FOLIAR NITROGEN AS AN INDICATOR OF NITROGEN DEPOSITION AND CRITICAL LOADS EXCEEDANCE ON A EUROPEAN SCALE

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Abstract. The foliar N content of bryophytes and *Calluna vulgaris* (L.) has been shown to be an indicator of atmospheric N deposition in the UK at a regional scale (1000km) and more recently on a smaller scale in the vicinity of intensive livestock farms. This work extends the geographical scale of the relationship between foliar N concentration of *Calluna vulgaris* and other ericaceous shrubs and N deposition with 2 measurement transects, one extending from northern Finland to southern Norway (2000 km) and the other extending from central Sweden to Stockholm, south east Sweden (330 km). Included in the second transect is a region of complex terrain in the Transtrand uplands, where the variation in N deposition with altitude and canopy cover was quantified using ^{210}Pb inventories in organic soil. The relationship between foliar N (F_N) and N deposition was shown to increase linearly with N deposition (N_D) over the range 0.8% N to 1.4% N according to $F_N = 0.040N_D + 0.793$ ($r^2 = 0.70$). The data are entirely consistent with earlier studies which together provide a valuable indicator of critical loads exceedance, the threshold value being approximately 1.5% N, which is equivalent to a N deposition of 20 kg N ha^{-1} y^{-1}.

Keywords. foliar N, N deposition, *Calluna vulgaris*, critical load exceedance, Europe

1. Introduction

In the last 2-3 decades, changes in species composition associated with increased N deposition have been reported in widely separated parts of Europe in a range of plant communities, including lowland heathlands, forest ground flora, calcareous grasslands, coastal dunes, wetlands and upland moorland (Sutton *et al.*, 1993). Both field and experimental studies have identified increased emissions of ammonia from intensive farming as the major cause of many of the changes particularly those occurring in heathland (Bobbink & Roelofs, 1996; van der Eerden *et al.*, 1991; Pitcairn *et al.*, 1991). Remote upland areas which receive large inputs of wet and cloud deposited N are also at risk although changes in such areas are less well documented.

The foliar N content of some species has been to shown to increase with atmospheric inputs of N (Pitcairn *et al.*, 1995,1998; Poikolainen *et al.*, 1998) and the value of foliar nitrogen content of bryophytes and *Calluna vulgaris* (L.) as an indicator of N deposition has been demonstrated on a regional scale in the UK (Pitcairn *et al.*, 1995). The largest concentrations of tissue N of selected bryophytes and *C. vulgaris* were found in the Breckland, East Anglia, followed by Cumbria, both areas of high N deposition >30 kg N ha^{-1} y^{-1}. The smallest

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concentrations were found in north-west Scotland where N deposition was <6kg N ha^{-1} y^{-1}. More recently, foliar N content of mosses has indicated changes in species composition of woodland ground flora and critical load exceedance on a smaller scale in the vicinity of intensive livestock farms in the UK (Pitcairn *et al.*, 1998). A critical load of 20 kg N ha^{-1} y^{-1} (species change in ground flora) was indicated by the field studies while a critical ectohydric moss foliar N concentration of 2% for woodland ground flora, was also demonstrated for the first time.

The scale of these observations has now been extended, by determining the foliar N content of samples of *C. vulgaris* and selected ericaceous shrubs along 2 transects in Northern Europe. Transect 1 extends from the Transtrand Mountains in central Sweden to Stockholm (330 km) and includes a range of altitudes, land uses and pollution climates. Transect 2 extends from northern Finland to southern Norway (2000 km) and covers a range of pollution climates. In earlier UK foliar N studies, atmospheric N deposition for each site where moss or *C. vulgaris* was sampled, was determined from UK monitoring networks and deposition models and from actual measurements of ammonia concentrations. For the Scandinavian transect studies, regional average atmospheric inputs of N were determined from EMEP monitoring and modelling data (EMEP, 1999). However for transect 1, inventories of atmospherically derived ^{210}Pb in soil were used to determine deposition of atmospheric aerosols which include wet deposited NO_3^- and NH_4^+, and cloud and aerosol dry deposition. This method does not quantify local variability in N deposition due to gaseous NO_2, HNO_3 or NH_3 deposition. However the wet deposition of NO_3^- and NH_4^+ is expected to dominate the deposited N in these transects, as ambient concentrations of HNO_3 and NH_3 are so small (EMEP 1999). The ^{210}Pb inventories have been shown to identify the local (0.5 – 1.0 km) scale variability in wet and cloud deposition due to the orographic enhancement of wet deposition in the uplands and the capture of aerosols and cloud deposition by forest canopies (Fowler *et al.,* 1998).

The relationships between foliar N and atmospheric N deposition for the 2 Scandinavian transects are examined in this paper and the data obtained are used to test and extend the relationship for *Calluna vulgaris* already obtained for the UK. In addition, the UK relationships have been tested by including foliar N data obtained from the literature. The use of foliar N content as an indicator of atmospheric inputs of N and more importantly as an indicator of critical loads exceedance is discussed.

2. Methods

In transect 1,bulk samples of *C. vulgaris* were taken at five altitudes (480-870m) on Gammalsaters Fjallet (61°N 13°E), Transtrand Mountains, Central Sweden in October 1994. Where possible, samples were collected in the open and within the tree canopy. A further five samples were collected from open areas within the forest at approximately 50 km intervals on a transect from Transtrand to Stockholm, a distance of 330 km.

In transect 2, samples of ericaceous shrubs were collected at 6 sites (Table I) between Lapland in northern Finland and southern Norway (a distance of >2000 km), in June/July 1997.

TABLE I
Sampling sites in Transect 2

Site Name	North / Eastings	Estimated N deposition Kg N ha^{-1} y^{-1}	Species sampled
Kaamanen, Finland	69/27	1	*C. vulgaris, Empetrum* spp.
Haparanda, Sweden	65/24	2	*Empetrum* spp, *Vaccinium vitis-idae*
Anaset, Sweden	64/21	2	*C. vulgaris, V.vitis idae*
Gnarp, Sweden	62/17	2	*V.vitis idae*
Orebro, Sweden	59/15	10	*C. vulgaris*
Vestre Amoy, Norway	59/05	15	*C. vulgaris, Empetrum* spp.

In both transects, current year foliage of each species was collected. Samples were dried and ground and foliar N was determined by acid digestion and the indophenol blue method (Allen, 1989).

EMEP estimates were used to provide the regional mean N deposition, while the ^{210}Pb inventory studies were used to quantify the local enhancement in N deposition in the Swedish uplands (EMEP, 1999). The measurements of ^{210}Pb inventories in soil were made by γ-ray spectrometry as described by Moghaddam (1998). When using foliar N data from the literature, total N deposition for each site was estimated from EMEP maps (EMEP, 1999).

3. Results

The ^{210}Pb inventories prepared by Moghaddam (1998) showed that deposition in the Gammalsaters sites in the Transtrand mountains was enhanced both orographically and by canopy cover, due to enhanced cloud droplet and aerosol deposition over forest.

TABLE II
Mean atmospheric ^{210}Pb inventories (from Moghaddam, 1998) and foliar N content of *Calluna vulgaris* at Gammalsaters sites. (* D is situated on Skaftasen, an adjacent mountain)

Site	Altitude	Open fields Bq m^{-2} y^{-1}	Forest canopy Bq m^{-2} y^{-1}	% Enhancement relative to C-open: altitude	canopy + altitude	% Foliar N content in *C. vulgaris*: Open	Forest
A	870	3636	-	31		0.74	-
B	740	3214	4376	16	58	0.88	1.09
C	540	**2708**	3668		32	0.87	0.94
D*	620	-	5381		94	-	0.88

The appropriate enhancement (Table II) was applied to the EMEP deposition value for the valley site (C-open) to quantify the local N deposition at the upland sites.

The data from both transects are shown in Figure 1. Foliar N content of the *C. vulgaris* in the Gammalsaters sites followed the pattern of canopy enhancement of the ^{210}Pb inventories and showed a good relationship with estimated N deposition throughout the transect. The very low foliar N content (0.74%) found at the highest altitude in very thin soils, and exposed conditions may be due to limiting concentrations of other nutrients (e.g. phosphorus content 0.02% compared with 0.035% at the other sites).

Foliar N concentrations from transect 2 also showed a good relationship with estimated N deposition, but values tended to be larger than in transect 1. This may be largely explained by seasonal differences in the sampling period between the 2 transects, transect 1 being sampled in October when foliar N concentrations in *C. vulgaris* are at a minimum, and transect 2 in early summer when foliar N concentrations are largest (Brunsting & Heil, 1985). Differences in species sampled, plant age (Robertson & Davies, 1965) and soil types of the sample sites will also contribute to differences between the transects.

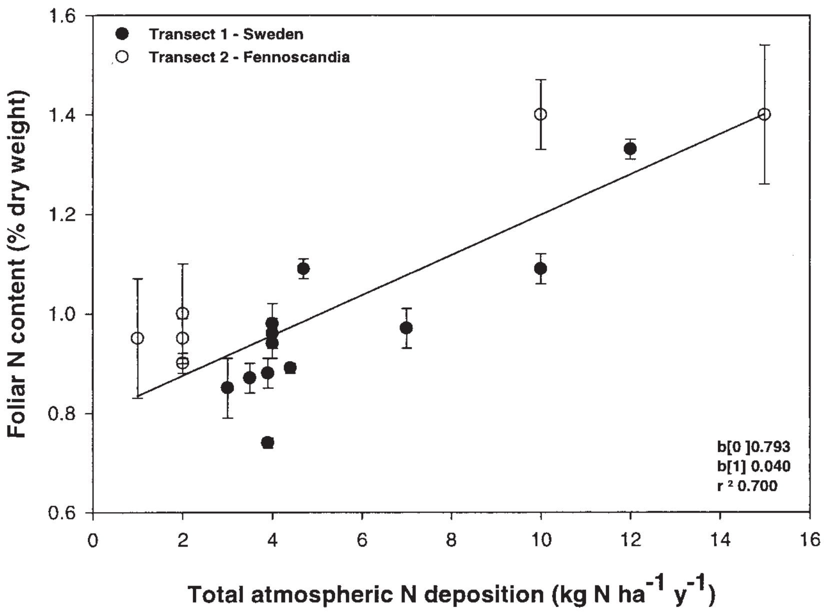

Figure 1. The relationship between foliar N content of *Calluna vulgaris* and other ericaceous species and total atmospheric N deposition, along transects from central Sweden to Stockholm, and northern Finland to southern Norway. (Error bar - standard deviation)

4. Discussion

The broad regional pattern in N deposition in Fennoscandia has been shown to be associated with a similar pattern in foliar N in *C. vulgaris* and other ericaceous species from the transect analyses in figure 1. The relationship between foliar N and N deposition in the range 0.8% to 1.4% is roughly linear with a slope of 0.04% N/kg N ha^{-1} y^{-1}. The data may be compared with more extensive data from UK and Netherlands sites (Pitcairn *et al.*, 1995), Scottish sites (Iason & Hestor, 1993; Hicks *et al.*, 2000) and other Scandinavian sites (Karlsson, 1987). These data plotted in figure 2 show a slope of 0.036 %N/ kg N ha^{-1} y^{-1}, remarkably close to that of the Scandinavian transects data, and obtained using different N deposition data sources. The robustness of the relationship between foliar N and N deposition for these species suggest the use of this simple bioassay for identifying areas of excess N deposition. The scatter in the field data is to be expected with considerable uncertainties in both variables. There is the additional problem that foliar N is influenced by other processes which regulate growth and development.

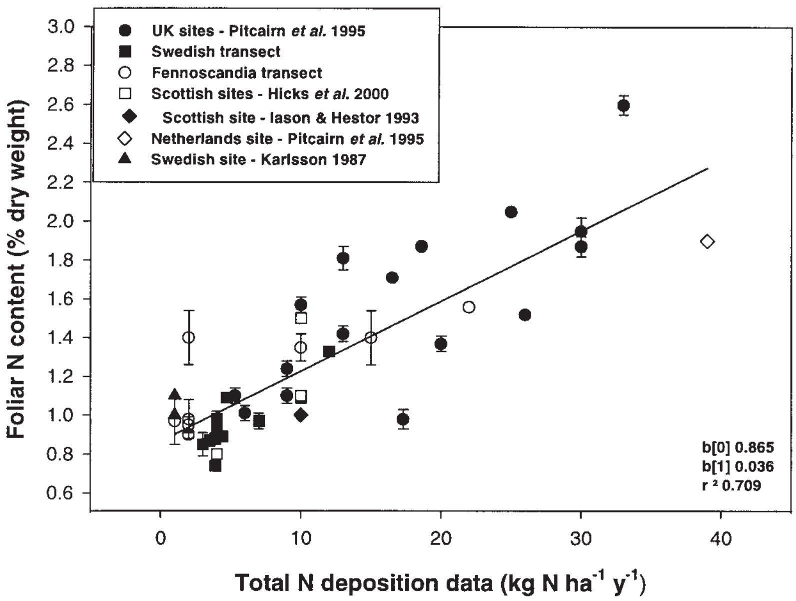

Figure 2. Relationship between foliar N content of *Calluna vulgaris* and other ericaceous shrubs and estimated total mean annual N deposition, at a range of sites in Northern Europe.
(Error bar - standard deviation)

For some bryophytes which are much less dependent on soils for nutrient uptake, the relationship between foliar N and N deposition is much closer, following an equation of the form $F_N = 8.01(1\text{-}e^{0.04ND})$ where F_N is foliar N concentration and ND is N deposition (Pitcairn *et al.*, 1998).

A practical application of the foliar N assay is in detecting or monitoring critical loads exceedance in field conditions. The critical load for nutrient N effects (eutrophication) for heathland is 15-20 kg N ha^{-1} y^{-1} (Bobbink & Roelofs, 1996), which from Figure 1 and 2, is consistent with foliar N concentrations in excess of approximately 1.5%. Mapped foliar N concentrations from direct observations can be compared with deposition maps, so that areas in excess of 20 kg N ha^{-1} y^{-1} or 1.5% foliar N would be candidate locations in which to seek evidence of changes in species composition or of physiological effects. The data presented here on foliar N in ericaceous species imply that substantial areas of the UK and Netherlands exceed the critical load but only small areas of Scandinavia, largely consistent with critical loads exceedance maps (EMEP, 1999).

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