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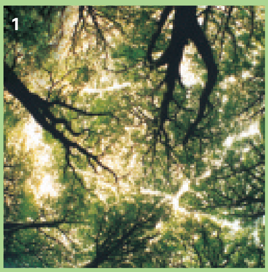
How extensive are the impacts of nitrogen pollution in Great Britain's forests?

Protecting our forests from pollutant deposition is and has been a topical issue for some time. Nitrogen, as well as being an essential nutrient for trees, is one of the most important of these pollutants. This article discusses the extent and severity of the issues associated with nitrogen pollution in our forests.



1. Canopy chemistry reflects nitrogen status: beech canopy at Myherin Woodland, Ceredigion.
2. Fungi thriving under beech woodland.
3. Ground flora under beech woodland at Bolton Abbey, Yorkshire.
4. Nitrate leaching is known to be high at this Intensive Monitoring plot at Thetford, Norfolk.

INTRODUCTION

Since the 1940s atmospheric nitrogen pollution has steadily increased, primarily as a consequence of the combustion of fossil fuels and agricultural intensification (Hornung and Langan, 1999). Nitrogen is an essential nutrient for plant growth, so why is nitrogen pollution an issue? While increases in the deposition of atmospheric nitrogen pollutants are likely to have contributed to improved forest productivity during the 20th century (Cannell, 2002), it is possible for a forest ecosystem to receive too much nitrogen.

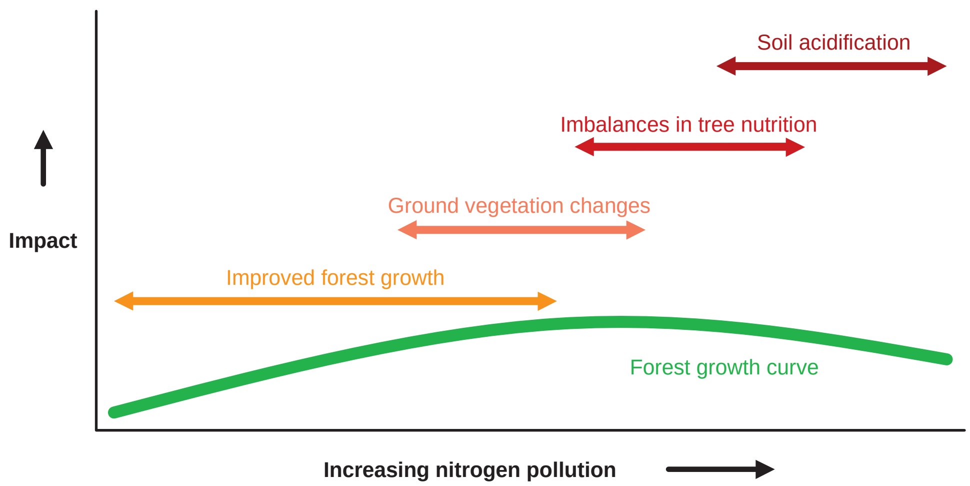
Gundersen (1999) has schematically summarised the effects of increasing nitrogen deposition on forests (Figure 1). Initially the forest canopy intercepts nitrogen and uses it for growth. As pollution levels increase, the nitrogen breaks through the canopy and reaches the forest floor. Here changes in response to nitrogen tend to be observed in the non-woody herbaceous ground flora first, due to their short life cycles in comparison to trees. Nitrophiles (nitrogen loving species) out-compete plants with lower nitrogen requirements, so in the first instance nitrogen deposition can impact upon biodiversity. Further increases in nitrogen deposition can result in imbalances in tree nutrition and when this occurs forest growth may be detrimentally affected relative to that under optimal nitrogen nutrition. Trees take up the nitrogen in excess, leading to deficiencies in other nutrients and increased susceptibility to insect attack and drought (Bobbink *et al.*, 1996). Finally, should nitrogen deposition reach a level at which inputs to the forest ecosystem are in excess of both biological demand and the storage capacity of the soil, then nitrate will begin to 'leak' out of the soil below the rooting zone. This state, which has been termed 'nitrogen saturation' (Aber *et al.*, 1989), has two key detrimental effects.

- Nitrate leakage disrupts the ion balance in the soil causing soil acidification, base cation depletion and increased aluminium toxicity to tree roots.
- The migration of nitrate out of the soil profile has the potential to contaminate surface and groundwater supplies, resulting in problems of eutrophication and algal growth.

The onset of changes in ground vegetation composition in Figure 1 overlaps with the 'improved forest growth' zone. This has important implications for the interpretation of national critical loads maps which identify thresholds of pollutant input that specific elements of the environment can withstand. The thresholds used to derive the critical loads for nutrient nitrogen in Great Britain and Northern Ireland are specifically aimed at protecting ground flora and epiphytic mosses and lichens. Thus a woodland located in an area in which the critical load for nutrient nitrogen deposition is currently exceeded will not necessarily have unhealthy trees or poor growth.

Figure 1

A schematic representation of the impacts of increased pollution on forest ecosystems (Gundersen, 1999).



THE GB SITUATION

Where do the forests in Great Britain (GB) sit on the schematic curve in Figure 1? Critical load maps for nutrient nitrogen are set to protect the most sensitive components of the forest ecosystem but how accurate are they? What percentage of GB forests are showing signs of nutrient imbalance? If nitrogen saturation is not necessarily occurring in all of the exceeded squares on the national critical load maps, how extensively is it occurring?

Changes in ground vegetation

In Europe there is now a considerable body of literature documenting changes in the species composition of woodland ground flora, macrofungi and mycorrhizae that are related to increased nitrogen deposition (Bobbink *et al.*, 1996). Fewer studies have been undertaken in Great Britain but these have found similar effects. Pitcairn *et al.* (1998) surveyed the wooded areas surrounding four livestock farms (which are significant point sources of nitrogen) in Scotland. These included a Scots pine plantation, two conifer shelter belts and some mixed deciduous woodlands with large beech and birch components. They found that species diversity in ground flora declined within 300 m of the emission source.

In autumn 2001 a survey of 20 beech woodlands distributed throughout Great Britain (Figure 2) was undertaken by the Environmental Research Branch of Forest Research. Results showed that changes in ground flora could be predicted by measuring the average distance from the centre of a 20 x 20 m survey plot to the edge of the woodland. The closer the woodland edge, the more nitrogen demanding the ground flora (Figure 3). The data show that the Ellenberg indicator values, which weight species on the basis of their nitrogen requirements (Hill *et al.*,1999), rise significantly as the distance to the edge of the wood declines. Unfortunately there are no data points in Figure 3 between 500 and 740 m, but on the basis of the available data, high Ellenberg values certainly begin to occur at sites within an average distance of 500 m from the woodland edge.

Much of the scatter in Figure 3 is because the distance to the edge of a woodland does not always represent the distance to a source of agricultural emissions of nitrogen from either livestock or fertilised arable farmland. However, it is still of interest to calculate the proportion of forest area in GB that is within 500 m of the edge of non-forested land. A calculation using data from a national survey of the size distribution of forests in Great Britain, which omits woodland types that tend to be densely planted and have minimal ground flora, places ~60% of the remaining GB woodlands within 400 m of woodland edges. This is a very approximate approach to quantifying the problem and suggests, as a rough estimate, that 60% of GB woodland ground flora could potentially have been altered. The current national critical load map for nutrient nitrogen estimates the extent of the problem using a different approach, namely comparing modelled maps of nitrogen deposition to a threshold based on expert opinion. This approach suggests that an area of over 80% may be affected (NEGTAP, 2001). The two estimates are considerably different, demonstrating that the uncertainty in any calculation of this nature is large. However, both estimates are high, indicating that nitrogen-enhanced changes in the composition of ground flora in GB forests are likely to be widespread and to have developed as agriculture has intensified and vehicle numbers have increased.

Imbalances in foliar nutrition and their effects

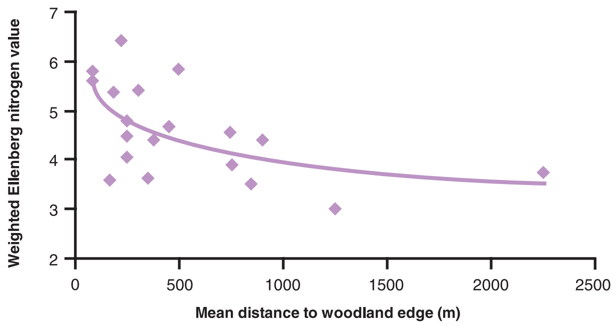
The best way to quantify tree nutrition at a large number of sites is to take foliar samples for chemical analysis. The largest survey of foliage chemistry undertaken in Great Britain in recent years was in 1995 when approximately 60 of the Forest Condition (Level I) monitoring plots, located throughout England, Scotland and Wales, were sampled under a European initiative (Stefan *et al.*, 1997). To provide as much information as possible, the foliar nitrogen data from the conifer sites in this survey have been combined in Figure 4 with those from the Intensive (Level II) monitoring plots (Durrant, 2000) and other surveys undertaken in recent years.

Figure 2

Locations of the 20 beech woodlands surveyed in 2001.

Figure 3

Changes in the nitrogen demand of beech woodland ground flora with proximity to the woodland edge; $R^2 = 0.35$, $p = 0.025$.



A foliar N content of >1.8% in Scots pine was found by Aronsson (1980) to increase frost damage but the value of 1.7 % is more widely used to indicate nutrient imbalance in conifers (Gundersen, 1999). It should be noted that this 'critical value' is close to the threshold for optimal nutrition (1.4%: Taylor, 1991), a key factor in site productivity. The results in Figure 4 show that approximately three-quarters of the Scots pine plots had nitrogen concentrations in needles in excess of 1.7%. Perhaps more significantly, there is a positive relationship between the estimated nitrogen deposition at the Scots pine plots (taken from the national 5 km x 5 km database for 1995-97; Fowler, personal communication) and foliar N content. Thus nitrogen pollution does appear to be a strong contributory factor in causing increased foliar N concentrations at the Scots pine sites. Increases in estimated nitrogen deposition also appear to impact upon foliar N concentrations at the Norway spruce plots, although the effect is less acute and, more crucially, the range of N contents is much lower. Only a quarter of all spruce plots (Sitka and Norway) were above the 1.7% threshold. There was no relationship between nitrogen deposition and foliar nitrogen concentrations in Sitka spruce.

Figure 4

Relationships between nitrogen deposition and foliar nitrogen in three conifer species in GB; Norway spruce: R^2=0.43, p=0.011; Scots pine: R^2=0.65, p=0.003.

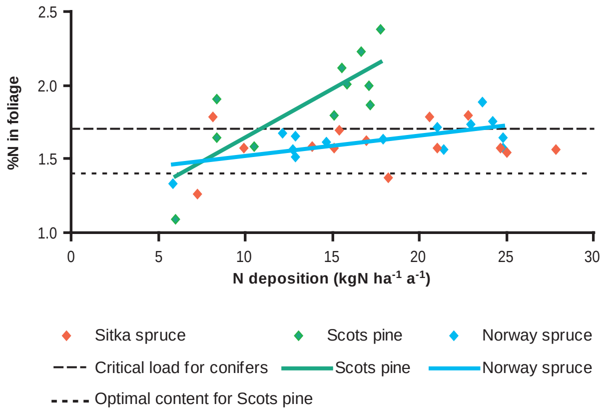
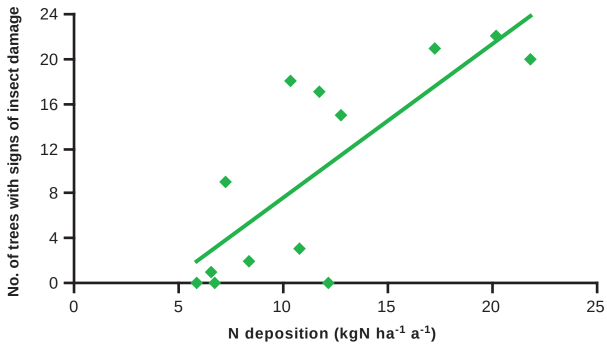


Figure 5

Relationship between nitrogen deposition and the occurrence of insect damage in Scots pine in Scotland in 1999 (24 trees assessed in each plot); R^2=0.61, p=0.002.



There is evidence that the high N concentrations in Scots pine needles are detrimental to forest health in some areas of Great Britain but not others. Figures 5 and 6, derived from forest condition data for the Level I plots, show both an increased occurrence of insect damage and a reduction in needle retention with increasing nitrogen deposition to Scots pine in Scotland. These relationships did not hold for either Norway or Sitka spruce (with the exception of a very weak decline in needle retention in Norway spruce). However, the relationships in both figures are, inexplicably, only apparent in Scotland. If the English and Welsh sites are included in the analysis both trends disappear and in England and Wales alone, needle retention improves with increasing nitrogen deposition. It is possible that these different responses are due to site quality; broadly speaking, the soils in England and Wales are more nutrient rich than those of Scotland. The possibility that nitrogen deposition in Figures 5 and 6 is acting as a surrogate for a temperature effect has been tested and rejected.

There is no evidence that nitrogen deposition is damaging the health of broadleaved plots. The phosphorus (P) concentration (Figure 7) and the N:P ratio (a useful nutritional indicator) increased in line with nitrogen deposition. There were no relationships between foliar P and N deposition in the conifers; in fact foliar P in Norway spruce fell slightly with increased N deposition. Unlike other countries such as Switzerland, where deposition levels have reached as high as 30–40 kgN ha^{-1} a^{-1} and detrimental effects on beech have been observed (Flückiger and Braun, 1998), it appears that nitrogen inputs are having a beneficial effect on broadleaved species in England and Wales. It can be speculated that the additional nitrogen has improved root growth and the ability of trees to obtain phosphorus. Whatever the mechanism, there are no detrimental effects of nitrogen deposition on foliar chemistry and, consequently, no detrimental effects on forest condition could be found when data for oak were investigated. This is perhaps not surprising as broadleaves naturally have higher nitrogen concentrations in their foliage than conifers and it is conceivable that the same level of nitrogen deposition would be beneficial to broadleaves and detrimental to conifers.

In summary, the health of Scots pine in some areas of Scotland is likely to have been detrimentally affected by nitrogen pollution. There is no evidence of detrimental health effects caused by nitrogen pollution in any of the other species investigated except possibly Norway spruce.

Figure 6

Relationship between nitrogen deposition and needle retention in Scots pine in Scotland in 1999 (24 trees assessed in each plot); $R^2=0.42$, $p=0.017$.

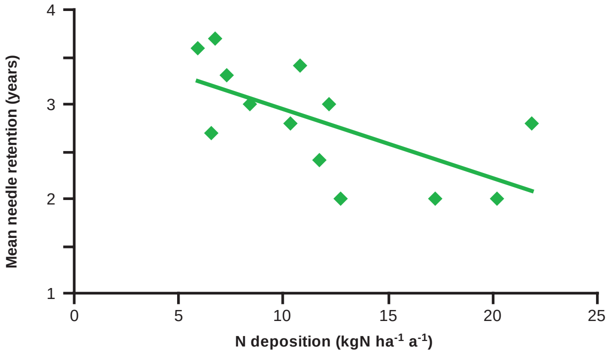
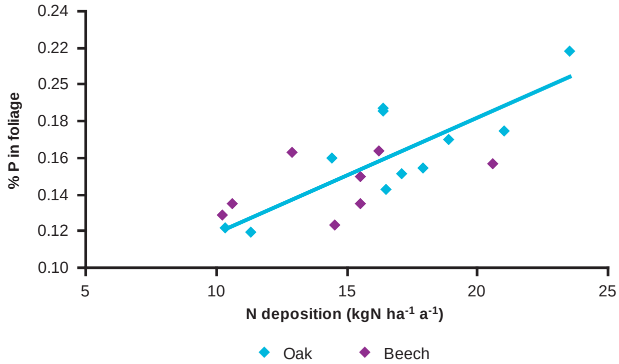


Figure 7

Relationship between nitrogen deposition and foliar phosphorus in oak and beech in England and Wales; $R^2=0.68$, $p=0.001$.



Nitrogen leakage

The dramatic differences in nitrogen concentrations that occur below the rooting zones of N saturated and unsaturated forests are demonstrated by data collected in the Level II Intensive Forest Health Monitoring network. Figure 8 shows that concentrations in soil solution at the site in Thetford Forest, Suffolk, can reach more than 100 times those recorded at the plot near Llyn Brianne reservoir in Dyfed. To some degree these differences in concentration are exaggerated by the considerably lower rainfall at Thetford, but a calculation of the fluxes of nitrate leaving the rooting zone in 1995/1996 revealed a leakage rate of 24 kgN ha^{-1} a^{-1} at Thetford and zero at Llyn Brianne.

A key threshold with regard to nitrogen leakage in the lowlands is the EC drinking water limit of 11.3 mg l^{-1}. At the seven Intensive Forest Health Monitoring sites at which subsoil water is collected, this limit is only exceeded in Thetford Forest. That we only see this at one out of seven of the plots is reassuring, but with data from so few sites, predictions cannot be made about the national extent of the problem. Furthermore, in the uplands of GB, where a number of the Level II plots are situated, soil and stream water acidification caused by the leaching of nitrate is also of concern.

The difficulty in assessing the extent of nitrate leaching is that the collection of data such as those presented in Figure 8 is labour and cost intensive. There are two ways to circumvent this problem. One is to collect data intensively at a larger number of sites, but for only a relatively short period of time, e.g. one to two years. The other is to collect one-off samples of subsoil water at a large number of sites during a sensitive period when nitrate levels are likely to be higher. (Note the seasonal cycle at Thetford Forest in Figure 8.) Three such surveys have been undertaken in recent years. These have concentrated on Sitka spruce (Emmett *et al*., 1993; Emmett *et al*., 1995) and more recently oak (Emmett, personal communication) and beech (Figure 2).

The Sitka spruce study was centred on stagnopodzols in upland Wales. Significant nitrogen leaching (in excess of that expected from known pristine sites located in northern Scandinavia) was found to occur at sites where the forest was over 30 years old and this was attributed to a decrease in nitrogen demand as the stand ages. From woodland inventories we know that Sitka spruce stands over 30 years old make up approximately 24% of the forest area in Wales, but these forests will cover a wide variety of soil types, not all of which will necessarily respond in the same way as the stagnopodzols in the study. In the more recent

Figure 8

Contrasting nitrate levels in the soil solution at 0.5 m depth at two of the sites belonging to the Level II Intensive Forest Health Monitoring network.

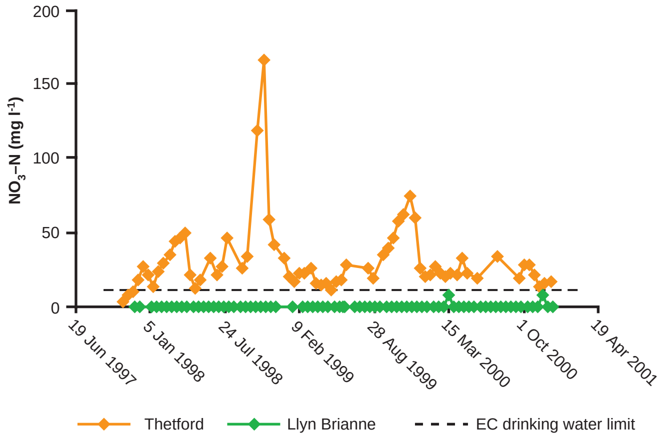
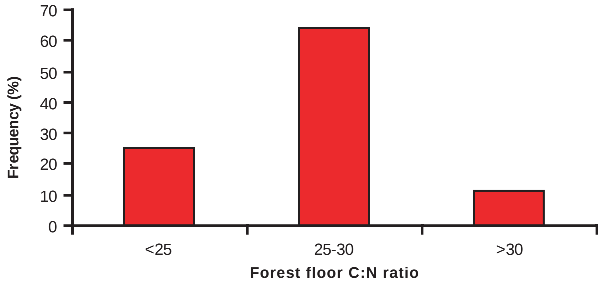


Figure 9

The distribution of C:N ratios in the forest floor of 36 Level I conifer plots in GB.



surveys of broadleaved species, Emmett (personal communication) found nitrogen leaching at three out of 19 oak plots in Wales and the northwest of England, and the beech survey on brown earth soils showed very similar results; nitrate leaching was observed in three out of 20 plots. These surveys all indicate that an estimate of 15–20% may be realistic for the fraction of woodlands experiencing nitrate leakage in England and Wales. Too few studies in Scotland have been undertaken to warrant even an estimate being made.

Using relationships between nitrate leaching and a more readily accessible indicator precludes the need for surveys such as those described above. Results using this approach can be compared to the above estimates with mixed success. For example, the ratio of carbon to nitrogen in the forest floor is often used as an indicator for nitrate leaching in conifer stands (Gundersen *et al.*, 1998). High nitrogen levels, and thus low carbon to nitrogen ratios, tend to indicate that the organic fraction of a soil no longer has the capacity to assimilate all incoming nitrogen and prevent it from leaching below the rooting zone. Data from a soil survey of 36 of the coniferous Forest Condition (Level I) plots in 1995 show that 25% had C:N ratios below the threshold value of 25 (Figure 9). This agrees well with the Welsh Sitka spruce study above, but unfortunately there is a 'grey' zone for C:N ratios, between 25 and 30, in which some sites leak nitrogen and others do not (Wilson and Emmett, 1999). There are various possible reasons for this but, as yet, there is no consensus as to the causal factors. Since most of the C:N ratios derived for the Level I sites sit in this grey zone, it is possible that more than 25% of coniferous sites are leaching nitrogen below the rooting zone, but how much more and in what fraction of these the nitrate reaches the stream water we currently cannot say.

IMPLICATIONS FOR FOREST DESIGN AND MANAGEMENT

As a consequence of pollution abatement agreements such as the Gothenburg Protocol and its predecessors, the deposition of nitrogen oxides in Great Britain has declined by 16% from its peak in 1990. Although this has had relatively little effect on total nitrogen deposition (which is dominated by ammonia) to date, declines are anticipated (NEGTAP, 2001). However, although this means improvements can be anticipated in the longer term, we cannot be sure how forest ecosystems will respond in the short to medium term. Even as nitrogen deposition begins to decline due to its historical accumulation in forests, it may still build up in the system and lead to further increases in leaching before we see signs of recovery.

Forest design and management can have a significant influence on the nitrogen status of woodlands. An effective course of action to combat nitrogen-related changes in ground vegetation would be to increase the size of woodlands, thus decreasing the relative area of 'edge'. This is not a new concept; Peterken and Game (1984) proposed a similar scheme. The de-fragmentation of woodlands would also go some way to reducing the occurrence of nitrate leaching.

Two further management options can also contribute to this reduction.

- It is known that in spruce stands of uniform age the occurrence of nitrate leaching is related to the age of the plantation (Emmett *et al.*, 1993). As vigorous early growth diminishes, so the use of nitrogen falls and it is more likely to leak from beneath the rooting zone. Recent moves for the expansion of mixed age plantations, such as those outlined in *Woodlands for Wales: The National Assembly for Wales strategy for trees and woodlands* (Forestry Commission, 2001), may improve the current situation. However, the potential effects of uneven-aged stands on air turbulence that could enhance deposition remain unquantified.
- The maintenance of a cover of ground vegetation can help to reduce nitrate leaching considerably. The survey of beech woodlands (Figure 2) demonstrated that nitrate leaching was only observed in the subsoil where the ground vegetation cover was less than 30%. However, in practice, establishing and maintaining ground vegetation is not necessarily straightforward or compatible with best practice for forest establishment. To this end, experimentation has begun to investigate the practicalities of establishing ground cover. In addition, the protection of watercourses from excess nitrate is best achieved through the recognised practice of establishing effective buffer and riparian zones (Forestry Commission, 2000).

CONCLUSIONS

Nitrogen deposition impacts on different elements of forest ecosystems to different degrees. While reductions in the species diversity of ground vegetation are undoubtedly widespread in Great Britain, it is thought that they are not as extensive as national critical loads maps may indicate.

Research suggests that the health of some Scots pine stands in Scotland (but not England and Wales) has been detrimentally affected by nitrogen deposition levels but whether this has impacted upon growth is not known. Some effect on the health of a small fraction of Norway spruce stands also cannot be ruled out, but Sitka spruce has remained unaffected to date. In contrast, the condition of oak and beech appears to have improved as a consequence of nitrogen deposition in GB. While there is little possibility of further increases in nitrogen deposition, it is unlikely that we will see the detrimental effects recorded in some continental European countries where pollution levels are higher (Flückiger and Braun, 1998).

A state of nitrogen saturation, and thus nitrate leaching, may occur in some 15% of broadleaved woodlands in Great Britain. While the incidence is probably slightly higher for conifers, we cannot be sure by how much. The difference between woodland types is thought to be due to the presence or absence of a cover of ground vegetation (its presence increases the overall biological demand for nitrogen) and soil characteristics.

While we can expect background levels of nitrogen deposition to fall over the next decade, we can also anticipate a lag effect in recovery due to the historical accumulation of nitrogen which has already occurred. Forest management can aid the recovery process by a move towards more mixed age and less fragmented crops, a reduction in large scale clearfelling, and the establishment of native woodland riparian buffer areas and woodland ground vegetation.

Finally, the need to continue monitoring forest condition, both intensively and extensively, is imperative if potentially complex responses to emission controls are to be detected, understood and used to guide changes in forest management.

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