# Reliability of Foliar Analyses of Norway Spruce Stands in a Nordic Gradient

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Norway spruce stands at eleven sites in Finland, Norway and Sweden have been studied under various climates, atmospheric deposition of N and S and fertilisation regimes. Nitrogen was growth restricting at eight inland sites, while P was growth restricting at three coastal sites. Liming and N fertilisation caused serious B deficiency on some of the inland sites. It is likely that liming affects uptake of B, whereas N fertilisation causes a dilution due to increased growth. Application of S combined with N probably caused K deficiency at one of the sites. The reliability of foliar analyses as a method to diagnose nutrient status and the likely changes after nutrient input to spruce forests in the Nordic countries, are discussed. The CR- and the DOP-method are evaluated for diagnostic purposes. Both methods seem to give reliable conclusions even if the CR-method often produces more specific results. Interpretation based on both current and one year old foliage improved the diagnostic prognoses. The accuracy of diagnosis also relies on knowledge and ability of the interpreter. Based on the results it is reason to be cautious about recommendations of single element fertilisations, e.g. with N alone, because the demand of other elements beyond available pools frequently occurs. Forest trees in the boreal region are probably well adapted to N deficiency, which means that they can handle the physiological consequences rather well, while deficiencies of other elements usually are more detrimental to growth vigour and stress related diseases.

**Keywords** Norway spruce, *Picea abies*, needle analyses, diagnostic methods, nutrient status, imbalanced nutrition, fertilisation, volume growth
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# 1 Introduction

The general principles of plant nutrition are well documented (e.g. Epstein 1972, Marschner 1995). As proper nutrition is important for the health of trees, this theme has received much attention, especially the problem of developing reliable field methods for diagnostic testing. Less expensive and more specific techniques than soil analyses are required to estimate the availability of nutrients. Good correlation between total N and P concentrations in humus and in foliage when nutrient supply is below optimal, encourages the use of foliar analyses techniques (e.g. Miller et al. 1977, Nohrstedt and Jacobson 1994, Brække 1996).

Foliar analyses as a diagnostic method was introduced in the early 1930's. Lundegårdh (1951) stated that internal nutrient concentrations in a plant could be taken as an integration of soil nutrient availability and time related uptake flux. Tamm (1964) summarised important principles of foliar analyses, practical application, foliar sampling technique and gaps in knowledge. Evers (1986) has given revised standards of the foliar sampling technique. One major problem has been to establish the relation between nutrient concentrations in the foliar tissue and growth rate under field conditions, i.e. response curves for individual elements. Critical optimum concentrations and ratios to nitrogen for different elements are available from laboratory experiments (Ingestad 1979, Ericsson et al. 1994). After corrections of concentrations and ratios these can be applied to field conditions (Brække 1994, Linder 1995).

Brække (1994) has coupled growth capacity or degree of deficiencies and ranges of nutrient concentrations in current foliage of Norway spruce (*Picea abies* L. Karst.) and Scots pine (*Pinus sylvestris* L.). Four ranges representing different physiological stress levels were defined: optimum, pre-optimum, deficiency, and strong deficiency (Table 1). The pre-optimum zone covers according to Ulrich and Hills (1967) the range from 80–100% of maximum growth. Two ranges were defined in the deficient zone when actual growth is below 80% of maximum growth, deficiency (50–80% of maximum growth) and strong deficiency (< 50% of maximum growth). The strong deficiency range usually corresponds to visible deficiency symptoms. Brække (1994) also defined criteria of balanced nutrition as critical ratios to N, based on the principles given by Ingestad (1979).

A number of methods are available for diagnostic interpretation of foliar data e.g. i). Concentrations and ratios (the CR-method: Brække 1994, 1996, Brække et al. 1998, Linder 1995),

**Table 1.** Ranges of concentrations and critical ratios of nutrients in current-year-needles (C) of Norway spruce and Scots pine at strong deficiency (SD), deficiency (D), pre-optimum (PO) and optimum (O). (From: Brække (1994) with adjustments).

| Elements | SD | D | PO | O | Ratios % |
|---|---|---|---|---|---|
| Macro: g kgDM$^{-1}$ | | | | | |
| N | <12 | 12–15 | 15–18 | >18 | 100 |
| K | <3.5 | 3.5–5.0 | 5.0–6.0 | > 6 | 33 |
| Ca | <0.4 | 0.4–0.6 | 0.6–0.7 | >0.7 | 4 |
| Mg | <0.4 | 0.4–0.6 | 0.6–0.8 | >0.8 | 4 |
| P | <1.2 | 1.2–1.5 | 1.5–1.8 | >1.8 | 10 |
| S | <0.4 | 0.4–0.6 | 0.6–0.8 | >0.8 | 4 |
| Micro: mg kgDM$^{-1}$ | | | | | |
| B | < 4 | | | > 8 | 0.04 |
| Fe | <20 | | | >20 | 0.11 |
| Mn | <10 | | | >15 | 0.08 |
| Zn | < 8 | | | >12 | 0.07 |
| Cu | < 2 | | | > 2 | 0.01 |
| Mo | <0.02 | | | >0.02 | 0.001 |

ii). Deviation from optimum percentage (the DOP-method: Montanes et al. 1993), iii). Diagnosis and recommendation integrated system (the DRIS-method: Beaufils 1973) and iv). Graphic vector analyses (the GVA-method: Kraus 1965, Timmer and Stone 1978, Valentine and Allen 1990, Brække 1996). These methods differ with respect to type of data required, diagnostic reliability and flexibility. The less flexible method are the DRIS, which requires a large and specific database to establish its standard reference values, and the GVA-method which requires a specific field plan for fertilisation and sampling. In addition a graphical method for displaying data on a relative scale is available, the RCC-method (relative concentration and content change: see e.g. Brække et al. 1998).

The aims of this project were to

1) summarise and adjust existing knowledge about diagnostic foliar analyses of Norway spruce to common criteria to detect nutrient deficiencies more precisely,
2) compare nutrient status of stands in a Nordic gradient of different climates under a wide N deposition range,
3) predict likely changes of stand nutrient status after input of different nutrients.

# 2 Materials and Methods

Eleven Norway spruce sites within the vegetation types, according to Kielland-Lund (1981), *Eu-Piceetum myrtilletosum* and *Eu-Piceetum dryopteridetosum* in Finland, Norway and Sweden were selected. Table 2 specifies location, altitude, temperature sums (degree-days > 5°C), N-deposition, site index of control plots and experimental parameters.

The experiments in Finland were on a factorial design, as were the Norwegian experiment Lontjern and the Swedish ones at Åseda and Farabol. The experiments Vardal and Løten in Norway and Norråker in Sweden were traditional N fertiliser experiments with supplemental treatments including K and/or P. All treatments including N at Kemijärvi and Sodankylä were supplemented with B in 1985–86 and 1990–91. Birkenes and Marnardal in Norway were designed for other aims than fertilisation. Some of the essential elements in the foliage samples were not analysed for Åseda and Norråker. The data from these sites were therefore supplemented with data of biomass trees sampled some years later. Further information about fertiliser input, types and doses are described by Andersson et al. (1998)

The foliar sampling was done on dominant and co-dominant trees according to specifications given in Table 3. The samples were kept

**Table 2.** Description of sites by location, altitude, DD (temperature sums as degree-days >5°C 1961–1990), N deposition (wet + dry 1986–1990, dry deposition 30% of wet), site index as stem increment with bark on control plots and some experimental parameters.

| Site | Long. East | Lat. North | Alt. m | DD >5 °C | N-dep. kg $ha^{-1}yr^{-1}$ | Site index $m^3ha^{-1}yr^{-1}$ | Experimental parameters Treat-ments | Repli-cations | Nutrients applied |
|---|---|---|---|---|---|---|---|---|---|
| 197 Sodankylä | 26°13’ | 67°42’ | 240 | 730 | 2 | 1.5 | 6 | 1 | N K P |
| 194 Kemijärvi | 27°08’ | 66°51’ | 280 | 760 | 3 | 2.0 | 10 | 1 | N K P Ca |
| 777 Norråker | 15°34’ | 64°27’ | 280 | 780 | 4 | 3.2 | 5 | 2 | N K P |
| 914 Vardal | 10°30’ | 60°48’ | 455 | 920 | 8 | 7.4 | 3 | 3 | N |
| 932 Løten | 11°35’ | 60°45’ | 335 | 1020 | 9 | 4.8 | 4 | 3 | N P |
| 113 Heinola | 26°03’ | 61°10’ | 115 | 1280 | 9 | 10.0 | 10 | 1 | N K P Ca |
| 63 Åseda | 15°29’ | 57°06’ | 225 | 1290 | 8 | 9.6 | 8 | 4 | N K P S |
| 973 Lontjern | 08°12’ | 58°43’ | 85 | 1305 | 17 | (3.2) | 9 | 5 | N K P |
| 970 Birkenes | 08°16’ | 58°19’ | 125 | 1310 | 18 | 11.7 | 1 | 3 | – |
| 972 Marnardal | 07°18’ | 58°33’ | 125 | 1310 | 18 | 8.9 | 1 | 1 | – |
| 131 Farabol | 14°35’ | 56°26’ | 130 | 1410 | 10 | 11.0 | 6 | 3 | N Ca S |

**Table 3.** Specifications of foliar sampling technique, age of the stands used in the study and delay in sampling after last treatment.

| Country<br>Site name | Foliar sampling<br>No.of plots | Yr./ month | Trees plot$^{-1}$ | Position in crown [1)] | Compass sector | Age total yrs. | Sampling yrs. after treatment |
|---|---|---|---|---|---|---|---|
| Finland | | | | | | | |
| 113 Heinola | 10 | 94/09 | 7 | upper 1/4 | S | 46 | 2 |
| 194 Kemijärvi | 10 | 93/10 | 5–7 | upper 1/4 | S | 59 | 4 |
| 197 Sodankylä | 6 | 94/09 | 6–7 | upper 1/4 | S | 90 | 4 |
| Norway | | | | | | | |
| 914 Vardal | 9 | 94/04 | 10 | upper 1/3 | SW-SE | 123 | 10 |
| 932 Løten | 9 | 93/11 | 10 | upper 1/3 | SW-SE | 124 | 10 |
| 970 Birkenes | 3 | 94/04 | 10 | upper 1/3 | SW-SE | 48 | – |
| 972 Marnardal | 1 | 94/04 | 10 | upper 1/3 | SW-SE | 64 | – |
| 973 Lontjern | 45 | 94/10 | 3 | whorl 3–7 | SW-SE | 17 | 1 |
| Sweden | | | | | | | |
| 131 Farabol | 18 | 90/10 | 10 | upper 1/3 | S | 70 | 4–6 |
| 63 Åseda | 32 | 89/10 | 10 | whorl 5 | S | 32 | 1 |
| 777 Norråker | 10 | 86/09 | 5 | upper 1/3 | S | 181 | 1 |

[1)] When "upper 1/3" or "upper 1/4" is specified then the sample is taken from the middle of that crown section.

at about 4°C between field sampling and being dried to constant weight at 60°C in Finland, 70°C in Norway and 85°C in Sweden. A sub-sample of 200 needles per plot was dried at 105°C to constant weight for needle-dry-mass estimation. In Norway, nutrient concentrations of current (C) and one-year-old needles (C+1) were analysed and used in data processing, whereas in Finland and Sweden only data of current needles were available.

The CR-method and the DOP-method were chosen for evaluation, as well as the RCC-method for graphical display. The first step in the CR-method uses the defined concentration ranges linked to nutrient stress levels and nutrient ratios as developed by Brække (1994). This step sort out the key element which are the growth restricting one. Only nutrient elements with concentrations in the strongly deficient and deficient ranges were considered critical. The second step ranks the remaining critical elements after the key growth restricting element found in step one. When e.g. N was found growth restricting, the other critical elements were ranked after N according to their relative position in the range judged by their concentrations, starting in the strongly deficient range. If another element than N was growth restricting, which means that the ratio to N for the element was below the critical limit, the other critical elements were ranked after this element as explained in the previous case. If more than one element had ratios at or below the critical ratio, the one with the lowest ratio relative to the limit was defined as the growth restricting one. The output is a predicted sequence of nutrient elements from the current restricting one to those, which potentially might be in short supply. If the actual deficiency of an element is eliminated by nutrient input, its position should be taken by the next element in the sequence.

The DOP-method produces a sequence based on the element concentration of the sample in per cent of optimum.

$$DOP = (C_n/C_o - 1) \cdot 100 \quad (1)$$

$C_n$ = foliar concentration of the tested element
$C_o$ = critical optimum concentration

The RCC-method displays the data graphically on relative scales by combining foliage concentrations and contents of nutrients and needle weight in one graph. The graphs compare the control with each of the other treatments on the individual site. Such graphs illustrate the dynamic changes of nutrient concentrations and contents after different treatments. This is a supporting tool for the interpreter, especially to get a starting view of the data. Only a few of the produced graphs are presented in this report.

# 3 Results

A screening of the data identified N, K, P, and B to be at concentrations below pre-optimums either generally or frequently. Only these elements were further processed by the CR-method, while elements at concentrations below optimums were processed by the DOP-method.

## 3.1 Predicted Nutrient Status by the CR- and the DOP-Method

*Finland*

The control plots at all Finnish sites showed deficient to strongly deficient N concentrations. Potassium was in pre-optimum range at Kemijärvi and P was in pre-optimum range at Sodankylä (Table 4a). Fertilisation with N alone or combined with other nutrients, raised the foliage concentration of this element considerably at Heinola, while changes were insignificant at the other sites. However, the doses of N at Heinola, 120–180 kg N ha$^{-1}$ every fifth year, were not sufficient to hold N concentration permanently at the

**Table 4a.** Finland. Mean nutrient concentrations and dry mass of 1000 current-year-needles (C). Elements with concentrations in pre-optimum range are in italics and those in deficient range as well as needle weights significantly higher than control ($p < 0.05$), are in bold face.

| Treatment | N | K | Ca | Mg<br>g kgDM$^{-1}$ | P | S | B<br>mg kgDM$^{-1}$ | Needle<br>mgDM<br>1000$^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Heinola 113, C=1994 | | | | | | | | |
| 1. Control | **12.3** | 6.9 | 6.0 | 1.3 | 2.1 | 1.0 | 14.7 | 4271 |
| 2. N | *16.8* | *5.5* | 3.8 | 1.2 | *1.7* | 0.9 | **6.0** | 4679 |
| 3. Ca | **13.4** | 7.0 | 6.3 | 1.5 | 1.8 | 1.2 | **6.9** | 3879 |
| 4. NCa | *15.4* | *5.7* | 5.0 | 1.4 | *1.7* | 0.9 | **5.5** | 4164 |
| 5. NK | *15.8* | 8.2 | 5.0 | 1.2 | **1.4** | 1.0 | **4.6** | 4501 |
| 6. NP | *16.6* | 6.3 | 4.8 | 1.6 | 2.1 | 1.0 | **5.2** | **5314** |
| 7. KP | **12.9** | 8.5 | 6.6 | 1.4 | 2.5 | 1.3 | 9.9 | 4129 |
| 8. KPCa | **12.8** | 8.7 | 6.6 | 1.5 | 2.2 | 1.2 | **5.5** | 4028 |
| 9. NKP | *16.8* | 8.2 | 5.4 | 1.4 | 2.2 | 1.0 | **5.5** | 4700 |
| 10. NKPCa | *16.1* | 8.6 | 5.4 | 1.4 | 2.2 | 0.9 | **3.9** | 4657 |
| Kemijärvi 194, C=1993 | | | | | | | | |
| 1. Control | **10.4** | *5.3* | 2.5 | 1.0 | 1.8 | 0.8 | 10.3 | 4180 |
| 2. NB | **11.2** | **3.8** | 3.6 | 1.3 | *1.6* | 0.8 | 23.8 | **5507** |
| 3. Ca | **9.0** | **3.4** | 3.6 | 1.5 | *1.7* | *0.7* | **6.3** | 4370 |
| 4. NCaB | **10.0** | **4.1** | 2.9 | 1.3 | **1.4** | *0.7* | 21.2 | 4671 |
| 5. NKB | **11.5** | 6.5 | 2.3 | 1.1 | **1.5** | 0.8 | 24.6 | 4800 |
| 6. NPB | **12.1** | *5.3* | 3.3 | 1.1 | 2.2 | 0.8 | 21.2 | 4658 |
| 7. KP | **10.6** | 6.2 | 2.8 | 0.9 | 1.9 | *0.7* | 8.8 | 3900 |
| 8. KPCa | **8.0** | *5.4* | 4.9 | 1.0 | *1.6* | – | 10.5 | 4276 |
| 9. NKPB | **10.0** | *5.8* | 2.5 | 1.1 | 2.0 | 0.8 | 22.0 | 4407 |
| 10. NKPCaB | **9.6** | *5.5* | 2.8 | 1.2 | *1.7* | 0.8 | 16.7 | 4908 |
| Sodankylä 197, C=1994 | | | | | | | | |
| 1. Control | **10.0** | 7.3 | 2.7 | 1.3 | *1.6* | 0.9 | 8.4 | 4279 |
| 2. NB | **9.9** | **4.6** | 1.6 | 0.9 | **1.2** | *0.7* | 19.3 | 4571 |
| 3. NKB | **11.2** | 6.5 | 2.4 | 1.1 | **1.2** | 0.8 | 24.6 | 4083 |
| 4. NPB | **10.8** | **3.7** | 2.6 | 1.2 | 1.9 | 0.8 | 16.9 | 4743 |
| 5. KP | **9.4** | 9.1 | 2.7 | 1.1 | 2.1 | 0.9 | 12.2 | 4143 |
| 6. NKPB | **9.5** | 7.3 | 2.5 | 1.3 | *1.6* | *0.7* | 18.4 | 4650 |

**Table 4b.** Finland. Current and potential restricting elements predicted by concentrations and ratios (CR) and by deviation from optimum percentage (DOP). "The true ranking" of current and potentially restricting elements (in italics) are based on an overall evaluation of the factorial effects within each experimental site.

| Treatment | CR ranking | Critical ratios | DOP ranking |
|---|---|---|---|
| Heinola 113, C= 1994 | *N>B>P* | | *N>B>P>K* |
| 1. Control | **N** | | **N** |
| 2. N | **B** | **K/N=33, B/N=0.036** | **B**>K>N>P |
| 3. Ca | N>B | | N>B |
| 4. NCa | **B** | **B/N=0.036** | **B**>N>P>K |
| 5. NK | **B>P** | **P/N=8.8, B/N=0.029** | **B**>P>N |
| 6. NP | **B** | **B/N=0.031** | **B**>N |
| 7. KP | **N** | | **N** |
| 8. KPCa | **N>B** | | **B**>N |
| 9. NKP | **B** | **B/N=0.033** | **B**>N |
| 10. NKPCa | **B** | **B/N=0.24** | **B**>N |
| Kemijärvi 194, C= 1993 | *N>B>K>P* | | *N>B>K>P>S* |
| 1. Control | **N** | | **N**>K |
| 2. NB | **N**>K | | **N**>K>P |
| 3. Ca | **N**>K>B | | **N**>K>B>S>P |
| 4. NCaB | **N**>K>P | | **N**>K>P>S |
| 5. NKB | **N**>P | | **N**>P |
| 6. NPB | **N** | | **N**>K |
| 7. KP | **N** | | **N**>S |
| 8. KPCa | **N** | | **N**>P>K |
| 9. NKPB | **N** | | **N**>K |
| 10. NKPCaB | **N** | | **N**>K>P |
| Sodankylä 197, C= 1994 | *N>B>P>K* | | *N>B>P>K>S* |
| 1. Control | **N** | | **N**>P |
| 2. NB | **N**>P>K | | **N**>P>K>S |
| 3. NKB | **N**>P | | **N**>P |
| 4. NPB | **N**>K | | **N**>K |
| 5. KP | **N** | | **N** |
| 6. NKPB | **N** | | **N**>S>P |

optimum level. Nitrogen fertilisation at Heinola and liming at Heinola and Kemijärvi made the trees susceptible to B deficiency. Nitrogen fertilised plots at Kemijärvi and Sodankylä, where B was added in 1985 and 1990, had high B concentrations. From the concentrations of this element at different treatments at Heinola, we concluded that N fertilisation without B would have caused critical concentrations of this element also at Kemijärvi and Sodankylä.

According to the CR-method (Table 4b) the specific growth restricting element at Heinola was N in the control and those treatments not given fertiliser nitrogen (Ca, KP, KPCa). In the remaining treatments B seems to be critical and growth restricting. Phosphorous was in deficient range at treatment NK, whereas K levels were always at pre-optimum or optimum. The overall ranking of critical elements was: N>B>P. Nearly all treatments at Kemijärvi and Sodankylä showed strong nitrogen deficiency. Potassium levels at Kemijärvi dipped into the deficiency and strong deficiency range at treatments NB, Ca and NCaB, while P levels dropped to deficiency range at treatments NCaB and NKB. Boron concentration was critical at treatment Ca. The overall ranking of critical elements was: N>B>K>P. Sodankylä showed relative low supply of P and the concentration level dropped from pre-optimum to 1.2 at treatments NB and NKB, while K level dropped from optimum in control to deficient range at treatments NB and NPB. The overall ranking was as follows: N>B>P>K. Limited but not critical supply of S is noted at the extreme northern sites at some

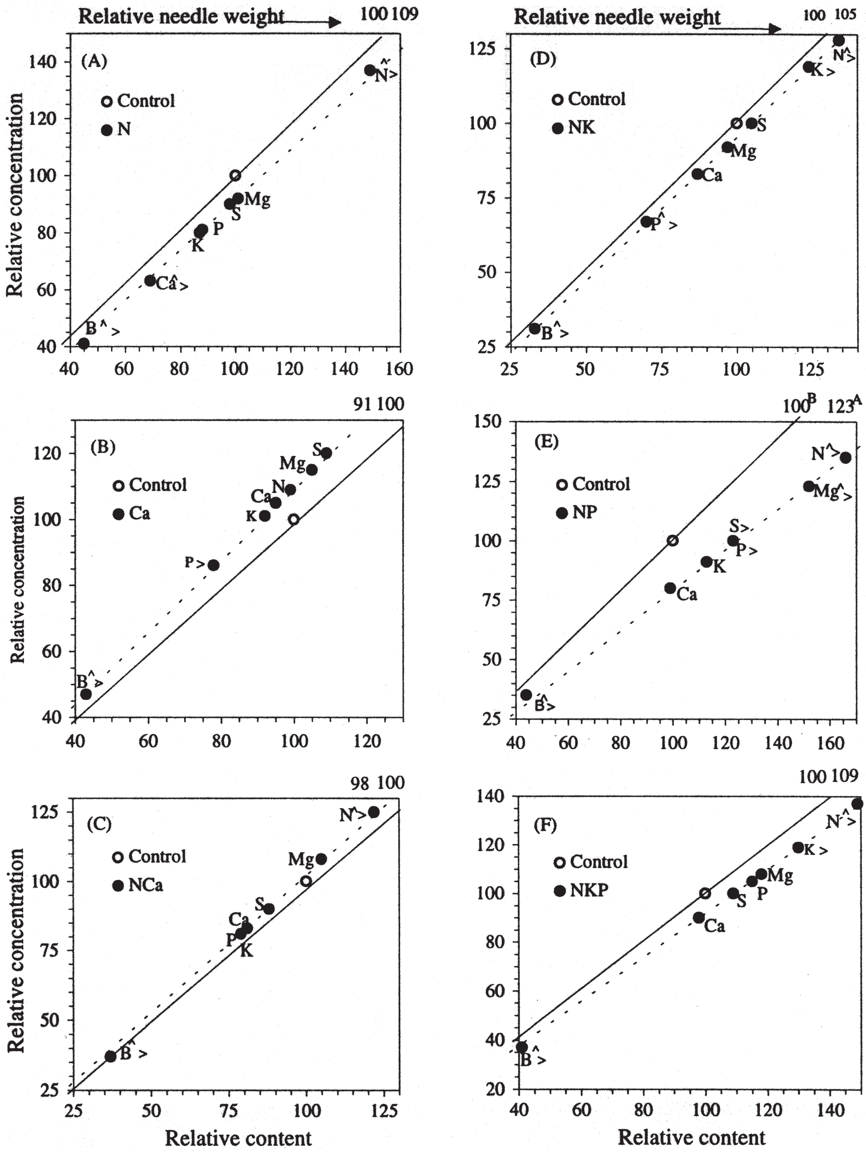


**Fig. 1a.** Finland. Relative needle nutrient concentration and content changes (RCC) at Heinola site. The full drawn line and the open circle denote relative needle weight and relative concentration/content of nutrients in control plot. The dottted line with filled circles display relative changes due to the given treatment. Significant differences ($p<0.05$) are given in the diagram by the signs: ^ significantly different relative nutrient contents, > significantly different relative nutrient concentrations.

fertiliser treatments. The DOP-ranking (Table 4b) deviated somewhat from the CR-ranking at certain treatments and was generally less specific. The main ranking, however, agreed well except that K was included at Heinola and S at Sodankylä and Kemijärvi.

The overall results from the RCC-diagrams are that N fertilisation at Heinola failed to cause significant needle growth response despite increased foliage N concentrations (N applied in 1993 and needle sampled in 1994), whereas N in combination with P did (Fig. 1a). All treatments reduced

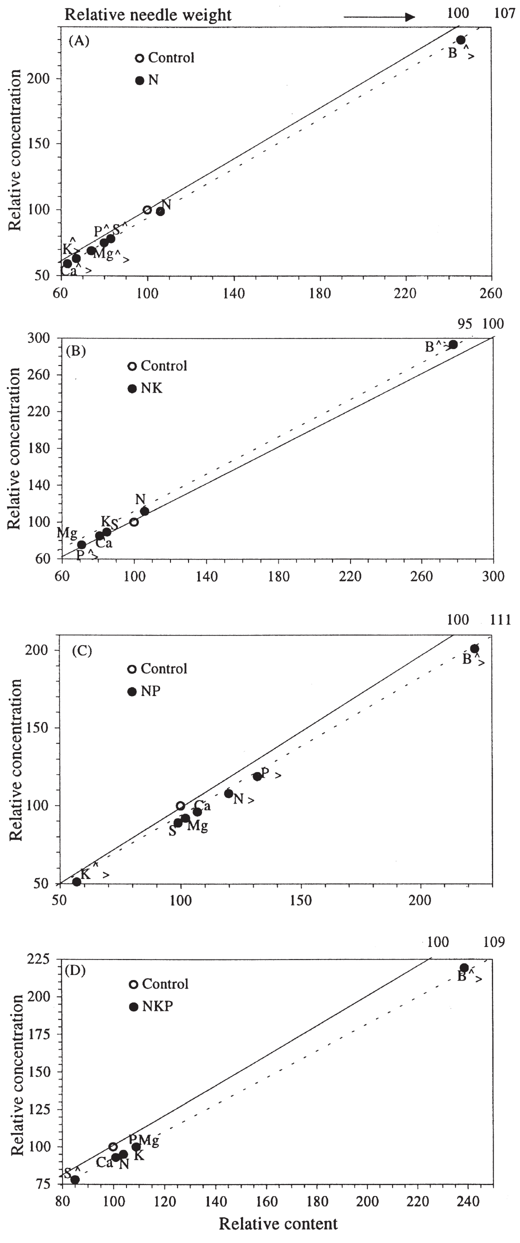


**Fig. 1b.** Finland. Relative needle nutrient concentration and content changes (RCC) at Sodankylä site. For further explanations, see Fig. 1a.

B concentrations significantly, least so at KP and rather much at NKPCa (Table 4a). The reduction in B concentration at NP treatment, which was accompanied by a significant higher unit needle weight, may be explained by a dilution effect. In the other treatments, where only a slight change in needle weight was detected, the reduction in B concentrations could not have been a dilution effect. In the limed plots the concentration of Ca was moderately elevated, probably because 17 years has past since application. The only significant response in terms of foliage weight at Kemijärvi was at treatment NB (Table 4a). Here liming without B addition also reduced B concentration, while concentrations and contents of Ca increased significantly (treatments Ca, KPCa, NCaB and NKPCaB). The more pronounced effect at this experiment than at Heinola, may reflect that the lime had been applied more recently (8 years previous). The largest relative response (not significant) on needle weight at Sodankylä was at treatment NPB (Fig. 1b).

### *Norway*

Nitrogen concentrations (Table 5a) were in the deficient and strongly deficient ranges on control plots at Vardal, Löten, Birkenes and Marnardal. Potassium was deficient or sub-optimum at all sites other than Lontjern, a deficiency that was exacerbated by N application. Similarly, at all sites P levels were inadequate, and remained so or were worse where N was applied without P. Boron levels were inadequate only when high doses of N was applied at Vardal, and there were no indications of problems with Mg and S.

The ratios indicate imbalanced nutrient uptake at treatments N and 3N at Vardal where probably potassium was growth restricting (Table 5b). The control plots at Birkenes, Marnardal, Lontjern and also the treatment N at Løten as well as treatment K at Lontjern had critical P/N-ratios. There are clear indications that C+1 needles reflect the nutrient status more precisely than the C needles probably because of intensive re-circulation of critical elements. The overall ranking of critical nutrient elements by the CR-method was as follows: Vardal – N>K>P>B, Löten – N>P>K, Birkenes and Marnardal – P>K>N and Lontjern

**Table 5a.** Norway. Mean nutrient concentrations and dry mass of 1000 current-year-needles (C). Elements with concentrations in the pre-optimum range are in italics and those in the deficient range as well as needle weight significantly higher than control ($p < 0.05$), are in bold face.

| Treatment | N | K | Ca | Mg | P | S | B | Needle |
|---|---|---|---|---|---|---|---|---|
| | | | | g kgDM$^{-1}$ | | | mg kgDM$^{-1}$ | mgDM 1000$^{-1}$ |
| Vardal 914, C=1993 | | | | | | | | |
| 1. Control | **13.0** | *5.2* | 4.5 | 1.1 | *1.7* | 0.8 | 10.1 | 5928 |
| 2. N | **12.5** | **4.7** | 4.6 | 1.1 | **1.4** | 0.8 | 8.6 | 5488 |
| 3. 3N | **12.9** | **4.0** | 4.4 | 1.1 | **1.3** | 0.8 | **6.7** | 5513 |
| Löten 932, C=1993 | | | | | | | | |
| 1. Control | **11.3** | **5.0** | 6.0 | 1.1 | **1.3** | 0.8 | 11.4 | 4483 |
| 2. N | **11.2** | **4.9** | 5.7 | 1.1 | **1.2** | 0.8 | 11.4 | 4075 |
| 4. NP | **11.3** | **4.7** | 6.4 | 1.3 | *1.6* | 0.8 | 9.6 | 4592 |
| Birkenes 970, C=1993 | | | | | | | | |
| 1. Control | **13.3** | **4.6** | 3.5 | 1.0 | **1.1** | 0.8 | 18.5 | 3229 |
| Marnardal 972, C=1993 | | | | | | | | |
| 1. Control | **13.2** | **4.8** | 5.4 | 1.3 | **1.2** | 0.8 | 17.5 | 4563 |
| Lontjern 973, C=1994 | | | | | | | | |
| 1. Control | *15.7* | 7.3 | 3.3 | 0.9 | **1.4** | 0.9 | 11.1 | 2635 |
| 2. N | 20.7 | 6.6 | 4.6 | 1.0 | *1.6* | 1.0 | 11.2 | **3168** |
| 3. K | *16.3* | 8.3 | 3.8 | 1.0 | **1.5** | 1.0 | 11.2 | 2805 |
| 4. P | *16.6* | 7.8 | 3.8 | 0.9 | 2.2 | 1.0 | 9.2 | 2810 |
| 5. NK | 23.3 | 7.4 | 4.4 | 0.9 | **1.5** | 1.0 | 11.3 | 2941 |
| 6. NP | 20.0 | 6.4 | 4.8 | 1.0 | 2.3 | 1.1 | 10.3 | 3042 |
| 7. KP | *15.5* | 7.7 | 4.7 | 0.9 | 2.1 | 1.0 | 10.6 | 3024 |
| 8. NKP | 21.8 | 7.6 | 4.4 | 1.0 | 2.1 | 1.1 | 11.3 | 3074 |
| 9. 2NP | 27.9 | 6.1 | 4.2 | 0.9 | 2.2 | 1.1 | 11.7 | 2902 |

– P. Ranking of elements by the DOP was similar except for some deviation in sequence and details.

The changes in relative needle weight and relative concentrations and contents, shown by the RCC method at Vardal and Löten, clearly reflect that nine years that had past since last fertilisation (Fig. 2). All treatments at Vardal and Löten had needle weights less or about equal to that of the control. Judged by these criteria, least stress was observed at treatment NP which also increased concentration and content of P, but reduced those of B. The stress, which was created by the 3N treatment at Vardal, significantly lowered the concentrations of B, P and K. The Lontjern data illustrate responses on needle weights at all treatments, however, the only significant one occurred at treatment N. The RCC results which indicate a general N limitation at Lontjern, are not confirmed by the height growth responses 1992–95 (Table 5c). The significant height growth response in 1994 at P treatment indicates a limitation of P. This result might have been due to the recovery process after the heavy drought in 1992, which were unevenly distributed between treatments at the drawing of plots. The trees subjected to both treatments K and P had longer shoots in 1992 and better growth up to 1994 (autocorrelation), compared to the other treatments. In 1995, however, there was a consistent height growth response at all plots treated with P supporting the conclusion that P was the actual growth restricting element at Lontjern. This conclusion was also predicted by using the CR- and the DOP-methods.

**Table 5b.** Norway. Current and potential restricting elements predicted by concentrations and ratios (CR) and by deviation from optimum percentage (DOP). "The true ranking" of current and potentially restricting elements (in italics) by the CR-method are based on C- and C+1-needles at different fertiliser treatments within the experimental site, while the ranking by the DOP-method is based on C-needles.

| Treatment | CR ranking | | Critical ratios [1)] | | DOP ranking |
|---|---|---|---|---|---|
| | C | C+1 | C | C+1 | C |
| Vardal 914, C=1993 | *N>K=P>B* | | | | *N>K>P>B* |
| 1. Control | **N** | **N**>K>P | | | **N**>K>P |
| 2. N | **N**>P>K | **P**>K>N | | **K/N=31.5**<br>**P/N=9.2** | **N**>P=K |
| 3. 3N | **K**>B>N>P | **P**>K>B>N | **K/N=31.0** | **K/N=27.0**<br>**P/N=8.0** | **K**>N=P>B |
| Löten 932, C=1993 | *N>P>K* | | | | *N>P>K* |
| 1. Control | **N**>P>K | **N**>P>K | | | **N**>P>K |
| 2. N | **N**>P>K | **P**>N>K | | **P/N=9.3** | **N**>P>K |
| 3. NP | **N**>K | **N**>K | | | **N**>K>P |
| Birkenes 970, C=1993 | *P>K>N* | | | | *P>K>N* |
| 1. Control | **P**>N>K | **P**>K>N | **P/N=7.9** | **P/N=6.7**<br>**K/N=28.7** | **P**>N>K |
| Marnardal 972,C=1993 | *P>K>N* | | | | *P>N>K* |
| 1. Control | **P**>N>K | **P**>K>N | **P/N=9.1** | **P/N=7.5**<br>**K/N=32.1** | **P**>N>K |
| Lontjern 973, C= 1994 | ***P*** | | | | *P>N* |
| 1. Control | **P** | **P** | **P/N=9.2** | **P/N=7.5** | **P**>N |
| 2. N | (Sub-opt.) | **P** | **–** | **–** | **P** |
| 3. K | **P** | **P** | **P/N=9.2** | **P/N=7.2** | **P**>N |
| 4. P | (Sub-opt.) | (Sub-opt.) | – | – | **N** |
| 5. NK | **P** | **P** | **–** | **–** | **P** |
| 6. NP | (Optimum) | (Optimum) | – | – | – |
| 7. KP | (Sub-opt.) | (Sub-opt.) | – | – | **N** |
| 8. NKP | (Optimum) | (Optimum) | – | – | – |
| 9. 2NP | (Optimum) | **K** | – | – | – |

[1)] Critical ratios were not calculated when N concentrations are beyond critical optimum

**Table 5c.** Norway-Lontjern. Height growth (cm) 1992–1995 and two-way analyses of variance. Significantly different figures according to Fisher LSD test (p < 0.05), are in bold face.

| Treatments | Year | | | | Tests | Year | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1992 | 1993 | 1994 | 1995 | | 1992 | 1993 | 1994 | 1995 |
| 1. Control | 24.4 | 28.6 | *29.0* | *32.0* | F | 0.60 | 1.08 | 2.32 | 5.15 |
| 2. N | 22.6 | 22.6 | 30.2 | 28.0 | p % | – | 40.0 | **4.3** | **<0.0** |
| 3. K | 31.0 | 34.6 | 37.8 | 41.4 | Fishers LSD | – | – | 9.5 | 14.7 |
| 4. P | 34.0 | 40.2 | **44.6** | **59.0** | | | | | |
| 5. NK | 28.8 | 32.6 | 34.6 | 32.0 | | | | | |
| 6. NP | 27.8 | 31.2 | 31.4 | **53.0** | | | | | |
| 7. KP | 24.4 | 27.6 | 38.4 | **57.8** | | | | | |
| 8. NKP | 25.2 | 31.4 | 30.2 | **47.8** | | | | | |
| 9. 2NP | 27.6 | 33.0 | 30.4 | **54.2** | | | | | |

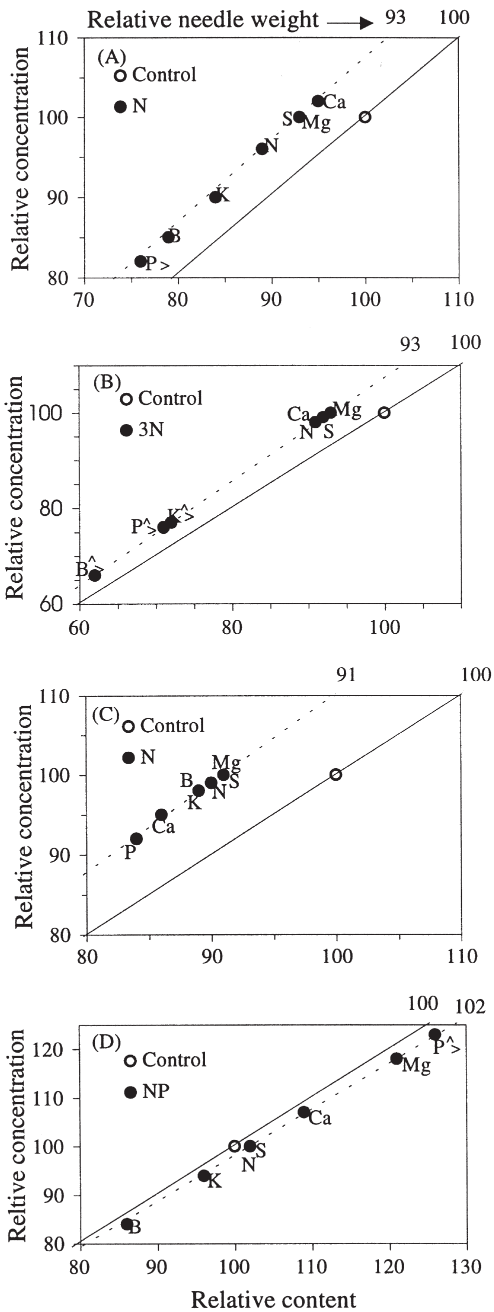


**Fig. 2.** Norway. Relative needle nutrient concentration and content changes (RCC) at Vardal (A, B) and Löten (C, D) sites. For further explanations, see Fig. 1a.

*Sweden*

The control plots of the Swedish sites had deficient to strongly deficient levels of N, whereas concentrations of K and P were deficient to optimum (Table 6a). As elsewhere on the inland sites, applications of N in the absence of K and P frequently lowered the concentration of these elements to critical levels. The ratio K/N = 33 in control plots at Farabol is a warning about temporary imbalanced uptake (Table 6b). However, the application of N seemed to have caused a deficiency of P, whereas NS treatment caused K limitation. At Åseda both treatment N and NS caused potassium deficiency. The overall CR ranking at Farabol was: N>P>K, and at Åseda: N>K>P. Magnesium and S might become in short supply at Farabol if uptake of N, K and P were optimised. At Norråker where trees had serious N deficiency, B came next in the ranking and was followed by P. There were some indications of short supply of K. The DOP-method gives similar ranking as the CR-method, although less detailed (Table 6b).

The RCC diagrams for Åseda, based on biomass tree-data from 1994, are presented in Fig. 3. Foliage unit dry mass weight was slightly changed at treatments N1S and reduced at all other treatments. Some patterns in concentration change should be noted. Application of N alone reduced P and K concentrations whereas Ca and Mg concentrations were increased. Application of S alone had an opposite effect. When N and S were combined, both concentrations and contents of all elements except P, increased. At treatment N1P2K2 the Mg concentration was reduced somewhat, although not critically.

### 3.2 Relationship Between N and P Concentrations and Foliar Unit Dry Mass

The control plots on sites where N was growth restricting had a weak, but significant linear relationship between needle weights and N concentrations (Fig. 4). A stronger relationship was found for control plots on sites where P was growth restricting. Extrapolating these functions to optimum nutrition gives needle weights at about 6000 mgDM 1000 needles$^{-1}$.

**Table 6a.** Sweden. Mean nutrient concentrations of current-year-needles (C). Elements with concentrations in the pre-optimum range are in italics and those in the deficient range are in bold face.

| Treatment | N | K | Ca | Mg<br>g kg$^{-1}$ | P | S | B<br>mg kg$^{-1}$ |
|---|---|---|---|---|---|---|---|
| Farabol 131, C=1990 | | | | | | | |
| 1. Control | **13.0** | **4.3** | 2.9 | 1.0 | **1.4** | 0.8 | 11.6 |
| 2. Ca | **12.1** | **4.2** | 5.2 | 0.9 | **1.3** | *0.7* | 9.6 |
| 3. S | **12.0** | **4.2** | 2.3 | 0.8 | **1.4** | 0.8 | 12.4 |
| 4. 2S | **12.0** | **4.3** | 2.2 | 0.8 | **1.5** | 0.9 | 13.3 |
| 5. N | **12.9** | **4.2** | 2.0 | 0.8 | **1.2** | *0.7* | 10.5 |
| 6. NS | **13.0** | **3.4** | 2.3 | ***0.7*** | **1.2** | *0.7* | 11.4 |
| Åseda 63, C=1989 | | | | | | | |
| 1. Control | **12.1** | **5.0** | 4.0 | 1.1 | **1.4** | – | – |
| 2. S | **11.4** | **4.4** | 3.3 | 1.1 | **1.5** | – | – |
| 3. N | **14.7** | **4.2** | 4.0 | 1.1 | **1.3** | – | – |
| 4. NS | *15.1* | **4.4** | 4.2 | 1.1 | **1.5** | – | – |
| 5. KP | **12.4** | 7.5 | 5.0 | 1.0 | 2.4 | – | – |
| 6. KPS | **11.8** | 6.6 | 4.3 | 1.0 | 2.2 | – | – |
| 7. NKP | *15.5* | 6.8 | 5.5 | 1.2 | 2.0 | – | – |
| 8. NKPS | **13.9** | 7.0 | 4.7 | 1.2 | 2.1 | – | – |
| Norråker 771, C=1986 | | | | | | | |
| 1. Control | **9.8** | 6.3 | 4.1 | 1.1 | 1.8 | – | – |
| 2. $N_{lime}$ | **13.2** | *5.6* | 4.4 | 1.4 | **1.4** | – | – |
| 3. $N_{urea}$ | **12.2** | *5.6* | 4.0 | 1.3 | **1.5** | – | – |
| 4. $N_{lime}$KP | **11.4** | 6.8 | 4.3 | 1.3 | 1.9 | – | – |
| 5. $N_{urea}$KP | **12.1** | 6.0 | 4.2 | 1.1 | 2.0 | – | – |

**Table 6b.** Sweden. Current and potential restricting elements predicted by concentrations and ratios (CR) and by deviation from optimum percentage (DOP). "The true ranking" of current and potentially restricting elements (in italics) are based on control as well as fertiliser treatments within the experimental site.

| Treatment | CR ranking | Critical ratios | DOP ranking |
|---|---|---|---|
| Farabol 131, C= 1990 | *N>P>K* | | *N>P>K>S>Mg* |
| 1.Control | **N=K**>P | **K/N=33** | **K=N**>P |
| 2.Ca | **N**>K>P | | **N**>K>P>S |
| 3.S | **N**>K>P | | **N**>K>P |
| 4.2S | **N**>K>P | | **N**>K>P |
| 5.N | **P**>N=K | **K/N=33, P/N=9.4** | **P**>K>N>S |
| 6.NS | **K**>P>N | **K/N=26, P/N=9.2** | **K**>P>N>Mg=S |
| Åseda 63, C=1989 | *N>K>P* | | *N>K>P* |
| 1.Control | **N**>P>K | | **N**>P>K |
| 2.S | **N**>K>P | | **N**>K>P |
| 3.N | **K**>P>N | **K/N=29, P/N=9.2** | **K**>P>N |
| 4.NS | **K**>P | **K/N=29, P/N=9.8** | **K**>P>N |
| 5.KP | **N** | | **N** |
| 6.KPS | **N** | | **N** |
| 7.NKP | (Sub-opt.) | | **N** |
| 8.NKPS | **N** | | **N** |
| Norråker 771, C= 1986 [1] | *N>B>P* | | *N>P>K* |
| 1.Control | **N**>B | | **N** |
| 2.$N_{lime}$ | **N**>B>P | | **N**>P>K |
| 3.$N_{urea}$ | **N**>B>P | | **N**>P>K |
| 4.$N_{lime}$KP | **N**>B | | **N** |
| 5.$N_{urea}$KP | **N**>B | | **N** |

1) the data on elemental concentrations used in the CR ranking were supplemented for the missing elements in Table 6a by using data from the chemical analyses on biomass trees

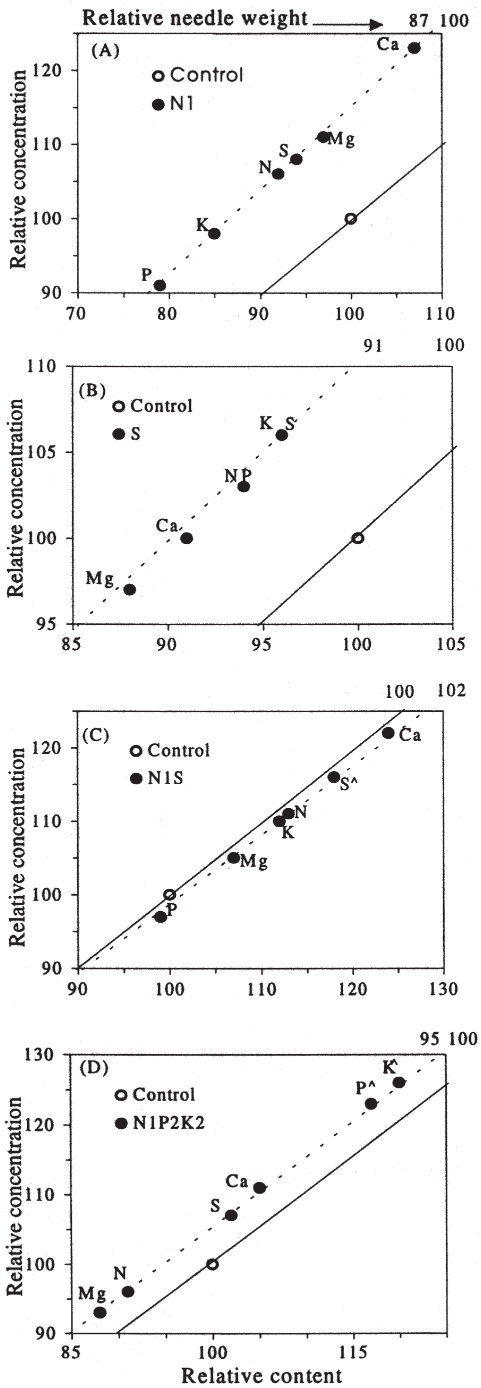


**Fig. 3.** Sweden. Relative needle nutrient concentration and content changes (RCC) at Åseda. The data set represent average values of the entire crown (biomass trees 1994). For further explanations, see Fig. 1a.

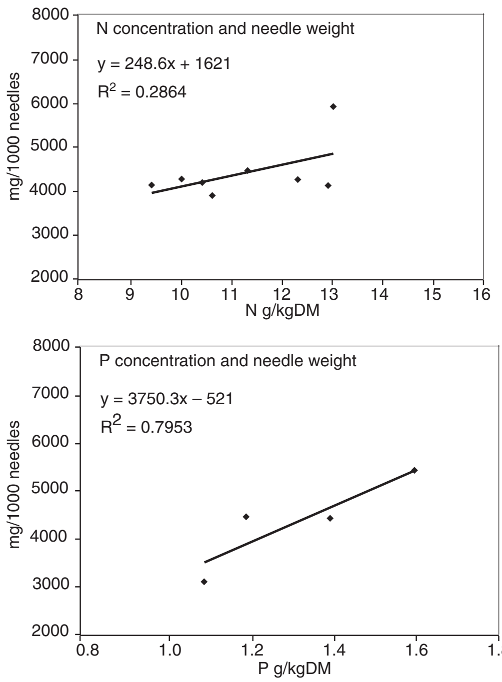


**Fig. 4.** Relations between needle weight and concentrations of N or P on control plots which were diagnosed to have growth restrictions by one of these elements.

# 4 Discussion and Conclusions

The DOP-method assumes that the physiological response to foliar concentrations of all nutrients is linear, starting from zero and ending at critical optimum. In principle optimum curves are S-shaped and do not start at zero. Despite this, the critical elements for individual sites were ranked satisfactory by the DOP when the CR-method was used as a standard. However, the rankings deviated in some cases at the plot or treatment level. The graphical RCC-method illustrates relative differences in concentrations, contents and specific unit needle weight between two samples representing different treatments, locations etc. This method cannot pinpoint growth-restricting elements unless the experiment is designed according to the specification required for the GVA-method (Brække 1996). Although the site Lontjern (973) in Norway had such specifications, no conclusive statements could be drawn from the RCC, probably because the site was subjected to a drought during the first growing season after nutrient application. The GVA pointed out N as growth restricting element in the first growing season, while the height growth response in the second growing season after fertilisation proved that P was the critical element. It is reasonable to conclude that the summer drought in 1994, had influenced N availability and that this element actually was growth restricting during the water stress. However, when water stress ended, P again became growth restricting. Such interactions must be considered seriously by the interpreter to avoid wrong conclusions (Brække, 1996). The CR-method turned out to be robust and pinpointed P as the growth restricting element, whereas the DOP added N as second element to the ranking sequence.

Diagnostic foliar analysis by the CR-method (Tables 4b, 5b and 6b) certainly provided much information about nutrient status and cycling at the sites. These results explain reasonably well the stem volume growth at different treatments (Table 7). However, the unit needle dry mass weight and the volume growth response were usually not correlated, probably because needle weight represents one specific year, whereas volume growth was integrated over several years. Generally spoken, this implies that unit needle weight for one single year does not necessarily reflect the total needle mass of a stand either for that particular year or the average for several years.

The experimental field methods were not designed to optimise nutrient supply according to the principles given by Linder (1995). At all sites, except Åseda, nutrients were applied at intervals from 3–10 years, which means that the nutrient status of trees usually fluctuated. This also implies that the sites never were brought to the maximum growth potential. The results demonstrate that if a primary deficiency is overcome by fertiliser a secondary deficiency of another element are encountered on most of the studied sites. Those located at the coast in southernmost Norway were exceptions. To overcome such problems a balanced fertiliser mixture of more elements are usually needed. Nitrogen and phosphorus should be key elements in such a mixture, but frequently also K and B are needed. This support the results from fertiliser optimising experiments reported by Tamm (1991).

It was difficult to find the complete ranking by just analysing current foliage (C) of control plots. The Finnish and the Swedish sites, where only current needles were analysed, showed a truncated ranking sequence of elements at the control plots compared to the overall ranking. At the Norwegian sites, where current and previous year's foliage were analysed, the two rankings agreed satisfactory. None of the control plots had B in the range of critical concentrations, even if the supply turned out to be inadequate when stand growth was improved by adding other critical elements. This means that a proper diagnosis of forest stand nutrition by foliar analyses must also rely on the knowledge and ability of the interpreter. One example of needed knowledge is the regional variation of potential B deficiency shown by Brække (1979). All sites in Sweden and Norway where potential B deficiency was indicated, are located inside the region proposed by Brække (1983). Adverse effects of liming on B uptake are documented by Lehto and Mälkönen (1994). Such effects were demonstrated on Heinola, Kemijärvi and Farabol.

Application of S combined with N at Farabol seems to have rendered the stands into serious K deficiency, but this effect was not supported by the results from Åseda. One likely explanation is that a critical amount of the available K-pool was leached out of the rhizospheric zone at Farabol because of higher annual S dose, which was 40 kg $ha^{-1}yr^{-1}$ at Farabol whereas only 15 kg $ha^{-1}yr^{-1}$ at Åseda).

Nitrogen was growth restricting on eight of eleven studied sites. The extreme northern ones, Norråker, Kemijärvi and Sodankylä, plus Löten in South Central Norway, had N concentrations in the strongly deficient range. The other four, Heinola, Farabol, Åseda and Vardal, had concentrations in the deficient range. This imply that the atmospheric input of N to these sites, which varied from 2 to10 kg N $ha^{-1}yr^{-1}$, had not changed the pattern of N limitation normally observed in boreal and boreonemoral forests.

The coastal sites Birkenes, Marnardal and Lontjern had a nutrient status different from the inland sites, as they suffered from P restrictions.

**Table 7.** Growth response in stem volume over bark at different treatments. Treatments which are significantly different from control have figures in bold face ($p < 0.05$). The Finnish sites are not tested statistically because data from only one block was available.

| Finland | | Norway | | Sweden | |
|---|---|---|---|---|---|
| Site | Stem volume $m^3\ ha^{-1}yr^{-1}$ | Site | Basal area $m^2\ ha^{-1}yr^{-1}$ | Site | Stem volume $m^3\ ha^{-1}yr^{-1}$ |
| Heinola 113 (1988–94) | | Vardal 914 (1984–94) | | Farabol 131 (1977–90) | |
| 1. Control | 16.0 | 1. Control | 0.65 | 1. Control | 10.6 |
| 2. N | 13.3 | 2. N | 0.55 | 2. Ca | 10.4 |
| 3. Ca | 17.1 | 3. 3N | 0.49 | 3. S | 10.3 |
| 4. NCa | 16.9 | | | 4. 2S | 9.3 |
| 5. NK | 16.9 | | | 5. N | **13.5** |
| 6. NP | 18.8 | | | 6. NS | **12.5** |
| 7. KP | 17.4 | | | | |
| 8. KPCa | 16.6 | | | | |
| 9. NKP | 15.9 | | | | |
| 10. NKPCa | 18.0 | | | | |
| Kemijärvi 194 (1990–93) | | Löten 932 (1984–93) | | Åseda 63 (1973–94) | |
| 1. Control | 2.0 | 1. Control | 0.40 | 1. Control | 5.1 |
| 2. NB | 3.1 | 2. N | 0.53 | 2. S | 4.6 |
| 3. Ca | 1.0 | 4. NP | 0.44 | 3. N | 6.5 |
| 4. NCaB | 3.7 | | | 4. NS | **7.3** |
| 5. NKB | 5.1 | | | 5. KP | 5.2 |
| 6. NPB | 5.6 | | | 6. KPS | 4.6 |
| 7. KP | 2.6 | | | 7. NKP | **8.4** |
| 8. KPCa | 1.2 | | | 8. NKPS | **9.2** |
| 9. NKPB | 5.9 | | | | |
| 10. NKPCaB | 6.1 | | | | |
| Sodankylä 197 (1991–94) | | Birkenes 970 (1991–94) | | Norråker 771 (1962–91) | |
| 1. Control | 1.3 | 1. Control | 1.16 | 1. Control | 2.4 |
| 2. NB | 2.6 | | | 2. $N_{lime}$ | **5.9** |
| 3. NKB | 2.4 | Marnardal 972 (1992–94) | | 3. $N_{urea}$ | **5.3** |
| 4. NPB | 2.6 | 1. Control | 0.75 | 4. $N_{lime}$KP | **5.7** |
| 5. KP | 1.2 | | | 5. $N_{urea}$KP | **5.1** |
| 6. NKPB | 5.3 | | | | |

High deposition rate of sea salts combined with increased deposition of S and N might explain this (Brække 1996). Likely hypotheses are: i) N deposition has improved forest growth rate and caused a P demand beyond available supply, ii) soil acidification has generated free Al, which has fixed P chemically in soil solution and also turned the organic matter into complexes with decreased mineralisation rate, iii) N deposition and soil acidification have caused changes in the mycorrhizal community and iv) N deposition has decreased decomposition rate of organic matter and increased the less available stores of organically fixed P (Fog 1988, Berg 1986).


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