in higher plant groups under oak.

THE FUTURE OF INTENSIVE FOREST MONITORING IN THE UK

Over the past ten years, the Level II forest monitoring programme has provided an effective methodology for ecological evaluation and modelling of forest processes and for investigating the effectiveness of a range of forestry and environmental policy measures. As we look forward, it must continue to support national and international reporting and the evaluation and application of sustainable forest management principles. However, as the emphasis of policy drivers has changed and will continue to change, the network must also evolve to reflect these new priorities. A revised list of monitoring tasks is therefore appropriate:

- to continue the periodic extensive and intensive monitoring of forest ecosystems, while integrating monitoring activities with national inventory and other suitable forest monitoring platforms;
- to extend monitoring to enhance the study of the impacts of climate change, carbon sequestration, biodiversity, and the protective function of forests;
- to consider extending the remit of the network to include non-plantation and other semi-natural ecosystems;
- to ensure effective reporting of monitoring results to relevant stakeholders.

Through focusing the intensive monitoring network on the effects of climate change and pollution and their interaction with pests and diseases, it will provide an early warning system for environmental change. This knowledge can then guide the development of adaptation and mitigation strategies and practices. Intensive monitoring will also inform the future maintenance of biodiversity in managed forests, and is relevant to the national greenhouse gas inventory process. In turn, this will aid the development of management strategies for the conservation of carbon in forests. Management of woodland for the production of woodfuel is increasingly important, and intensive monitoring can provide valuable information to support this initiative.

Britain will continue its clean air policy. Forestry policy will also promote sustainable forest management to ensure that ecological, economic and social benefits continue in a changing environment. Indicators of sustainable forestry will continue to be valued as policy and political instruments. It is important, therefore, that a sound scientific methodology underpins their use, and intensive monitoring has shown how it can contribute to ensure this. The opportunity for association and harmonisation of the intensive forest monitoring network with other environmental monitoring networks in Britain (e.g. Countryside Survey, National Inventory of Woodland and Trees, Environmental Change Network, UK National Ammonia Monitoring Network, BioSoil) provides a wider benefit and added value to policy makers and scientists. A robust environmental evidence base is essential for policy-making, regulation and the promotion of sustainable services and economic growth.

ACKNOWLEDGEMENTS

This Information Note reports the work of numerous members of Environmental and Human Sciences Division, Chemical Analysis Laboratory, and the Technical Support Unit of Forest Research over the past ten years. In particular, the contribution is acknowledged of Peter Crow, Samantha Broadmeadow, Matthew Wilkinson, Matthew Williams, Lorraine Adams, François Bochereau, Tracy Houston and Paul Taylor. The work and enthusiasm of Dave Durrant in establishing the network should not be forgotten.

The work was co-funded by the European Commission and the Forestry Commission, with additional funding provided by Defra under the Terrestrial Umbrella for Acidification and Eutrophication.

REFERENCES AND USEFUL SOURCES OF INFORMATION

BINNS, W.O., REDFERN, D.B., RENNOLLS, K. and BETTS, A.J.A. (1985).
Forest health and air pollution: 1984 survey. Forestry Commission Research and Development Paper 142. Forestry Commission, Edinburgh.

CRONAN, C.S. and GRIGAL, D.F. (1995).
Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. *Journal of Environmental Quality* **24**, 209–226.

DURRANT, D.W. (2000).
Environmental monitoring in British forests. Forestry Commission Information Note 37.
Forestry Commission, Edinburgh.

EMMETT, B.A. (2002).
The impact of nitrogen deposition in forest ecosystems: a review. CEH Project No: C00311, Defra Terrestrial Umbrella Phase II.

EVANS, C. and REYNOLDS, B. (2003).
An assessment of the suitability of the Very Simple Dynamic (VSD) model for UK national-scale application: model and data issues. Report to Defra, May 2003, Centre for Ecology and Hydrology, University of Wales, Bangor.

EVANS, S. RANDLE, T., HENSHALL, P., ARCANGELI, C., PELLENQ, J., LAFONT, S. and VIALS, C. (2005).

Recent advances in the mechanistic modelling of forest stands and catchments. In: *Forest Research annual report and accounts 2003–2004*.
The Stationery Office, Edinburgh, 98–111.

FORESTRY COMMISSION (2002).
UK indicators of sustainable forestry.
Forestry Commission, Edinburgh.

FORESTRY COMMISSION (2004).
The UK forestry standard: *the government's approach to sustainable forestry*, 2nd edition.
Forestry Commission, Edinburgh.

GUNDERSEN, P. (1999).
Nitrogen status and impact of nitrogen in forests – indicators and their possible use in critical load assessment. Paper presented at Conference on Critical Loads, Copenhagen, November, 1999.

HALL, J., ULLYETT, J. *et al.* (2003).
Status of UK critical loads – critical loads methods, data and maps. Centre for Ecology and Hydrology, Huntingdon. www.critloads.ceh.ac.uk/reports.htm

HENDRY, S.J., POOLE, E.J., CRAIG, I. and PROUDFOOT, J.C. (2005).
Forest condition 2004. Forestry Commission Information Note 75.
Forestry Commission, Edinburgh.

HILL, M.O., MOUNTFORD, J.O., ROY, D.B. and BUNCE, R.G.H. (1999).
Ellenberg's indicator values for British plants. ECOFACT Volume 2 Technical Annex. ITE, Huntingdon.

HULME, M., JENKINS G.J., LU, X., TURNPENY, J.R., MITCHELL, T.D., JONES, R.G., LOWE, J., MURPHY, J.M., HASSELL D., BOORMAN, P., McDONALD, R. and HILL, S. (2002).
Climate change scenarios for the United Kingdom: The UKCIP02 scientific report. Tyndall Centre for Climate Change Research, School of Environmental Science, University of East Anglia, Norwich.

KIRBY, K.J., SMART, S.M., BLACK, H.I.J., BUNCE, R.G.H., CORNEY, P.M. and SMITHERS, R.J. (2005).
Long term ecological change in British woodland (1971–2001). A re-survey and analysis of change based on 103 sites in the Nature Conservancy 'Bunce 1971' woodland survey. English Nature Research Report number 653. English Nature, Peterborough.

MCPFE (2002).
Improved Pan-European indicators for sustainable forest management. www.mcpfe.org/publications/pdf

NEGTAP (2001).
Transboundary air pollution: acidification, eutrophication and ground-level ozone in the UK. Report of the National Group on Transboundary Air Pollution. Defra, London.

NILSSON, J. and GRENNFELT, P. (1988).
Critical loads for sulphur and nitrogen. NORD 1988: 15 Nordic Council of Ministers, Copenhagen. Miljörapport 15.

PITCAIRN, C.E.R., LEITH, I.D., SHEPPARD, L.J., SUTTON, M.A., FOWLER, D., MUNRO, R.C., TANG, S. and WILSON, D. (1998).
The relationship between nitrogen deposition, species composition and foliar nitrogen concentrations in woodland flora in the vicinity of livestock farms.
Environmental Pollution **102** (S1), 41–48.

SEMENOV, S.M. and KOUKHTA, B.A. (1996).
Ozone influence on tree and crop growth: modelling the effects and estimating critical levels. In: *Critical levels for ozone in Europe: testing and finalising the concepts*.
Eds. L. Karanlampi and L. Skarby.
University of Kuopio, Finland.

SPARKS, T. and GILL, R. (2002).
Climate change and the seasonality of woodland flora and fauna. In: *Climate change and UK forests*. Ed. M.S.J. Broadmeadow. Forestry Commission Bulletin 125.
Forestry Commission, Edinburgh, 69–82.

TAYLOR, C.M.A. (1991).
Forest fertilisation in Britain. Forestry Commission Bulletin 95. HMSO, London.

UNECE (2006).
Forest condition in Europe. 2006 Technical Report of ICP Forests. BFH, Hamburg.

Van Den BURG, J. (1985).
Foliar analysis for determination of tree nutrient status – a compilation of literature data. Report No 414. Rijksinstituut voor Onderzoek in de Bos – en Landschapsbouw 'de Dorschkamp', Wageningen, The Netherlands.

European Legislation

Council Regulation (EEC) No. 3528/86 on the protection of the Community's forests against atmospheric pollution.

Commission Regulation (EC) No. 1091/94 on the protection of the Community's forests against atmospheric pollution laying down certain detailed rules for the implementation of Council Regulation (EEC) No. 3528/86.

Regulation (EC) No. 2152/2003 of the European Parliament and of the Council concerning monitoring of forests and environmental interactions in the community (Forest Focus).

Biogeochemical enquiries relating to this publication should be addressed to:

Elena Vanguelova
Biogeochemist
Environmental and Human Sciences Division
Forest Research
Alice Holt Lodge
Farnham
Surrey
GU10 4LH

T: 01420 526174
F: 01420 520180
E: elena.vanguelova@forestry.gsi.gov.uk

Other enquiries about the Intensive Forest Monitoring Network should be addressed to:

Nadia Barsoum
Intensive Forest Monitoring Network Project Leader
Environmental and Human Sciences Division
Forest Research
Alice Holt Lodge
Farnham
Surrey
GU10 4LH

T: 01420 526219
F: 01420 520180
E: nadia.barsoum@forestry.gsi.gov.uk

ISSN 1460-3802
ISBN 978-0-85538-737-2

FCIN088/FC-GB(CLA)/WP-1.5K/AUG07