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Tamm Review: Revisiting the influence of nitrogen deposition on Swedish forests

Dan Binkley [a,b,*], Peter Högberg [a]

[a] Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, S-901 83 Umeå, Sweden
[b] School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, USA

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ABSTRACT

Are the health and productivity of Sweden's forests at risk from too much nitrogen (N) from acid deposition? Twenty years ago we assessed the evidence available for several aspects of this question (Binkley and Högberg, 1997). We found little evidence for risks other than potential shifts in ground flora, but concerns continued to arise across Europe and elsewhere. We took advantage of two decades of accumulated evidence to re-evaluate whether Swedish forests are threatened by N deposition. During this time, N deposition declined by about 25% across the southern half of Sweden, and sulfur deposition declined by more than half. The growth rates of forests across the country continued the long-term trend of increasing by about 1–1.5% annually; average growth rates are now about 20–25% greater than in the mid-1990s. Forest soils often acidify by about 0.5–1.5 pH units during a rotation, but some evidence indicated that acidification may have occurred beyond this age-related pattern. Any average change in soil pH across the country appeared to relate more strongly to increases in carbon concentrations rather than cation leaching and declining base saturation. No evidence of N saturation (with outputs matching inputs) has been reported in Sweden, and nitrogen-limitation remains widespread. Fertilization with elements other than N generally does not increase growth unless N is also added, especially on mineral soils. Long-term fertilization experiments demonstrated that growth responses depended heavily on the dose rate of N application, not just cumulative totals. Repeated low rates of addition (20–50 kg N ha^{-1} yr^{-1}) provided greater growth increases per kg N added than higher rates, illustrating that the possible impacts of N deposition could not be reliably gauged by shorter-term experiments with unrealistically high dose rates. The composition of ground flora appeared to be sensitive to N additions, in studies across geographic gradients of N deposition and with high rates of N fertilization. Any long-term effects of N deposition on ground flora may be difficult to separate from long-term changes in stand structure and growth. Aluminum toxicity concerns do not appear to be supported by evidence, and liming generally does not increase forest growth. We discuss broader implications that arise from this assessment, including approaches to evaluating support for assumptions, the varying quality of types of evidence, and in some cases the irreducibility of uncertainty about elucidating cause-and-effect responses in complex forest systems.

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* Corresponding author at: School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, USA.
E-mail address: Dan.Binkley@alumni.ubc.ca (D. Binkley).

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1. Introduction

Nitrogen (N) became a major focus for forest research in the second half of the 20th century. Basic research investigated the biogeochemistry of this often-limiting nutrient, and major fertilization programs substantially increased the growth of forest plantations around the world. A third focus developed in the 1970s and 1980s: could a forest have too much N? Vitousek and Reiners (1975) pointed out that if accretion of N in tree biomass was the major pool accounting for N retention, then forests with low or declining growth rates might have high rates of N losses. The deforestation experiment at Hubbard Brook in the northeastern United States supported this idea: plant uptake of N was stopped by cutting all the trees and preventing regrowth for three years, leading to soaring concentrations of nitrate in stream water (Likens et al., 1970). Might similar increases in N leakage develop if tree accumulation of N remained constant but N additions (from fertilization or atmospheric deposition) increased? Concerns about high rates of N deposition in acid rain led to questions of whether forests might not just leak excess N, but actually be harmed by it (Aber et al., 1989). Decades of research demonstrated that the biogeochemistry of N was more complicated than these early conceptualizations. The relatively high rates of nitrate loss from streams in New England dropped dramatically after the 1970s, even as some forests experienced lower rates of biomass accumulation (Martin et al., 2000; Goodale et al., 2003). These widespread declines in nitrate export remain largely unexplained (Judd et al., 2011; Lovett and Goodale, 2011).

Rates of N deposition were greater across much of Europe than in North America in the late 20th Century. Most forests in Europe continued to be net sinks for deposited N, but some actually reached a point of N saturation where losses rivaled inputs (cf. Rothe et al., 2002). Since the 1970s, deposition of sulfur compounds in Europe declined by about 75%, along with a 25% decline in N deposition (Tørseth et al., 2012). Throughout the decades of heightened concern about acid deposition, forest growth across Europe accelerated by about 0.5–2% annually with no evidence of regional declines (Kauppi et al., 1992, 2014; Spiecker et al., 1996; Solberg et al., 2009; Pretzsch et al., 2014).

The monitoring of tree crowns in Europe showed that trees of all species showed 15–30% defoliation throughout the period of 1997–2011 (Becher et al., 2012). A wide variety of agents were responsible for defoliation among the 135,000 trees in the most recent sampling, including mammalian browsing, insects, cutting by people, harvesting, and fire. Atmospheric pollution appeared to play no role in defoliation, except for a minor indication from Latvia.

It may seem that questions regarding risks of N deposition may no longer be important, but major concerns continue to be raised. The European Nitrogen Assessment concluded that N threatens soil quality, alters ground flora, acidifies soils and may lead declines in productivity (Velthof et al., 2011). Deposition of N has declined across Europe, but some parts of northern Europe have shown no decline or a slight increase, leading some scientists to conclude further reductions in deposition are required to avoid harm forests (Reinds et al., 2009; Waldner et al., 2014). Indeed, a recent summary of long-term trends in foliar nutrition of trees across Europe found "alarming trends" of declining phosphorus (P) and "unbalanced" ratios of N:P that may limit the ability of European forests to respond to increased atmospheric CO_2 (Jonard et al., 2015). Although de Vries et al. (2014) found no evidence supporting the idea that N deposition was currently harming forests, they remained concerned about a wide variety of risks, including aluminum toxicity in soils, depleted supplies of cation nutrients, loss of mycorrhizal associations, increased susceptibility to diseases and insects, increased water stress, and even concerns that increased growth would lead to nutrient imbalances that threaten faster-growing forests.

Can excess nitrogen harm forests? A few cases have demonstrated that very high doses of N fertilization can lower forest growth and increase mortality (e.g., Magill et al., 2004), but additions at high rates give qualitatively different responses from rates that are closer to rates for atmospheric deposition (Högberg et al., 2006). Twenty years ago, Binkley and Högberg (1997) examined the issues and evidence for nitrogen issues in Swedish forests. We concluded that the evidence currently available did not warrant substantial concerns, but that several key questions would benefit from more evidence. This review summarizes the evidence that has accumulated over the past two decades on the status and trends of nitrogen deposition and forest growth in Sweden. Five specific questions are revisited (from Binkley and Högberg, 1997):

1. Have Swedish forest soils acidified in recent decades?
2. Are Swedish forests saturated with N?
3. Do Swedish forests have an excess of N?
4. Will excessive N lead to forest decline:
   - by creating nutrient imbalances?
   - by acidification and aluminum-induced problems?
   - by increasing drought stress or the incidence of insect and disease problems?
5. Will liming or fertilization with elements other than N improve forest nutrition and health?

These questions are examined after providing some context on changes in atmospheric deposition and forest growth across Sweden. Many of the references from the earlier review remain relevant, but in this update we concentrate on newer work. The challenges of combining evidence with simple and complex