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RECENT RESULTS AND UPDATING OF SCIENTIFIC AND TECHNICAL KNOWLEDGE

# CARBON-NITROGEN INTERACTIONS AND NITROGEN EFFECTS

Report by the International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP Integrated Monitoring)

## INTRODUCTION

1. Carbon (C) and nitrogen (N) cycles are interdependent. In forests, C and N accumulate together in soil organic matter and the processes are closely linked. It is important to understand these processes to assess long-term impacts of N emission reduction policies of the Convention and the European Union (EU). The EU project CNTER (Carbon and nitrogen interactions in forest ecosystems, www.flec.kvl.dk/cnter) has increased the understanding of these links. Data from both ICP Integrated Monitoring and ICP Forests were used. Main results (Gundersen et al.

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2006) are presented in this report, in accordance with the Convention on Long-range Transboundary Air Pollution's 2007 workplan (item 3.6).

## I. CYCLE INTERACTIONS

### A. Carbon interactions in the nitrogen cycle

2. In many forest ecosystems, especially in north-western and central Europe, N deposition currently exceeds the capacity of the vegetation to accumulate and remove nitrogen through net primary production. Most of the excess N is retained in soil or leached as nitrate, which could acidify and eutrophy soils and downstream water bodies. Soil capacity to retain N seemed to depend on C availability in soil organic matter, which was related to the carbon-nitrogen (C/N) ratio of these pools (e.g. Gundersen et al. 1998, MacDonald et al. 2002). The C/N ratio might decrease over time if more N-rich organic matter was accumulating. Ultimately, if the C/N ratio were to reach a critical threshold for effects, the ecosystem might become N saturated and nitrate ($NO_3$) would eventually "break through" and leach. Quantifying the rate of such C/N ratio changes over time is crucial to predicting future N retention and $NO_3$ losses from forest ecosystems. In critical loads for eutrophication and acidification, long-term soil N retention is one of the most uncertain parameters.

### B. Nitrogen interactions in the carbon cycle

3. The largest amount of C in forest ecosystems of the Northern Hemisphere is stored in soil. C is fixed by photosynthesis and it ultimately moves via litterfall to the soil, where it is only partially decomposed. Soil is the ultimate long-term sink or source of carbon dioxide ($CO_2$) in forests. N is usually the limiting nutrient in forest ecosystems, therefore C sequestration is closely linked to the N cycle. N deposition has increased in large regions of Europe (and parts of North America) and may have led to increased net primary production in many forest ecosystems. This could have increased sequestration of atmospheric $CO_2$. Understanding the N cycle in forests leads to understanding C sequestration and the strength of long-term C source or sink in soils. The effect of increased N deposition on C sequestration in forests could be a significant sink in the global C budget, but the magnitude is unknown and debated. Nadelhoffer et al. (1999) suggested that currently this was minor, and that soil and vegetation capacities were equal. In the Kyoto Protocol of the United Nations Framework Convention on Climate Change, terrestrial $CO_2$ sinks were recognized and may be accounted for in the agreed international $CO_2$ emission reductions in future. This would require methods to reliably quantify these C sinks.

## II. RESULTS

### A. Nitrogen leaching

4. Databases on C and N fluxes and pools in European forests were compiled for 400 sites. They were used to create empirical models that predict C accumulation, N retention and $NO_3$ leaching based on N deposition, and climate and ecosystem characteristics. For $NO_3$, leaching analyses showed there was a threshold deposition of 8–10 kg N $ha^{-1}$ $a^{-1}$, below which practically no leaching occurred (see also Forsius et al., 2001). Parameters that determined $NO_3$ leaching and also N retention were: N deposition, C/N ratio in the organic soil layer and annual mean temperature. At low C/N ratios (<23), N throughfall deposition determined $NO_3$ leaching (figure 1). At higher C/N ratios, both N throughfall deposition and temperature were important. Results were robust in validation tests.

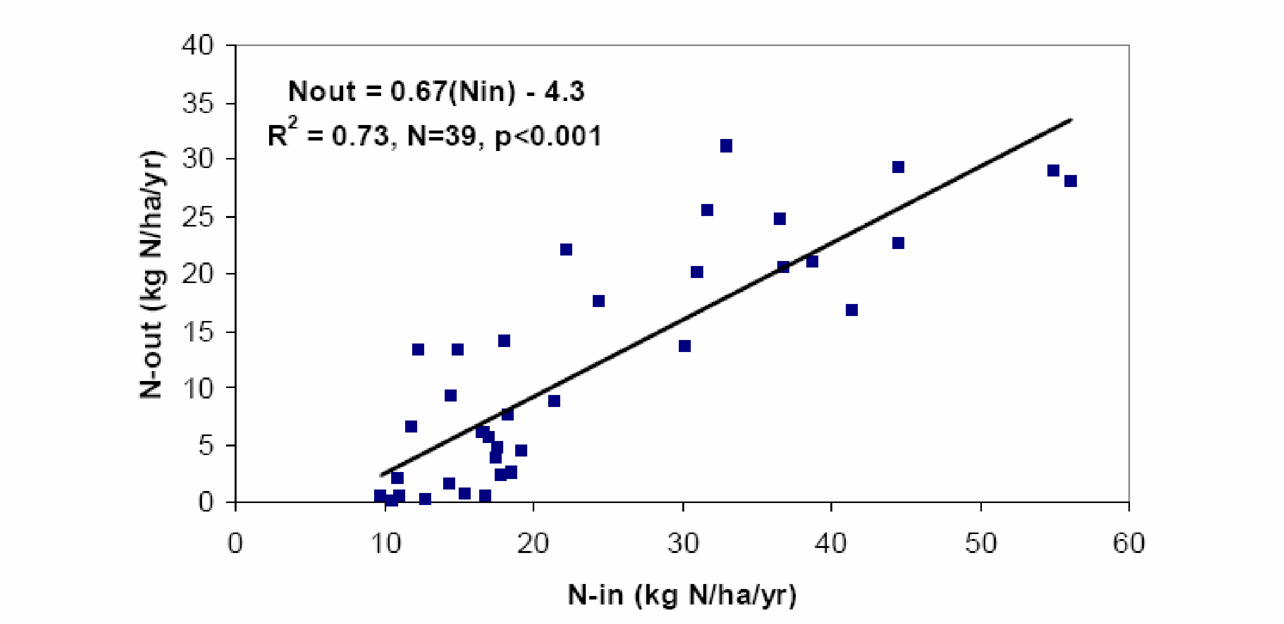


**Figure 1.** N leaching (N-out) against N throughfall deposition (N-in) in throughfall, both in kg N $ha^{-1}$ $a^{-1}$, for forests with soil organic layer C/N ≤ 23. The regression equation and its statistical significance are also shown.

### B. Nitrogen impact on carbon sequestration

5. Based on a " N balance" approach where estimates C sequestration rates in soils were calculated by multiplying soil N retention (calculated as the difference between N deposition, tree uptake and leaching) with soil C/N ratio, the mean sequestration rate for European forests in the study was 190 kg C $ha^{-1}$ $a^{-1}$. The data were biased towards central Europe,where the rates were highest (figure 2). An unbiased but more uncertain extrapolation to all Europe resulted in 70 kg C $ha^{-1}$ $a^{-1}$.

6. Estimates of C and N sequestration rates in the forest soil organic layer were also calculated for specific sites based on the "limit value" concept that uses data on organic matter decomposition. Decomposition of plant litter is one of the most important processes determining C turnover and soil C storage. Earlier, Berg et al. (2001) found empirical relationships between litter chemical composition and the remaining recalcitrant fraction. This method was further validated in this study. It was upscaled to Europe for 150 sites with sufficient data, resulting in 400 kg C $ha^{-1}$ $a^{-1}$. The method was also applied in Sweden, where sequestration rate ranged from 40 to 400 kg C $ha^{-1}$ $a^{-1}$. Estimates obtained by the N balance approach throughout Sweden were below those for the limit value approach, but both methods followed the same spatial gradients.

7. Estimates of C sequestration in the organic layer, using the limit value method, were usually higher than those using the N balance approach for two reasons: (i) the limit value approach cannot account for negative C sequestration (i.e. C loss), unlike the N balance method; and (ii) the limit value approach estimates C accumulation in the top part (forest floor), which has the highest C accumulation rate of the soil, whereas the N balance approach accounts for the whole soil profile (down to ca. 50 cm).

8. Regional and European estimates of present C sequestration rates in forest soils using several methods were made. They consistently showed that rates were low, 0–400 kg C $ha^{-1}$ $a^{-1}$. Assuming a likely mean of 100 kg C $ha^{-1}$ $a^{-1}$, the amount of sequestration in Europe would be 13 Mt C $a^{-1}$. Trees additionally accumulate of 70 Mt C $a^{-1}$ in their biomass. These estimates were much lower than earlier published estimates based on other approaches. This study assumed that C accumulated with N, i.e. C/N ratios did not increase. High N deposition in Europe is likely to decrease C/N ratios, thus C sequestration rates would probably be lower than estimated. Further research is needed to established soil C sequestration numbers to reduce uncertainties on the size of biological C sinks in Europe.

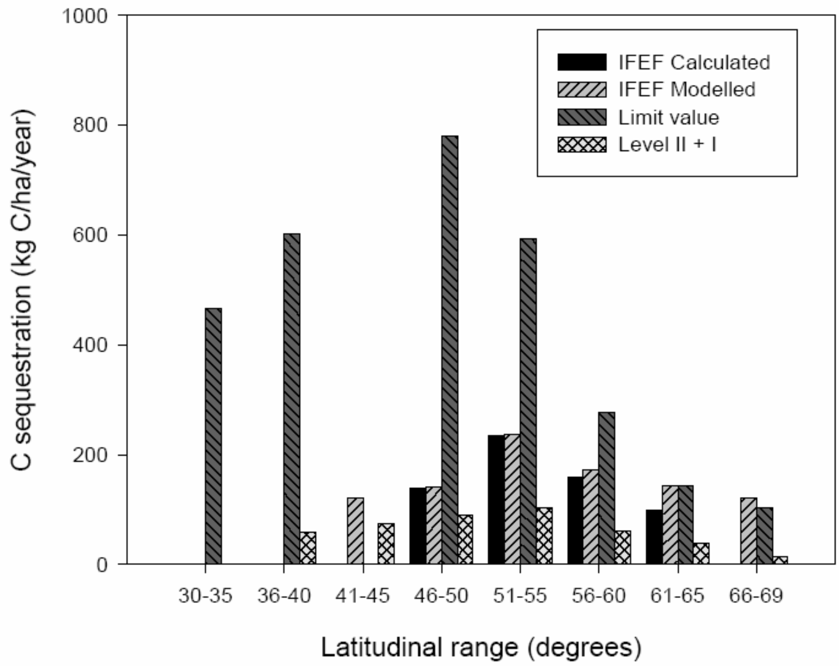


**Figure 2.** C sequestration across Europe estimated by the N balance method using two databases (the "Indicators of forest ecosystem functioning" (IFEF) database, improved during the CNTER project, and levels I and II database of ICP Forests), and the limit value method. For the IFEF-database, C sequestration was calculated using both measured and modelled (from regression equations) N leaching.

## C. Results from long-term field experiments

9. Soil and vegetation from long-term field experiments, where stable N isotopes had been added, were re-sampled to gain insight into C and N interactions. After 10 years, most of the N applied over the first year was still present in the soil in amounts comparable to those measured after one to three years. These resamplings allowed for a thorough testing and validation of a process model, which predicted the fate of N ecosystems. Tree species trials (12 species planted at 13 locations), plantation mosaics, and felling experiments were resampled to gain insight into forest management options (tree species, age and felling regime) for increasing C sequestration and protecting downstream water against eutrophication. In humid temperate climate regions, the impact of felling increased with decreasing thickness of the organic layer. There was no consistent effect of tree species on N leaching between the different geographical regions in these trials. On a cross-European basis, conifer forests receiving inorganic N in throughfall of 10–25 kg N $ha^{-1}$ $a^{-1}$ appeared to have enhanced N leaching compared with deciduous forests receiving the same amount of N throughfall deposition. The most likely reason for this is that

full-year filtering of atmospheric dry deposition by needles enriches the N status of the site, thus enhancing N leaching.

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