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Contents

Preface

This dissertation is part of the acquisition of the Ph.D. degree at The Royal Veterinary and Agricultural University, Copenhagen. The study was carried out at The Danish Forest and Landscape Research Institute, Department of Forest Ecology. I was enrolled as a Ph.D. student at The Royal Veterinary and Agricultural University, Department of Agricultural Sciences. During the Ph.D. study two Ph.D. courses were passed: "Advanced Plant Nutrition, Part A and B" by preparation of literature review manuscripts entitled: "Copper, boron, and manganese deficiency and fertilization in Norway spruce (*Picea abies* [L.] Karst.) plantations on nutrient poor soils in western Denmark" and "Geochemical effects of liming in Spruce on nutrient poor soils - Liming management in Norway spruce stands in western Denmark". Supervisors were Jan K. Schjørring (The Royal Veterinary and Agricultural University), Lennart Rasmussen (Risø National Laboratory) and Per Gundersen from the 1. February 1996 (Danish Forest and Landscape Research Institute).

The Ph.D. project was a part of The Nordic Forest Research Co-operation Committee project; "Imbalanced Forest Nutrition - Vitality Measures", which started in 1993. The following co-operating institutions were involved in the project: The Danish Forest and Landscape Research Institute, The Finnish Forest Research Institute, The Norwegian Forest Research Institute and The Swedish University of Agricultural Sciences. The Danish part of the project has been focused on the potential to improve the vitality of mature Norway spruce stands on nutrient poor soils in western Denmark by fertilization and liming. The need for discussing revitalization actions is at present highly relevant, since the health status of these stands has been declining over the last decade. The project contained the following main questions:

- How should nutritional imbalances, deficiencies, and the need for fertilization and liming be identified?

- How should tree vitality be defined and measured in relation to the nutritional status of the trees?

- How does fertilization and liming affect the forest ecosystem and the nutritional status of the trees?

This dissertation is based on four paper manuscripts (Paper I-IV) which contain the results obtained in the Ph.D. project, and a compilation of the main findings from these papers and the relevant literature. The second author on two of the manuscripts Leif Hallbäcken has given a co-author declaration in Appendix I.

Apart from the present dissertation, results and conclusions from the study have been presented in two final reports from connecting research programs, at international and national conferences, symposiums, seminars and workshops, and in information sheets to the forest management sector (Appendix II).

Acknowledgments

Co-operation with people from different scientific areas has taught me how important this kind of constructive co-operation is in the process of reaching new scientific knowledge. But primarily, I have enjoyed and been encouraged by the friendliness, interest and rewarding discussions that have been offered me by a number of people.

First of all I would like to thank Lennart Rasmussen for thorough and constructive criticism of my scientific work and of various manuscripts, showing openness and respect for my suggestions, good coaching, and last but not least for showing confidence in me by putting me in charge of the major part of the Danish activities within the Nordic project "Imbalanced Forest Nutrition - Vitality Measures". Per Gundersen has through the whole period of this study, whether being the supervisor or not, taken the time for valuable constructive criticism and discussions, especially concerning my manuscripts. I am grateful to Jan K. Schjørring for supervision during my Ph.D. courses in "Advanced Plant Nutrition", and for rewarding criticism. I am also thankful to Karsten Raulund-Rasmussen for showing great interest in my work, bringing up new perspectives, constructive criticism, and establishing a foundation for the finishing of this dissertation. It has been a vitalizing experience to co-operate with Leif Hallbäcken, to whom I am thankful for many valuable discussions and interesting hours of calculating biomass and nutrient distribution. Henrik Vejre deserves my full gratitude for rewarding co-operation, provoking discussions, and good humor even in the darkest hours.

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In connection with the Nordic project "Imbalanced Forest Nutrition - Vitality Measures" I have had the great fortune of co-operating with Eino Mälkönen, Heljä-Sisko Helmisaari, Mikko Kukkola, Tapio Ylimartimo and Pasi Aatsinki from Finland (METLA); Finn Brække and Jon Frank from Norway (NISK); and Folke Andersson, Johan Bergholm, Leif Halbäcken, and Nagwa Salih from Sweden (SUAS). I am thankful to you for a constructive co-operation and many hours of rewarding discussions. During my stays in Sweden and Finland, Leif Hallbäcken and Heljä-Sisko Helmisaari respectively and their families have shown me an immense hospitality. In this connection I would like to thank Heljä-Sisko Helmisaari for valuable discussions of the vitality concept.

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I am profoundly grateful to my family; Grith, Hans and Niels Ingerslev for support, encouragement, and patience, especially during the last intensive period of dissertation writing.

The Klosterheden State Forest (Jens Erling Handberg, Niels Toftegaard Jensen and Preben Fiskbæk) has been very helpful in the process of fertilizing and managing the experimental site.

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To Hans and Niels Hørsholm, December 1997, Morten Ingerslev

Summary

During recent years indications of nutritional imbalances in coniferous forest ecosystems have become more common in southern Scandinavia and central Europe; Denmark being no exception. Deposition of acidifying substances, relative deficiencies of nutrients, and soil acidification are supposed to be important contributing factors in the picture of the observed forest damages. It has been suggested that nutritional disorders mainly involving N, P and K, and soil acidification can impair the vitality of the Norway spruce plantations in western Denmark. The need for counteractions such as liming and fertilization is thus pressing.

The purpose of the present study was to continue and further develop an existing fertilization and liming experiment in a mature Norway spruce stand (58 years old) on a nutrient poor soil at Klosterheden, Lemvig, in western Denmark in order to investigate the effects of soil amelioration on the nutritional balance of the ecosystem and on forest health conditions and production. Different strategies and methods have been applied to clarify and develop the tree vitality concept and its applicability.

Two types of lime (calcite and dolomite combined with additional kieserite and phosphorus) were applied alone and in combination with conventional NPK fertilizer to form five different treatments. All the treatments were carried out in 1986 and in 1994 and the NPK treatment was additionally carried out in 1991.

All treatments increased the leaching of ions from the soil significantly ($P \leq 0.05$) within the first 8 months after treatment. Application of kieserite combined with calcite induced acidification pushes in the soil solution in the first period after the treatments. The magnitude of these changes varied strongly according to the different treatments. The effects on chemical composition of the soil solution seemed to peak within 8 months following the treatments. They were largely eradicated 8 years after establishment of the trial, and 3 years following the last NPK fertilization.

The expected geochemical changes of the soil solid phase regarding the counteraction of acidification were only achieved in the upper horizons of limed plots (decreased exchangeable acidity and concentration of exchangeable Al^{3+}, and increased concentration of exchangeable Ca^{2+} and Mg^{2+}, base saturation, cation exchange capacity, and pH_{H_2O}). Results from the O horizons (N and C concentration, C/N-ratio, and horizon thickness) indicated that mineralization of nitrogen had not been increased notably within the first eight years of treatment in the limed plots, even though the pH_{H_2O} in the O horizon was increased and the C/N-ratio was below 30.

The various treatments caused no significant ($P > 0.05$) differences in growth increment. The strongest effect observed was a growth rate reduction caused by application of kieserite and calcite. This reduction could presumably be ascribed to stress or even toxicity caused by the increased concentrations of Al^{3+} and SO_4^{2-}, and decreased pH in the soil solution in the first period after the treatment.

Five sample trees of different size classes were felled in four of the treatment plots and the concentrations of N, P, K, Ca, Mg and S were analyzed at various heights, dividing the biomass in seven compartments (stem wood, stem bark, living branches, dead branches, current year needles, older needles and cones). The nutrient concentrations were generally highest in the actively growing parts of the trees (e.g. needles and stem bark). The concentrations of N, P, K and S were generally higher in

current year needles than in older needles, whereas the opposite pattern was observed for the concentration of Mg and Ca. The concentrations of N, P, S and Ca were increased by the treatments, most pronounced in the actively growing parts of the trees. However, the concentration of K and Mg seemed unaffected by the treatments. The above ground biomass and nutrient distribution was determined for the sample trees and the total above ground biomass and nutrient content in all trees was calculated and related to the ground surface area. The biomass was closely correlated with the tree size (height*DBH^2) for stem wood, stem bark, living branches and older needles ($R^2 \geq 0.70$). The biomass accumulation was not affected significantly ($P > 0.05$) by the different treatments. However, an increase in the above ground biomass caused by NPK fertilization was indicated. The stem wood and living branches contained the main part of the above ground biomass (approx. 80 %, corresponding to 70 t dry weight ha^{-1}). The main part of the N, P, K, Mg and S was in the living branches and needles (>60 %), while stem bark, living branches and needles contained a significant part of the Ca content (>70 %). The accumulation of nutrients in stem bark and needles increased significantly following fertilization and liming, especially in the current year needles. The calculated annual mean accumulation of P in the above ground biomass increased from 2.3 kg ha^{-1} for the control plot to more than 5 kg ha^{-1} for the strongest treatments (approx. 200 kg P ha^{-1}).

Analysis of the current year needles from the control plot indicated N and P deficiencies. Nitrogen, P and Ca concentrations in the current year needles and the relative nutrient uptake (RNU) in the above ground biomass were generally increased by the lime and fertilization treatments. The effect of conventional NPK fertilization on the nutrient status in current year needles seemed to have ceased five years after treatment.

The needle biomass was found to be better correlated with the cross-sectional sapwood area at canopy limit than with the sapwood area at breast height. Furthermore, the treatments appeared to have altered the slope and intercept of the linear correlation between the sapwood area and the needle biomass.

The effects of the treatments on the measured vitality indicators (defoliation, needle discoloration, “index of vigour”, needle productivity, presence of cones) was small. Defoliation and “index of vigour” was not dependent on the stem volume increment within the treatment period or on the total stem volume. Even though the nutritional status of the needles was improved significantly by the treatments with respect to N and P, some of the measured vitality indicators did not reflect this improvement (needle discoloration, presence of cones). Some of the indicators gave even contradictory results. The reason presumably being that the trees at the initiation of the experiment did not show low vitality due to deficiencies of any of the applied nutrients. However, the treatments combining liming with NPK fertilization were found to overcome the N and P deficiency significantly, increasing the “index of vigour”, the needle productivity, and the accumulation of above ground biomass, and decreasing the defoliation notably. But these effects were disturbed by considerable “within plot” variation and they were not statistically significant.

In comparison with similar data from other Norway spruce plantations in western Denmark, soil and needle analysis have shown that soil acidity, nutrient availability and tree nutrient status vary considerably both between stands and sites. Therefore, it is not possible to point on a single specific growth and vitality limiting nutrient in this area of Denmark. Since the demand for fertilization and/or liming obviously differs from site to site it is recommended that soil analyses and diagnostic analyses of the nutritional status of the trees are carried out before fertilizers and/or lime is applied.

Resumé (In Danish)

I de seneste årtier er der fundet tegn på næringsstofubalance i nåleskovenes økosystemer i det sydlige Skandinavien og Centraleuropa. Disse observationer er blevet hyppigere i de seneste år. Deposition af forsurende stoffer, relativ næringstofmangel samt jordbundsforsuring antages at være vigtige faktorer i den forringede skovsundhed, som er blevet iagttaget i de vestjyske rødgranplantager. Det er blevet foreslået at manglende balance mellem næringsstofferne; N, P og K og jordbundsforsuring kan indvirke på rødgranernes vitalitet. Der eksisterer derfor et aktuelt behov for at modvirke dette ved hjælp af f.eks. kalkning og gødskning.

Formålet med denne undersøgelse har været at fortsætte og videreudvikle et eksisterende gødsknings- og kalkningsforsøg i en ældre rødgranbevoksning (58 år gammel) på næringsfattig jord i Klosterheden plantage ved Lemvig i Vestjylland, med henblik på at undersøge effekten af gødskning og kalkning på skovøkosystemets næringstofbalance og på træernes sundhedstilstand og vækst. Forskellige strategier og metoder er blevet benyttet for at illustrere og videreudvikle et praktisk anvendeligt vitalitetskoncept for skovtræer.

De anvendte behandlinger bestod af to forskellige typer kalkninger (calcit og dolomit kombineret med kieserit og fosfor) og en almindelig NPK gødskning, samt NPK gødskningen kombineret med hver af kalkningerne (i alt fem forskellige behandlinger). Alle behandlingerne blev udført i 1986 og 1994. Herudover blev der gødsket med NPK i 1991.

Alle behandlingerne forårsagede en signifikant ($P \leq 0{,}05$) forøget udvaskningen af ioner fra jordbunden i de første otte måneder efter behandling. Behandling med calcit kombineret med kieserit medførte en forsuring af jordvæsken i perioden umiddelbart efter behandling. Størrelsen af de fem behandlingers påvirkning af jordbunden og jordvæsken varierede stærkt. Behandlingernes påvirkning af den kemiske sammensætning af jordvæsken syntes at være aftagende efter en periode på cirka otte måneder. Endvidere var disse påvirkninger stort set forsvundet i 1994; 8 år efter den første behandling, og tre år efter den sidste NPK gødskning.

Kalkningerne modvirkede kun jordbundsforsuringen i de øvre jordbundshorisonter inden for den undersøgte periode på 8 år (lavere aciditet og lavere koncentration af ombyttelig Al^{3+}, samt forøget koncentration af ombyttelig Ca^{2+} og Mg^{2+}, forøget basemætningsgrad samt forøget kationdbytterkapacitet og hævet pH_{H2O}).

Resultaterne fra O horisonterne (N og C koncentrationerne, C/N-forholdet, samt tykkelsen af jordbundshorisonterne) indikerede at N-mobiliseringen ikke var væsentligt påvirket af behandlingerne i de første otte år efter forsøgets start, på trods af at pH_{H2O} i O horisonten var forøget i de kalkede parceller og C/N-forholdet generelt var under 30.

Ingen af behandlingerne påvirkede stammevolumentilvæksten signifikant ($P > 0{,}05$). Den tydeligste observation var en tilvækstnedgang forårsaget af behandling med kieserit kombineret med calcit. Denne tilvækstnedgang skyldes formodentlig stress eller endog toksicitet forårsaget af en forøget koncentration af Al^{3+} and SO_4^{2-}, samt lavere pH i jordvæsken i perioden efter behandling.

Fem forsøgstræer repræsenterende forskellige størrelsesklasser blev fældet i fire af behandlingsparcellerne og koncentrationerne af N, P, K, Ca, Mg, og S blev analyseret i forskellige højder i syv forskellige biomass fraktioner (stammeved, stammebark,

levende grene, døde grene, årsnåle, ældre nåle og kogler). Koncentrationen af næringsstoffer var generelt højest i de aktivt voksende dele af træerne (f.eks. nålene og stammebarken). Koncentrationerne af N, P, K og S var generelt højere i årsnålene end i ældre nåle, hvorimod det modsatte gjorde sig gældende for koncentrationerne af Mg og Ca. Behandlingerne forøgede koncentrationerne af N, P, S og Ca; mest markant i de aktivt voksende dele af træerne. Derimod forblev koncentrationerne af K og Mg tilsyneladende upåvirkede af behandlingerne. Forsøgstræernes overjordiske biomasse- og næringsstoffordeling blev bestemt, og den samlede mængde af overjordisk biomasse og næringsstoffer blev beregnet på arealbasis. Biomassen i stammeved, stammebark, levende grene og gamle nåle var tæt korreleret med træernes størrelse (træhøjde*DBH^2)($R^2 \geq 0{,}70$). Behandlingerne påvirkede ikke akkumuleringen af biomasse signifikant ($P > 0{,}05$). Derimod indikerede resultaterne at biomassen var blevet forøget ved NPK-gødskningen. Stammeveddet og de levende grene udgjorde hovedparten af den overjordiske biomasse (ca. 80 %, svarende til 70 ton tør vægt ha^{-1}). De levende grene og nåle indeholdt hovedparten af N, P, K, Mg og S (over 60 %), hvorimod stamme bark, levende grene og nålene indeholdt størstedelen af Ca (over 70 %). Akkumuleringen af næringsstoffer i stammebarken og nålene steg signifikant efter gødskning og kalkning, specielt i årsnålene. Den beregnede gennemsnitlige akkumulering af P i den overjordiske biomasse, steg fra 2,3 Kg ha^{-1} år^{-1} i kontrolparcellen til mere end 5 kg ha^{-1} år^{-1} for behandlingen med den største tilførsel af P (ca. 200 kg P ha^{-1}).

En analyse af årsnåle fra kontrolparcellen indikerede N og P mangel. Koncentrationerne af N, P og Ca i årsnålene, og "det relative næringsstofoptag" (RNU) af disse stoffer i den overjordiske biomasse blev generelt forøget ved behandlingerne. Almindelig NPK-gødsknings påvirkningen af næringsstofkoncentrationerne i årsnålene var tilsyneladende ophørt fem år efter behandlingen.

Nåle-biomassen var bedre korreleret med tværsnitsarealet af det væskeførende ved i kronegrænsehøjde end i brysthøjde. Desuden, syntes behandlingerne at have påvirket hældningskoefficienten og skæringspunktet for den lineære korrelation mellem nålebiomassen og tværsnitsarealet af det væskeførende ved.

De målte vitalitetsindikatorer (nåletab, nålemisfarvning, "vitalitetsindeks", nåleproduktivitet, kogleproduktion) virkede forholdsvis upåvirkede af behandlingerne. Nåletab og "vitalitetsindeks" var ikke afhængig af stammevolumentilvæksten i behandlingsperioden, eller af det totale stammevolumen. På trods af at behandlingerne forøgede årsnålenes koncentration af N og P signifikant og dermed forbedrede træernes næringsstofstatus, blev denne forbedring ikke entydigt reflekteret af de målte vitalitetsindikatorer (nålemisfarvning, kogleproduktion). Nogle af indikatorerne gav modstridende resultater. Begrundelsen for dette er sandsynligvis at træerne ikke led af udtalt mangel på de tilførte næringsstoffer ved forsøgets begyndelse. Resultaterne fra de behandlinger hvor kalkningerne blev kombineret med NPK gødskningen, viste dog at disse behandlinger modvirkede N og P manglen signifikant, og forøgede "vitalitetsindekset", nåleproduktiviteten og akkumuleringen af overjordisk biomasse, samt mindskede nåletabet. Disse behandlingseffekter kunne dog ikke påvises at være statistik signifikante, da variationerne indenfor de enkelte parceller var store.

Data fra nåle- og jordbundsanalyser fra de vestjyske rødgranplantager viser, at forsuringen af jordbunden, næringsstoffernes plantetilgængelighed og træernes næringsstof-status varierer betydeligt imellem de forskellige bevoksninger og lokaliteter.

Det er derfor ikke muligt at pege på et specifikt næringsstof som værende generelt vitalitets- og tilvækstsbegrænsende i de vestjyske rødgranplantager. Da behovet for gødskning og/eller kalkning tydeligvis varierer fra lokalitet til lokalitet anbefales det, at man undersøger behovet for tilførsel af næringsstoffer og/eller kalkning via analyse af jordens og nålenes næringsstofindhold før man gødsker og/eller kalker.

Introduction

Atmospheric deposition of acidifying N and S compounds as well as removal of biomass from forests, contribute to the acidification of forest soils. Soil acidification and N deposition may lead to an imbalanced forest nutrition and, eventually, a decreasing forest health condition, especially on nutrient poor soils (Berdén et al., 1987; Liljelund et al., 1990; Evers and Hüttl, 1990/91; Nihlgård, 1996).

Soil acidification and increased base cation leaching in forest ecosystems, caused by deposition of acidifying air pollution compounds have been indicated or documented in a large number of countries in Europe (e.g. Denmark: Rasmussen, 1988; Bille-Hansen, 1990; Rasmussen and Hansen, 1992; Pedersen, 1993. England: Billett et al., 1990. Germany: Ulrich et al., 1980; Hüttle, 1986; Zoettl and Huettl, 1986. Netherlands: Breemen et al., 1983; Vries and Breeuwsma, 1986. Norway: Steinnes et al., 1993, and Sweden: Hallbäcken and Tamm, 1986; Tamm and Hallbäcken, 1988; Falkengren-Grerup and Tyler, 1992) and in the United States (e.g. Breemen et al., 1984; Reuss et al., 1987).

Soil acidification and a subsequently increased concentration of inorganic Al in the soil solution may cause Al toxicity and disturbed nutrient uptake in tree roots (Ulrich et al., 1980; Ulrich, 1983; Eldhuset et al., 1987; Godbold et al., 1988). The increased concentration of inorganic Al can furthermore lead to P immobilization and deficiency (Andersson, 1988).

It is hypothesized that Norway spruce has adapted to low N availability within its natural geographical distribution area over a long time period, probably by genetic adaptation, and that Norway spruce can grow well under conditions where N is the growth limiting element (Aber et al., 1989; Brække et al. 1997). Nitrogen deposition, soil acidification, and nutrient leaching may lead to a relative deficiency of nutrients such as P, Ca, Mg, K and other elements in relation to N (Ulrich, 1983; Roelofs et al., 1985; Schulze, 1989; Evers and Hüttl, 1990/91).

Wood production increases the risk of development of nutrient deficiencies within the forest ecosystem by removal of biomass and thereby nutrients from the forest ecosystem (Berdén et al., 1987; Liljelund et al., 1990; Nihlgård, 1996). Although atmospheric S deposition has decreased in Europe during recent years the deposition of N is still constant or slightly increasing (Galloway, 1995). Therefore, the need for investigation of possible counteractions of soil acidification, nutrient depletion and nutritional imbalances, in the form of liming and fertilization is highly relevant.

In many areas of central Europe it has been shown that the forest stands are suffering from soil acidification, nutrient leaching and nutrient deficiencies due to an increased deposition of air pollution compounds (Huettl et al., 1990; Katzensteiner et al., 1995). The observed nutrient imbalances and deficiencies involve first of all Mg, but also K, Ca, Mn and Zn (Huettl and Zoettl, 1993). Fertilization and liming of forests in central Europe has been shown effectively to be able to counteract the deficiencies and the soil acidification (Huettl and Zoettl, 1993; Katzensteiner et al., 1995; Meiwes, 1995a). Especially, application of dolomite ($MgCa(CO_3)_2$) has appeared to increase both growth and vitality of stands suffering from Mg deficiency and soil acidification

A series of research projects concerning forest liming in approx. 150 experiments were started or reexamined in Sweden and Finland in 1983 (reviewed by Staaf et al., 1996a). Results from these experiments showed that liming with more than 5 tons ha^{-1} often lead to an increased soil pH and base saturation and a decreased concentration of Al in the soil solution, and that these geochemical changes could be expected to last for a relatively long period of time (30-70 years).

Fertilization trials conducted in Denmark in the 1950's and 60's in Norway spruce plantations suggested that stem volume increment could be expected to increase by 3-4 m^3 ha^{-1} year^{-1} measured over a five year period, when NPK fertilizers (120 kg N ha^{-1}) were applied on nutrient poor soils every fifth year (Lundberg and Ravnsbæk, 1992). Nitrogen was at that time assumed to be the main limiting nutrient for the growth of Norway spruce in western Denmark. Later studies from the 1970's and 80's have shown that these expectations could not be fulfilled. NPK fertilization (120 kg N ha^{-1}) applied every fifth year only increased the stem volume increment by 0.76 m^3 ha^{-1} year^{-1} over a ten year period (Dralle and Larsen, 1995). Furthermore, the increase in stem volume increment in NPK treated plots was only found to be statistically significant one of the 11 investigated regions. The same authors concluded that the assumption of N being the main limiting nutrient for tree growth no longer seemed valid and that this might be a result of the increased N deposition during the 1970's and 80's.

At present it is not clear how the ongoing N deposition, soil acidification, and removal of wood in the long-term will affect the health condition of Norway spruce stands on the nutrient poor soils in western Denmark. However, the health condition of these stands expressed in terms of needle loss declined from 1989 to 1994 and is now stabilized at a low level (Danish Forest and Nature Agency, 1996). Results from long-term investigations of forest soils and stand growth in western Denmark indicated that K deficiency, and to some extent P deficiency, may be contributing factors (Lundberg and Ravnsbæk, 1992; Clausen, 1995; Dralle and Larsen, 1995; Pedersen and Bille-Hansen, 1995a). However, severe nutrient deficiencies in Norway spruce plantations have in Denmark so far only been documented in very few cases by means of diagnostic needle analyses (Lundberg and Ravnsbæk, 1992; Raulund-Rasmussen and Vesterdal, 1996).

The aim of fertilization and liming in forest management has changed during the last decades from increasing the stem volume increment to revitalizing the forests by counteracting the ongoing acidification of the soil and stabilizing a sufficient and balanced nutrient uptake for the trees. In this perspective it is essential that parameters such as tree vitality, nutrient availability, imbalanced tree nutrition and nutrient deficiencies are well defined and transformed to measurable and applicable forest management strategies.

The purpose of this study was to continue and further develop an existing fertilization and liming experiment in a mature Norway spruce stand on a nutrient poor soil in western Denmark in order to restore the nutritional balance of the stand and study the liming and fertilization effects on the chemical composition of the soil and soil solution and on the forest production. Different strategies and methods were applied to clarify and develop the vitality concept and its applicability. Furthermore, various strategies for detecting the need for fertilization and/or liming in Norway spruce stands in western Denmark have been examined.

Is fertilization and liming of Norway spruce stands needed in Denmark?

This chapter presents an analysis of growth and vitality limiting factors, with special emphasis placed on nutritional disorders. The study focus on examining the current situation in Norway spruce stands on nutrient poor soils in western Denmark. Various strategies for detecting the need for soil amelioration by fertilizer and/or lime application have been examined and likely responses to applications are discussed. Furthermore, the vitality concept and methods for measuring tree vitality are discussed and some fertilization and liming recommendations are given.

The chapter is a compilation of the main findings from Paper I-IV and a review of the literature. The four papers are based on a study of a fertilization and liming experiment in a mature Norway spruce stand on a nutrient poor soil at Klosterheden, Lemvig, in western Denmark. At the "Klosterhede site" two types of lime (calcite and dolomite combined with additional kieserite and phosphorus) were applied alone and in combination with conventional NPK fertilizer to form five different treatments. All the treatments were carried out in 1986 and in 1994 and the NPK treatment was additionally carried out in 1991. The effects of the treatments on: i) chemical composition of the soil and soil solution, ii) stem volume increment, iii) biomass and nutrient accumulation, iv) nutritional status of the trees, and v) vitality, were examined at the Klosterhede site. Treatments, treatment abbreviations and site and stand description are presented in detail in Paper I-IV.

1. Growth factors: water and nutrients

The growth rate of Norway spruce stands in western Denmark is in general highly dependent on water and nutrient availability (Holstener-Jørgensen and Holmsgaard, 1988; Beier and Rasmussen, 1993). Naturally, the nutrient uptake is closely related to, and to some extent restricted by, the water availability. Combined irrigation and fertilization experiments in two mature Norway spruce stands on nutrient poor soils in western Denmark showed that stem volume increment mostly depended on the water supply, especially in the spring and early summer. The stem volume increment was increased 25-30 % by irrigation in these stands. No further growth response was observed by adding fertilizers to the irrigated plot (Beier and Rasmussen, 1993). Fertilization with conventional NPK (23:3:7) fertilizer without irrigation (only applied in one of these experiments) did not affect the growth rate notably (Holstener-Jørgensen and Holmsgaard, 1988).

Results from irrigation and fertilization experiments conducted in Ireland, Netherlands and Germany generally confirmed that stem growth was increased by irrigation, whereas combined irrigation and modest fertilization did not improve the growth rate notably compared to irrigation alone (Beier and Rasmussen, 1993). They concluded that either the water supply was the most important growth limiting factor at the investigated sites, or that due to increased decomposition of organic matter in the irrigated plots, the nutrient availability was improved sufficiently to ensure a growth response similar to that in the both fertilized and irrigated plots.

Drought episodes presumably play a dominating part in growth limitation of Norway spruce in Denmark. Results from Danish fertilization experiments in middle-aged to old Norway spruce stands show a relatively large variation in the growth response. The effect of the nutrient application is often lacking in dry years (Lundberg and Ravnsbæk, 1992). Optimization of the nutrient supply to the trees by fertilization and liming should therefore aim at an improvement of the nutritional status and thereby the vitality of the trees; more than controlling the growth rate, since the growth rate seem to be more restricted by the water supply than the nutrient availability.

2. Detecting the need for fertilization and liming

The effect of fertilization and liming has been found to be site and stand specific (Evers and Hüttl, 1990/91). Huettl (1988) stated that fertilization and liming experiments have demonstrated that a swift and sustained revitalization of declining forest ecosystems marked by nutritional disturbance can be achieved in young, as well as in old, forest stands. However, a prerequisite for achieving good results is a stand and site specific fertilizer and lime application strategy, based on sufficient knowledge of the nutritional status of the ecosystem (foliage and soil analysis) (Huettl 1988). Methods for detecting a need for fertilization and liming and methods for diagnosing nutritional disorders in the trees are discussed in the following.

2.1. Soil acidification and liming

Liming serves the purpose of counteracting the ongoing acidification and supplying nutrients (Ca in calcite, $CaCO_3$ and Ca and Mg in dolomite, $CaMg(CO_3)_2$). The need for liming is normally investigated by measurements of parameters related to the soil acidity (pH, concentration of Al in the soil solution, base saturation (BS), and Ca/Al-molar-ratio in the soil solution) and the actual deposition and effect of acidifying compounds (Staaf et al., 1996b).

In Sweden, Lundmark (1988) investigated the need for liming by using pH_{H2O} = 4.4 in the upper part of the B-horizon as a threshold value. This pH_{H2O} value has been used in several studies because Al generally is mobilized from the mineral soil at pH_{H2O} below 4.4-4.5 (Staaf et al., 1996a). Rosén and Lundmark (1990) suggested that liming should be carried out when pH_{H2O} is below 4.3 and that liming should be seriously considered when pH varies between 4.3 and 4.5. At the investigated Klosterhede site the pH_{H2O} value was below 4.1 in the Bh horizons in all the treated plots, indicating a need for liming (Paper I). No notable differences in pH_{H2O} values beneath the AE horizons were found between the different treatments 8 years after liming.

The combination of $pH_{H2O}<4.5$ and $BS<3$ % in the upper part of the B-horizon has also been used as threshold values (Staaf et al., 1996b). The BS was above 3 % in the Bh horizon for all the treatments at the Klosterhede site (Paper I). The lowest values were found in the NPK fertilizer- and/or dolomite applied plots (BS: 4-7 %).

Soil acidification and a subsequent increased concentration of Al in the soil solution may cause Al toxicity, root damage, disturbed nutrient uptake and reduced growth (Ulrich et al., 1980; Ulrich, 1983; Eldhuset et al., 1987; Godbold et al., 1988).

The concentration of Al in the soil solution has therefore been proposed as a parameter to detect the need for liming. The literature points at a threshold value around 1-8 mg Al l^{-1} for Norway spruce (Göransson and Eldhuset, 1991; Sverdrup and Warfvinge, 1993), but large variations from this value can be found in the literature. Another problem by using the concentration of Al is that the concentration varies notably both in space and time. At the Klosterhede site, the Al concentration in the soil solution in the lower part of the Bs horizon was generally below 3 mg l^{-1} before new treatments were carried out in 1994, indicating a low risk for Al stress (Fig. 5) (Paper I). However, the concentration of Al was increased notably in the period following fertilization and liming, indicating a severe risk for Al stress. The increased Al concentration in the soil solution can be explained by ion exchange of adsorbed Al from the soil and cations from the applied fertilizer and lime; mainly Mg^{2+} and Ca^{2+} (Paper I). The concentration of Al seemed to peak within eight months following the treatments, but notably elevated Al concentrations could still be observed 17 months after the treatments (Fig. 5). Comparison of Al concentrations from the Klosterhede site with threshold values from the literature should be made with the provision that the soil solution was sampled under the root zone.

Relatively high concentrations of base cations in the soil solution may restrict the Al stress (Godbold et al., 1988). The ratio between the molar concentration of Ca and Al (Ca/Al-molar-ratios) in the soil solution has thus been found to be a better indicator of Al stress than just the concentration of inorganic Al (Sverdrup and Warfvinge, 1993; Cronan and Grigal, 1995). However, Staaf et al. (1996b) concluded that there were some general problems involved in applying the Ca/Al-molar-ratio as an indicator of the need for liming, because many of the studies concerning the Ca/Al-molar-ratio were carried out in the laboratory with small plants and not in the field with big trees. Furthermore, the soil solution in the rhizosphere may have a different chemical composition compared to the soil solution in the rest of the soil. On the other hand, Staaf et al. (1996b) also concluded that it is unlikely that the roots will be damaged due to acidification at a Ca/Al-molar-ratio above 1.0, whereas the risk is considerably increased when the Ca/Al-molar-ratio is below 0.1. There is a risk for growth reduction and imbalanced nutrient uptake of base cations and P compared to N at Ca/Al-molar-ratios between 0.1 and 1.0. (Staaf et al., 1996b). At the Klosterhede site, the Ca/Al-molar-ratio below the root zone generally varied between 0.1 and 1.1 in the period before treatment (Fig. 1) (Paper I). However, the Ca/Al-molar-ratio increased notably in the CaMgPS and CaMgPS+NPK applied plots during the following five months after treatment. Over the next couple of months, the Ca/Al-molar-ratio decreased to a level close to 2 and seemed relatively constant during the next ten months (Fig. 1). These variations can be explained by the different dissolution rates of the applied compounds and the involved ion exchange processes (Paper I). In the period after treatment the Ca/Al-molar-ratio varied between 0.06 and 0.38 in the control and NPK treated plots, and between 0.15 and 1.1 in the CaMgP and CaMgP+NPK treated plots.

At the Klosterhede site, the pH_{H2O}, the concentration of Al, and the Ca/Al-molar-ratio indicated a need for liming in the control plot. However, in some of the already limed plots these parameters also indicated a need for liming. This may be explained by the fact that the calcite and dolomite used in the first application in 1986 had a relative low dissolution rate. The amount of exchangeable ions in the soil was only affected in the upper horizons during the first 8 years after application (Paper I).

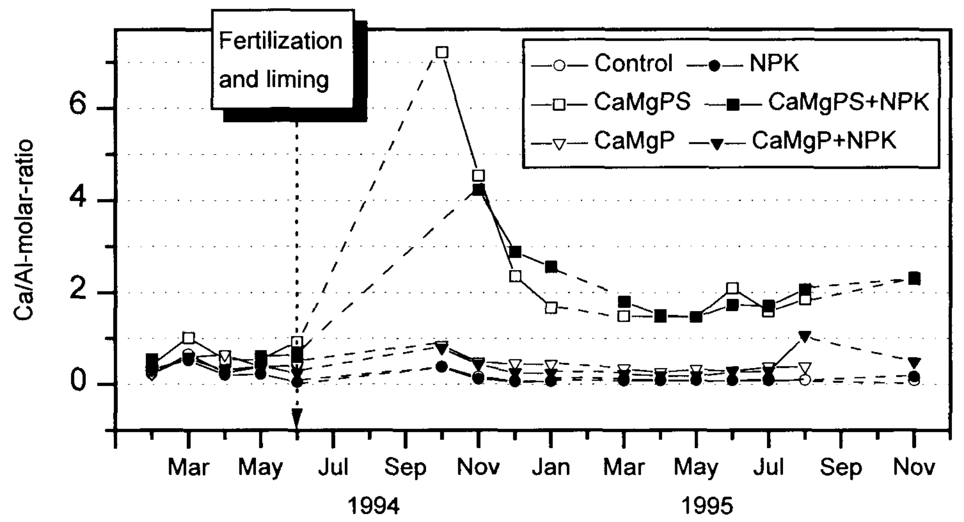


Figure 1. Ca/Al-molar-ratio in the soil solution from February 1994 to November 1995 at the Klosterhede site. Sampling and analysis is described in Paper I.

2.2. Critical load for acidification

The critical load for acidification can be defined as: "The highest deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function" (Nilsson and Grennfelt, 1988). Determination of the need for liming by application of the critical load for acidification has the advantage of taking into account both the deposition of acidifying compounds and the capability of the soil to counteract the acidification load (Staaf et al., 1996b). The critical load for acidification can be calculated in different ways. These calculation methods will not be presented here, but can be found in Nilsson and Grennfelt (1988), Sverdrup et al. (1990), Hettelingh et al. (1991), Sverdrup et al. (1992) and Sverdrup and Warfvinge (1995). Reynolds et al. (1997) calculated the critical load for a Norway spruce stand at Klosterhede situated close to the Klosterhede site examined in the present study and with similar stand and soil conditions. The critical load (4.2 keq ha^{-1} yr^{-1}) slightly exceeded the actual acid deposition with S and N compounds (3.9 keq ha^{-1} yr^{-1}) indicating no pressing need for counteractions.

2.3. Soil analyses and nutrient status of the trees

Chemical analyses of the exchangeable nutrients in the soil have traditionally been used to assess the nutrient supply in Denmark (Møller, 1965). However, the nutrient concentration in the soil does not necessarily correlate with the nutrient concentration in the foliage of the trees.

Nohrstedt and Jacobson (1994) investigated the relationship between the nutrient concentrations in the current year needles and the corresponding nutrient concentrations in the humus layer and the upper five cm of the mineral soil (N, P, K, Ca and Mg) in 63 control plots in middle-aged to old coniferous stands located all over Sweden. They concluded that the nutrient concentrations in Scots pine needles were, with the exception of N, not related to the corresponding nutrient concentrations in the soil. Similar observations were obtained for Norway spruce. However, significant ($P \leq 0.05$), but weak (slope<0.1 for mg g^{-1} in needles vs. mg $100g^{-1}$ in humus layer) positive linear correlations were found for the concentration of P, K and Ca in the humus layer in Norway spruce stands. For both tree species, the concentration of N in the needles was positively correlated with the N concentration in the soil. The correlation coefficients were generally higher for the humus layer than for the mineral soil. Nihlgård (1992) found that the nutrient concentration (Ca, K, Mg and P) in current year needles from 42 middle-aged coniferous stands in Sweden were, with the exception of Ca, not correlated with the corresponding concentration of exchangeable nutrients in the soil. The Ca concentration in the needles was found to be significantly positively correlated with the Ca concentration in the humus layer. Liu and Truby (1989) found no or very weak correlations between the nutrient concentrations (K, Mg and Ca) in the current year needles and in the upper 20 cm of the soil (incl. a thin humus layer) in 44 Norway spruce stands in Germany. By use of diagnostic foliage analysis, Liu and Truby (1989) observed K, Mg and Ca deficiency and suggested threshold values for the corresponding concentration in the upper 20 cm of the soil (incl. a thin humus layer): K<0.20 cmol+ kg^{-1}, Ca<0.10 cmol+ kg^{-1} and Mg<0.20 cmol+ kg^{-1}. At the Klosterhede site, the similar concentrations of Ca and Mg in the O+A+AE horizons were well above these deficiency values (NPK: Ca=0.71 cmol+ kg^{-1}, Mg=0.50 cmol+ kg^{-1}; CaMgPS: Ca=4.9 cmol+ kg^{-1}, Mg=0.85 cmol+ kg^{-1}; CaMgPS+NPK: Ca=4.2 cmol+ kg^{-1}, Mg=1.07 cmol+ kg^{-1}; CaMgP: Ca=2.7 cmol+ kg^{-1}, Mg=2.3 cmol+ kg^{-1}; CaMgP+NPK: Ca=2.9 cmol+ kg^{-1}, Mg=2.2 cmol+ kg^{-1}). However, the concentrations of K were below the deficiency value (NPK: K=0.19 cmol+ kg^{-1}; CaMgPS: K=0.14 cmol+ kg^{-1}; CaMgPS+NPK: K=0.11 cmol+ kg^{-1}; CaMgP: K=0.15 cmol+ kg^{-1}; CaMgP+NPK: K=0.09 cmol+ kg^{-1}) indicating a need for K fertilization; most pronounced in the CaMgPS, CaMgPS+NPK, CaMgP and CaMgP+NPK treated plots. A diagnostic needle analysis did, however, not indicate K deficiency (Paper IV).

Aamlid et al. (1992) examined 18 coniferous stands in Norway and found significant positive correlations between the concentration of N, Ca and Mn in the needles and in the humus layer, whereas no correlation could be found for K. Raulund-Rasmussen and Vesterdal (1996) investigated 7 middle-aged to old Norway spruce stands located in western Denmark and found that the concentration of P, K and Ca correlated positively with the corresponding nutrient concentration in the soil. The correlations for N was not examined.

Examination of the correlations between the nutrient concentration in the soil, soil solution and needles (N, K, Ca and Mg) within the different treatment plots at the Klosterhede site (Ingerslev, 1997, in Appendix II, 2.) showed that: i) the correlations between the nutrient concentrations in the soil solution and needles were relatively strong for Ca and N, and weaker for K and Mg, ii) the correlations between the nutrient concentrations in the soil and needles were very strong for Ca, whereas no significant correlations could be established for N and K, and iii) generally, the nutrient concentration in the needles appeared to be better correlated with the nutrient concentration in the soil solution than in the soil.

The nutrient concentrations in the soil were not in general closely correlated with the nutrient status of the trees, represented by the corresponding nutrient concentrations in the needles with the exception of the concentrations of N. However, in cases where severe nutrient deficiency occurs due to low nutrient availability, it may be logical to believe that the concentration of the deficient nutrient in the needles is better correlated with the corresponding nutrient concentration in the soil solution and soil than in cases where the nutrient availability exceeds the actual need. Only few studies have provided deficiency threshold values for the nutrient concentrations in the soil and such values may turn out to be very site specific due to differences in soil properties and root distribution.

2.4. Nitrogen leaching

In several of our neighboring countries N leaching caused both by increased N deposition and by the inability of the trees and other plants to sequestrating excess N has been observed; e.g. Sweden, Germany and the Netherlands (Gundersen and Bashkin, 1994; Nohrstedt et al., 1996). Nitrogen leaching from the root zone indicates that the forest ecosystem is in a stage of N saturation (Aber et al., 1989). Nitrogen leaching is not only a threat to our ground water quality but also to the nutrition of the trees since N leaching often involves leaching of essential nutrients such as Ca, Mg and K (with nitrate) and/or mobilization of Al. When N leaching occurs other nutrients than N, or water or light may become growth limiting. In Norway spruce stands on nutrient poor locations, these relative nutrient deficiencies compared to N may turn out to be serious threats to the forest nutrition and health status, because Norway spruce is believed to grow quite well without losing the vitality when N is the growth limiting element. For other elements, the trees do not tolerate deficiencies to the same extend (Aber et al., 1989; Brække et al., 1997). In stands where N leaching occurs fertilization with the growth limiting nutrients may lead to a more balanced forest nutrition, increased biomass accumulation and N uptake, and decreased N leaching (Liljelund et al., 1990).

Nitrogen leaching from intensively studied Danish forest ecosystems has only been determined in few cases (e.g. Gundersen, 1992; Pedersen and Bille-Hansen, 1995b). However, Callesen et al. (1996) examined the nitrate concentration in 111 different Danish forest soils (the soil was sampled from different depths down to 100 cm and KCl-soil suspensions were analyzed) and found that the concentration of nitrate in the soil was generally dependent on the: i) size of the forest (forests smaller than 10 ha had higher N concentrations than forest larger than 50 ha), ii) type of forest (newly established stands and greenerys had higher N concentrations than more extensively managed forest types), and iii) type of soil (soils with a high content of humus had a high N concentration and soils with a high clay content had a higher concentration of N than more sandy soils). No general differences in the N concentrations in the soils were found between different tree species (spruce, pine and various deciduous tree species). They concluded that the nitrate concentration in the soil solution under the Danish forests in general was low and that this indicated that the investigated forests were not yet in a stage of N saturation. However, relatively high N concentrations (>11.3 mg

NO_3^--N l^{-1}) were observed in the soils in approx. 10 % of the investigated sites. These cases were explained by high N deposition caused by neighboring animal farms, and forest management related disturbances of the ecosystem (e.g. thinning or draining of the soil) (Callesen et al., 1996). This study also indicated that there was a large variation in the leached amount of N between different sites. Some of the stands that showed high N concentrations in the soil were located on relative nutrient poor sandy soils. These stands may suffer from relative nutrient deficiencies compared to N and fertilization with the deficient nutrients may appear to improve the nutrient status in the trees and decrease the N leaching. At the Klosterhede site the N concentration in the soil solution was relatively low (<1.2 mg NO_3^--N NH_4^+-N l^{-1}) in time-periods apart from the 9-10 months following treatments (Fig. 5).

2.5. Diagnostic foliage analysis

Diagnostic foliage analysis has proven to be one of the most powerful tools for determination of the current nutrient status in the trees and the plausible need for fertilization (Huettl et al., 1990; Evers and Hüttl, 1990/91; Brække, 1994; Rosengren-Brinck, 1994; Linder, 1995; Bække, 1996; Andersson et al., 1997). However, the needle sampling strategy influences the results and thus caution should be taken when choosing a strategy. Differences in nutrient concentrations occur within the canopy between different branch whorls, light conditions, needle age classes, and positions of shoots (Walker, 1991; Raitio, 1994; Rosengren-Brinck, 1994; Paper II; IV). Furthermore, inter-annual variations (temperature and precipitation), seasonal changes, and the social status of the tree affects the nutrient concentration in the needles (Helmisaari, 1990; Walker, 1991; Raitio, 1994). The sampling method used at the Klosterhede site (Paper IV) followed the guidelines from the 'International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests' (UN/ECE, 1994). Diagnostic use of foliage analysis was initiated in the early 1930's, and since then different interpretation methods has been developed. These methods are discussed in the following.

2.5.1. Nutrient concentrations and diagnostic threshold values.

Various deficiency threshold values (critical levels) for the nutrient concentration in current year needles from Norway spruce have been provided by a large number of studies (e.g. Van den Burg, 1985; 1990; Hüttl, 1986; Nihlgård, 1990; Bække, 1994; Linder, 1995). These values normally refer to a certain reduction in tree growth or visible deficiency symptoms on the needles. A basic assumption for the use of deficiency threshold values is that the trees are suffering from growth limiting deficiency when the concentration of the nutrient in question is below the chosen critical level. On the other hand, optimal nutrition is assumed when the concentration is above this critical level. The critical level is often determined under laboratory and growth chamber conditions (with seedlings exposed to controlled climatic conditions) which are not comparable to field conditions for mature trees. The closer the experimental conditions match the environmental conditions and sampling strategy, the better the nutritional diagnosis is likely to become (Leaf, 1973). The interpretation is relatively simple when the concentration is far above or far below the critical value, but when the concentration is within the range of the critical level the interpretation is difficult. Brække (1994) compiled the findings for current year needles from Norway spruce and Scots pine from a large number of studies and provided tables of threshold values for macro-nutrients (N, P, K, Ca, Mg and S) and micro-nutrients (B, Fe, Mn, Zn, Cu and Mo), separating the nutrient concentrations into four diagnostic classes (strong deficiency, deficiency, pre-optimum and optimum) (Table 1). This set of diagnostic classes has the advantage of dividing the traditionally used critical value into more sensible and easily interpreted concentration ranges. The optimum level for N given by Brække (1994) may seem relatively high (18 mg g^{-1} N). However, Table 1 aims at optimizing the growth rate and not only stabilizing a healthy tree nutritional status. Aiming at a relatively high optimum level for the concentration of N in the current year needles, may prove to be sensible for optimizing the growth rate, but at the same time imply a risk for increasing the N leaching (Paper IV). The toxic levels has not been included in Table 1, since only very few investigations and data on toxic levels for Norway spruce has been reported in the literature.

Table 1. *Diagnostic levels for nutrient concentrations in current year Norway spruce needles (C0), sampled from the upper 1/3 of the canopy for optimization of the growth rate (Brække, 1994 revised by the author in 1996). Nutrient/N-ratios is given for optimal growth rate; N=100 %.*

Elements	Strong deficiency	Deficiency	Pre-optimum	Optimum	Nutrient/N -ratio (%)
N (mg g^{-1})	<12	12-15	15-18	>18	100
K (mg g^{-1})	<3.5	3.5-5.0	5.0-6.0	>6	33
Ca (mg g^{-1})	<0.4	0.4-0.6	0.6-0.7	>0.7	4
Mg (mg g^{-1})	<0.4	0.4-0.6	0.6-0.8	>0.8	4
P (mg g^{-1})	<1.2	1.2-1.5	1.5-1.8	>1.8	10
S (mg g^{-1})	<0.4	0.4-0.6	0.6-0.8	>0.8	4
B (µg g^{-1})	<4			>8	0.04
Fe (µg g^{-1})		<20		>20	0.11
Mn (µg g^{-1})	<10			>15	0.08
Zn (µg g^{-1})	<8			>12	0.07
Cu (µg g^{-1})		<2		>2	0.01
Mo (µg g^{-1})		<0.02		>0.02	0.001

Increasing N concentration with increasing needle age and high concentrations of arginine in the needles are considered to indicate N saturation, under which conditions other elements may be growth limiting (Aber et al., 1989; Nohrstedt et al., 1996).

In order to make the comparison with literature values more quantitative the DOP index (Deviation from Optimum Percentage) has been proposed (Montañés et al., 1993).

The DOP index gives the deviation between the observed nutrient concentration and the corresponding optimum threshold reference value, in percentage. The DOP index is given by: $DOP_x=((C_x*100)/C_{x,ref.})-100$, where C_x is the observed concentration of nutrient x, $C_{x,ref.}$ is the optimal nutrient concentration used as a reference value (Montañés et al., 1993). The advantage of the DOP index is claimed to be that deficiency (negative DOP index), excess (positive DOP index), and the nutritional limitation order (the most restricting nutrient has the most negative DOP index) are easily detected through standard methodology (Montañés et al., 1993). DOP does not include any new interpretations, because the reference values are the same.

Table 2. *DOP ("Deviation from Optimum Percentage") calculated for current year needles sampled at the Klosterhede site in autumn 1995 (Paper IV).*

Treatments	DOP_N	DOP_P	DOP_K	DOP_{Ca}	DOP_{Mg}	DOP_{Mn}
Control	-28	-25	20	230	46	710
NPK	-8	-9	34	210	45	560
CaMgPS	-21	25	20	610	63	780
CaMgP+NPK	-12	19	40	630	75	740
CaMgP	-18	36	26	540	75	890
CaMgP+NPK	-11	26	29	390	61	440
Optimum reference values[a]	18 (mg g^{-1})	1.8 (mg g^{-1})	6 (mg g^{-1})	0.7 (mg g^{-1})	0.8 (mg g^{-1})	15 (μg g^{-1})

a: Brække (1994)

Diagnostic foliage analyses is widely used in our neighboring countries. Mg and K deficiency and low status of Ca and Zn have been detected in a number of studies; e.g. in Germany and Austria, by means of needle analysis and thereafter cured by fertilization and/or liming (Hüttl, 1990; Huettl et al., 1990; Evers and Hüttl, 1990/91; Liu and Huettl, 1991; Katzensteiner et al., 1995). Low status or deficiencies of N, P, K, Cu and B have also been detected in Sweden by means of needle analyses (Rosengren-Brinck, 1994; Andersson et al. 1995; Linder, 1995; Thelin et al., 1996. Brække et al., 1997).

However, in Denmark the use of diagnostic foliage analyses in relation to fertilization experiments have until now been limited. Needle analyses (N, P, K, Ca, Mg and Cu) have been carried out in fertilization experiments on relative nutrient poor soils in western Denmark by Lundberg and Ravnsbæk (1992). Their results generally indicated N, P and/or K deficiencies in the control plots, when compared to the threshold values given by Brække (1994). They found that the concentration of K and Cu had declined significantly in the control plots during the experimental period (approx. 1965-1988). Raulund-Rasmussen and Vesterdal (1996) presented results from analysis of Norway spruce needles from 31 relative nutrient poor sites in western Denmark. The nutrient status in the investigated trees varied for N from optimum (11 sites) over pre-optimum (17 sites) to deficient (3 sites), for P from optimum (1 site) and pre-optimum (21 sites) over deficient (8 sites) to strong deficiency (1 site), and for K from optimum

(13 sites) over pre-optimum (13 sites) to deficiency (5 sites) according to Brække (1994). For both studies large variations between the different sites were found.

The threshold values given by Brække (1994) were used for interpretation of needle analyses carried out at the Klosterhede site, and N and P deficiencies were detected in the control plot (Paper IV). It could not be assessed which of the two nutrients were the growth limiting element. A similar conclusion is reached using the DOP indexes presented in Table 2. DOP_N and DOP_P for the control plot are at the same level which again makes it difficult to decide which of the two nutrients is growth limiting. Gundersen and Rasmussen (1995) presented needle analyses from another Norway spruce stand at Klosterhede which also showed N and P deficiency.

In general, the results from western Denmark express a considerable variation in the nutrient status of the trees between different sites, often involving deficiencies of N, P and/or K, whereas Ca and Mg deficiencies were not revealed by diagnostic needle analysis. Our knowledge concerning the micro nutrients is at present very limited. Hence, general conclusions concerning the need for fertilization with a specific nutrient or combination of nutrients in Norway spruce stands in western Denmark should not be attempted. But, it is recommended that diagnostic needle analyses is carried out to verify the specific need for nutrient applications in cases where fertilization is considered.

At the Klosterhede site, the concentrations of N and P in the needles in the control plot were highest in the upper part of the canopy (Paper II). The results indicated that N and P deficient trees preferentially have retranslocated these nutrients to the upper part of the canopy to maintain a relatively higher concentration in the part of the tree where the photosynthetic activity is highest. When N and P were applied, the concentrations were increased, especially for needles in the middle and lower parts of the canopy, to a level that could be considered above deficiency in all parts of the canopy. The sampling strategy given in the UN/ECE (1994) protocol (taking one sample from the upper 1/3 of the canopy) is suitable for diagnostic comparison with literature values on nutrient status. However, Paper II showed that other needle sampling strategies, such as sampling from various heights in the canopy, may preferentially be used to obtain additional knowledge concerning the nutrient status of the trees. Results from the Klosterhede site showed that fertilization with nutrients which are mobile within the trees (e.g. N and P) in stands suffering from low nutritional status or deficiency may show the largest effects on the nutrient concentrations in needles from the lower part of the canopy (Paper II).

2.5.2. Ratios between nutrient concentrations

The proportions between the concentrations of different nutrients are often used for diagnostic interpretation of nutrient concentrations in needles because the influence of inter-annual variation and growth dilution is decreased compared to interpretation of the specific nutrient concentrations (Schutz and de Villiers, 1987; Rosengren-Brinck, 1994). Especially, the nutrient/N-ratio is often used for Norway spruce (Brække, 1994; Rosengren-Brinck, 1994; Linder, 1995; Brække et al., 1997), since this tree species can be vital and grow quite well with N as the growth restricting element, if not severely N deficient (Andersson et al. 1997). Various threshold values for the nutrient/N-ratio can be found in the literature (e.g. van den Burg, 1985; 1990; Brække, 1994; Linder, 1995).

In Denmark, the K/N and P/N-ratios have been calculated for 31 Norway spruce stands in the western part of the country (Raulund-Rasmussen and Vesterdal, 1996). In five of these stands, one or both of these ratios were more than 30 % lower than the optimum ratios given by Brække (1994). In the stands where low K/N-ratios were observed, also K deficiency was detected. In case of low P/N-ratios either pre-optimum, P deficiency, or strong P deficiency was detected. Results from needle analysis from the control plots of 28 older (1953-1988) fertilization experiments in middle-aged to old Norway spruce stands on relatively nutrient poor soils in western Denmark also showed several cases with either low K/N or P/N-ratios (Lundberg and Ravnsbæk, 1992). Nutrient/N-ratios were calculated at the Klosterhede site and interpreted in Paper IV. For the control plot the P/N-ratio was at the level of optimum and the other nutrient/N-ratios were considerably above the optimum levels (more than 70 %) when compared to the threshold values given by Brække (1994) and Linder (1995).

A more advanced system for analyzing nutrient proportions in the foliage and/or soil is the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils, 1973). DRIS consider all nutrient concentration ratios in the foliage and/or soil along with various yield data and suggests: i) which nutrient is likely to be the most yield restricting, and ii) the order in which other nutrients are likely to limit the yield (Schutz and Villiers, 1987; Walworth and Sumner, 1987; Sumner, 1990). The calculations implied in DRIS are described in detail by Jones (1981), Letzch and Sumner (1984), Schutz and de Villiers (1987), Walworth and Sumner (1987) and Sumner (1990). DRIS was originally developed for agricultural crops as a system for recommendation of fertilizer application. Since the 1980's, the system has been experimentally applied to different tree species (Leech and Kim, 1981; Schutz and de Villiers, 1987; Alkoshab et al., 1988; Hockman and Allen, 1990; Shumway and Chappell, 1995; Romanyá and Vallejo, 1996). DRIS was proven to be a powerful tool for interpretation of the nutritional balances in the foliage. However, before DRIS can be made fully useful a large number of data from various stands with different nutritional status is required for establishing the basic norms used by DRIS (Letzch and Sumner, 1984). Alkoshab et al. (1988) found that DRIS failed in diagnosing some deficiencies, and they recommended that DRIS should be used as a supplement to the traditionally used deficiency threshold values to obtain the best conclusions regarding the nutritional status of the trees.

DRIS has not yet been applied to Danish forests. The Danish data material on the nutrient compositions of foliage may at present be considered too limited for establishing the basic DRIS norms necessary for an application of the system to Danish stands. The most serious lack in the Danish data material is that it does not contain result from repeated sampling during the growing season in different stands representing different age classes and locations.

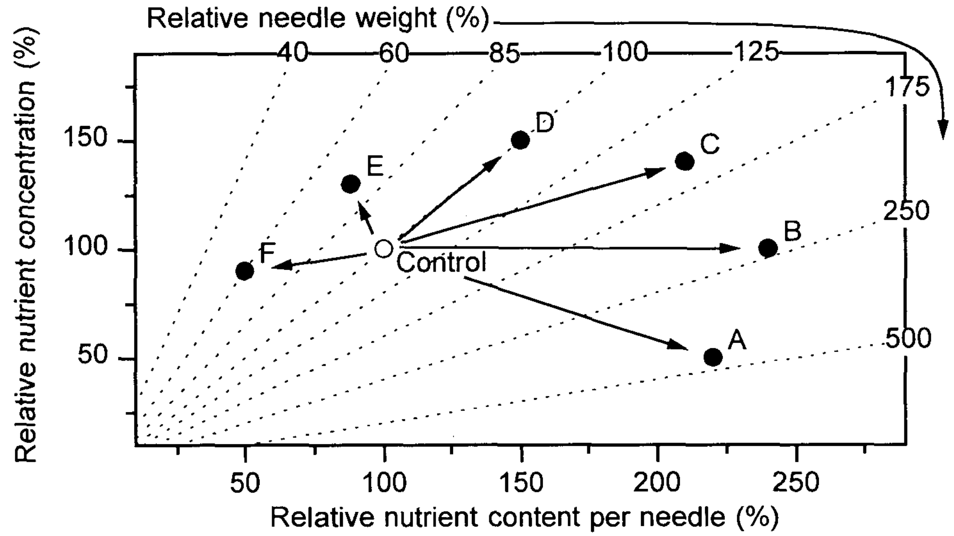
The concentration of N in the current year needles from the Klosterhede site indicated N deficiency which makes an interpretation of the nutrient/N-ratios difficult (Paper IV). However, the use of DRIS may be a way to overcome such interpretation problems in the future (when a sufficient amount of data is available for initiating DRIS) since DRIS interprets a larger number nutrient ratios.

2.5.3. Graphical vector analysis

Graphical vector analysis originates from agriculture and has been successfully used in evaluating the nutritional status and fertilization growth response potential in forest stands (Timmer and Stone, 1978; Timmer and Morrow, 1984; Weetman, 1989; Valentine and Allen, 1990; Rosengren-Brinck, 1994; Swift and Brockley, 1994; Brække, 1996; Brække et al., 1997; Thelin et al., in prep.). The idea underlying the method is to alter the nutrient supply in various ways by the use of different fertilization regimes and then draw conclusions concerning the nutritional status of the unfertilized stand by examining the growth and the fertilizer responses in the foliage. The method is thoroughly described by Timmer and Stone, (1978), Timmer and Morrow (1984) and Weetman (1989). It may also be used to assess the nutritional effects of forest management practice other than fertilization, such as thinning, irrigation, and removal of competing vegetation and brush (Timmer and Morrow, 1984; Weetman, 1989). The method relies on sampling of current year needles from the upper third of the tree, preferably lateral terminal shoots sampled at the end of the first growing season after treatment (Weetman, 1989). The vector analysis technique evaluates the fertilization induced changes in needle weight (weight of a fixed number of needles; 100-500), nutrient concentration and nutrient content per needle by applying the system presented in Fig. 2. The nutrient status of the control trees and the fertilization response potential are examined by interpreting the relative alterations of the nutrient composition in the needles from the fertilized trees compared to the control trees - examining the direction and magnitude of the response vectors illustrated in Fig. 2.

The vector analysis technique uses the needle weight as a relative measure of the biomass growth response, to reveal dilution effects and luxury consumption. A prerequisite for this method is therefore the existence of a correlation between the needle weight and the biomass growth response. This requirement seem to be met by *Abies*, *Picea*, *Pseudosuga*, and most *Pinus* species during the first growing season after treatment, where the fertilizer biomass growth response is reflected by the current year needle biomass and the number of the current year needles on the shoots is unaffected by the treatment; fixed in the buds before treatment (Timmer and Stone 1978; Timmer and Morrow, 1984; Weetman, 1989). However, this requirement is not necessarily met after more than one growing season after treatment because both the needle weight and the number of current year needles on the shoots can be affected by the treatment (Timmer and Stone, 1978). Weetman (1989) suggests that verification of the correlation between the needle weight and the fertilizer biomass growth response is carried out by additional measurement of leader and/or basal area growth in the years following treatment. Timmer and Morrow (1984) examined 8 fertilization trials in 28-year-old pine stands by use of vector analysis and by measuring the basal area increment during the years following treatment. Nitrogen deficiency was successfully detected and overcome by fertilization. In the first season current year needle weight was found to be closely correlated ($R^2 \geq 0.88$) to the basal area increment (during 6 years following treatment). Similar observations have been done in several other studies e.g. Keay et al. (1968), Weetman and Algar (1974), Timmer and Stone (1978) and Valentine and Allen (1990). It has therefore been suggested that the fertilizer biomass growth response within several years following treatment may be estimated with reasonable accuracy from initial foliage biomass growth response such as the current year needle weight measured after the first growing season after treatment (Timmer and Morrow, 1984).

A second prerequisite for the use of the graphical vector analysis method is that the stand is not subject to stress factors which interact seriously with the nutrient availability and/or determine the growth and needle weight during the test period such as for example drought episodes (Brække, 1996).



Direction of shift	Relative needle weight	Relative nutrient concentration	Relative nutrient content per needle	Interpretation	Possible Diagnosis
A	+	-	+	Dilution	Non limiting
B	+	0	+	Sufficiency	Non limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consumption	Non toxic
E	-	+	+ or -	Excess	Toxic
F	-	-	-	Excess	Antagonistic

Figure 2. *Interpretation of directional relationships between foliage concentration and absolute content of an element following fertilization (A-F) relative to the control (adapted from Timmer and Stone, 1978 and Timmer and Morrow, 1984). + and - indicates that the value of the response variable is increased or decreased respectively, and 0 indicates no significant response.*

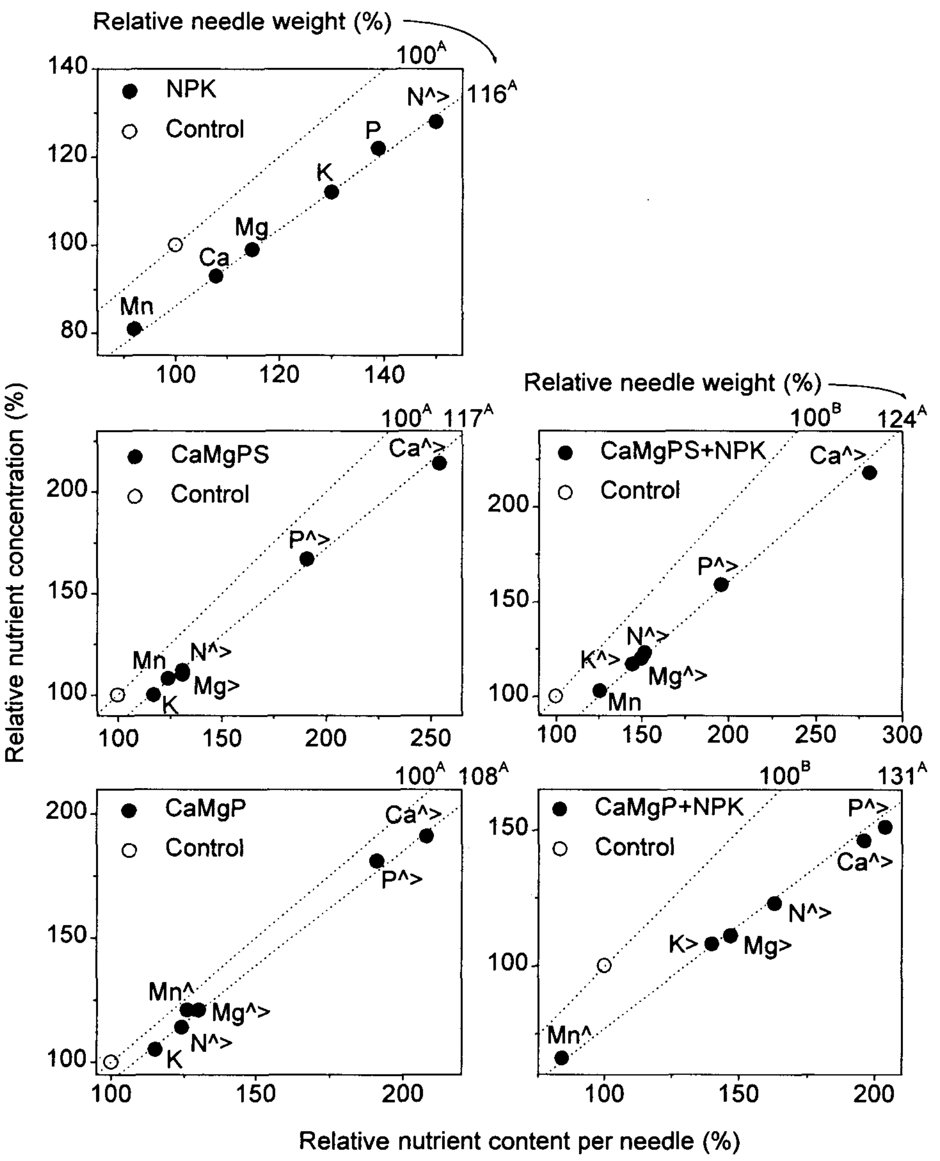


Figure 3. *Graphical vector analysis of needles from the Klosterhede site (Paper IV). Different capital letters denotes significant ($P \leq 0.05$) differences between the relative needle weights. > and ^ denotes that the relative nutrient content per needle or the relative nutrient concentration respectively is significantly ($P \leq 0.05$) different in the treated plot compared to the control. Note that the axes have different scales.*

A third and logic prerequisite is that the applied nutrients should be available for root uptake during the growing season preceding needle sampling, which is not always the case, since the dissolution rates of the applied fertilizer are strongly influenced by the current climate. Brække (1996) suggests that this problem can be solved by fertilizing in the autumn the year before needle sampling. However, this may introduce undesirable leaching of the applied nutrients from the root zone during the following winter (Paper I).

The graphical vector analysis method has the advantage of examining both the concentration and the nutrient content per needle and thereby taking into account both dilution effects and luxury uptake. Other diagnostic methods based only on the nutrient concentrations (e.g. use of diagnostic threshold values for nutrient concentrations) may misinterpret the fertilizer responses (Weetman, 1989). However, the graphical vector analysis method has the disadvantage of not directly examining the ratios and interrelations between the different nutrients and if more than one nutrient is deficient, the method does not directly rank the deficient nutrients. Furthermore, the graphical vector analysis does not provide information concerning the nutritional status of the fertilized trees such as deficiencies induced by the treatment. Brække (1996) gives an example of a N deficient spruce stand that became B deficient when the N deficiency was corrected by fertilization. Some of the mentioned disadvantages of the graphical vector analysis method may be more or less eliminated by combining the graphical vector analysis method with the use of diagnostic threshold values for nutrient concentrations and nutrient concentration ratios.

Valentine and Allen (1990) examined several fertilization experiments in N and/or P limited 9 to 14 years old loblolly pine stands by using different diagnostic methods. They made the following conclusions concerning the vector analysis method: i) The method did not give consistently more accurate nutrient limitation assessments compared to the use of diagnostic threshold values for nutrient concentrations; ii) The method should be limited to the element added (foliage responses of non-applied nutrients were found to have little relationship with the current deficiencies); and iii) The method may overestimate the number of limiting nutrients when the treatment contains several nutrients (the needle weight may increase in response to addition of the truly limiting nutrients but the concentration of other nutrients added may at the same time increase falsely indicating deficiency of these nutrients; shift C in Fig. 2).

Graphical vector analysis of current year needles sampled at the Klosterhede site in autumn 1995 (Paper IV) is presented in Fig. 3 with the major aim of illustrating this method, although the experimental design used at the Klosterhede site is not particularly suitable for vector analysis, since: i) no control plots were included at the time of establishment, ii) thorough chemical analysis of the needles was not carried out before autumn 1995 (two growing seasons after the last treatments in spring 1994 and 9 years after the first treatments were initiated), iii) all treatments contained several nutrients, and iv) both growing seasons after the last treatments and before the needle sampling were relatively dry. Thus caution should be taken by the interpretation of the results. In spite of the mentioned drawbacks, there seem to be an agreement between the needle weights (Fig. 3) and the biomass accumulation measured in Paper III in the four of the treatment plots at the Klosterhede site (Control, CaMgPS, CaMgPS+NPK and CaMgP+NPK). According to Fig. 2 and 3 the effect of the treatments on the nutrient composition of the needles can be ascribed to luxury consumption of the examined nutrients in the NPK, CaMgPS and CaMgP treated plots, because the needle weight was not affected significantly by these treatments. However, the needle weight was significantly increased in the CaMgPS+NPK and CaMgP+NPK treated plots (Fig. 3). When the graphical vector analysis was combined with the threshold values for nutrient concentrations given by Brække (1994) (Paper IV) the following conclusions were reached: i) The increased concentration and content per needle of Ca, Mg and K can be ascribed to luxury consumption. ii) The increased concentration and content per needle of N and P indicated that these nutrients were deficient and growth limiting in the control plot. It could not from the graphical vector analysis be determined which of these two nutrients that were growth limiting.

The graphical vector analysis method appears to be a strong tool for assessment of the nutritional status and the fertilization growth response potential, especially when combined with the use of threshold values for the foliage nutrient concentrations. However, the fact that drought episodes during the growing season often determines the growth of Norway spruce stands on nutrient poor soils in Denmark may make a sufficient water supply a serious prerequisite for the method that can not easily be met.

2.6. Sustainable forest management and input-output budgets

Investigations concerning the specific need for fertilization are often focused on diagnosing nutritional deficiencies and imbalances in the trees. However, in a long-term and in a system ecological perspective the stability and productivity of the forest ecosystem relies on the nutritional balance of input and output processes. The most important nutrient input processes are soil mineral weathering within the root zone, atmospheric deposition, and fertilization. The most important nutrient output processes are leaching and removal of biomass from the ecosystem. The forest ecosystem includes in this context the total biomass, humus layer, and forest soil layers within the root zone. The basic principle of a nutritionally sustainable forest ecosystem is that the nutrient inputs equal or exceed the outputs.

Danish forestry is at present in the process of establishment of a sustainable forest management practice (Ministry of Environment, 1994). An important part of this aim is to insure the long-term soil fertility (Larsen, 1995). Hence, the soil should have the ability of supporting stable and continued forestry: i) provide the trees with sufficient amounts of water and available nutrients to ensure a balanced and healthy nutrition, and ii) support a continuous biomass harvesting without risking a nutrient source drainage. Furthermore, the soil should have the ability to buffer soil acidification caused by biogeochemical processes in the soil and deposition of acidifying atmospheric N and S compounds.

Vejre (1995) discussed the nutritional sustainability of the Norway spruce ecosystems in western Denmark. He emphasized that the most important ecological problems in these stands are: i) the soils are relatively nutrient poor, ii) the water storage capacity in the soil is relatively poor, iii) the precipitation surplus mitigates nutrient leaching (mainly during winter time), iv) the current biomass harvest provides a serious threat to the continuous nutrient supply by depleting the nutrient sources, v) the mineral weathering rates are too slow to provide a substantial nutrient input compared to the outputs, and vi) an increasing amount of nutrients are immobilized in the humus layer due to a relatively low turnover rate. An increasing amount of N is thus being accumulated in the humus layer, which explains why the trees can be exposed to a relatively high atmospheric N deposition and still suffer from N deficiency (Paper IV). After clearcutting, the turnover rate of the humus layer is rapidly increased and potentially large amounts of nutrients may, during the first yeas, be leached from the forest ecosystem, because the remaining vegetation lacks the capability to take up the excess nutrients.

In a laboratory experiment Vejre (1995) investigated the nutrient release from weathering of soils from 22 Norway spruce stands in western Denmark. From input-output budget comparisons (deposition, leaching, nutrient uptake and nutrient export from biomass harvesting) Vejre (1995) concluded that in the future Ca and P deficiencies were likely to occur in most of the investigated stands, because the estimated outputs of these nutrients exceeded their inputs. Therefore, forest management should be changed towards a more nutritionally sustainable practice for example by changing tree species and/or biomass harvesting strategy. If the current growing and harvesting practice of Norway spruce stands on the nutrient poor soils in western Denmark is continued, then the application of additional nutrient inputs, e.g. via compensatory fertilization, is necessary in many stands in order to maintain a balanced nutrient input-output budget (Vejre, 1995). Similarly Pedersen and Beier (1996) found that the output of Ca was greater than the input in a 75-year-old Norway spruce stand at Klosterhede in western Denmark. This finding agreed with Vejre (1995), that Ca deficiency may appear in the future in Norway spruce stands on nutrient poor soils in western Denmark, even though the marine input is high in this part of the country. Input-output budgets have not been made for the Klosterhede site, since it is similar to that investigated by Pedersen and Beier (1996). However, at the Klosterhede site, Ca deficiency was not detected by means of diagnostic needle analysis within the examined period of time (Paper IV).

Monitoring of nutritional input-output budgets is the only long-term way to show that a given forest management practice is nutritionally sustainable. Such monitoring will at the same time naturally provide valuable information for implementation of fertilization strategies. The method and results from the measurements of the biomass and nutrient accumulation within the Klosterhede site (Paper III) may aid the establishment of input-output budgets in the future.

2.7. A dichotomous system for assessment of the need for fertilization and liming

A series of nutritional status parameters and some more general health indicators (needle loss and/or discoloration) has been compiled in a theoretical dichotomous system for assessment of the need for fertilization and liming (Fig. 4) (Liljelund et al., 1990). The dichotomous system aims at establishment of a balanced and sufficient tree nutrition and is not focused on increasing the growth rate. The system has the advantage of not recommending fertilization and liming in cases where an observed decline in tree health conditions is caused by other factors than nutritional disturbances and/or soil acidification. The system may thus act as a useful toll in practical decision making concerning forest fertilization and liming. However, practical application of the system in forest management demands intensive chemical soil and needle analysis.

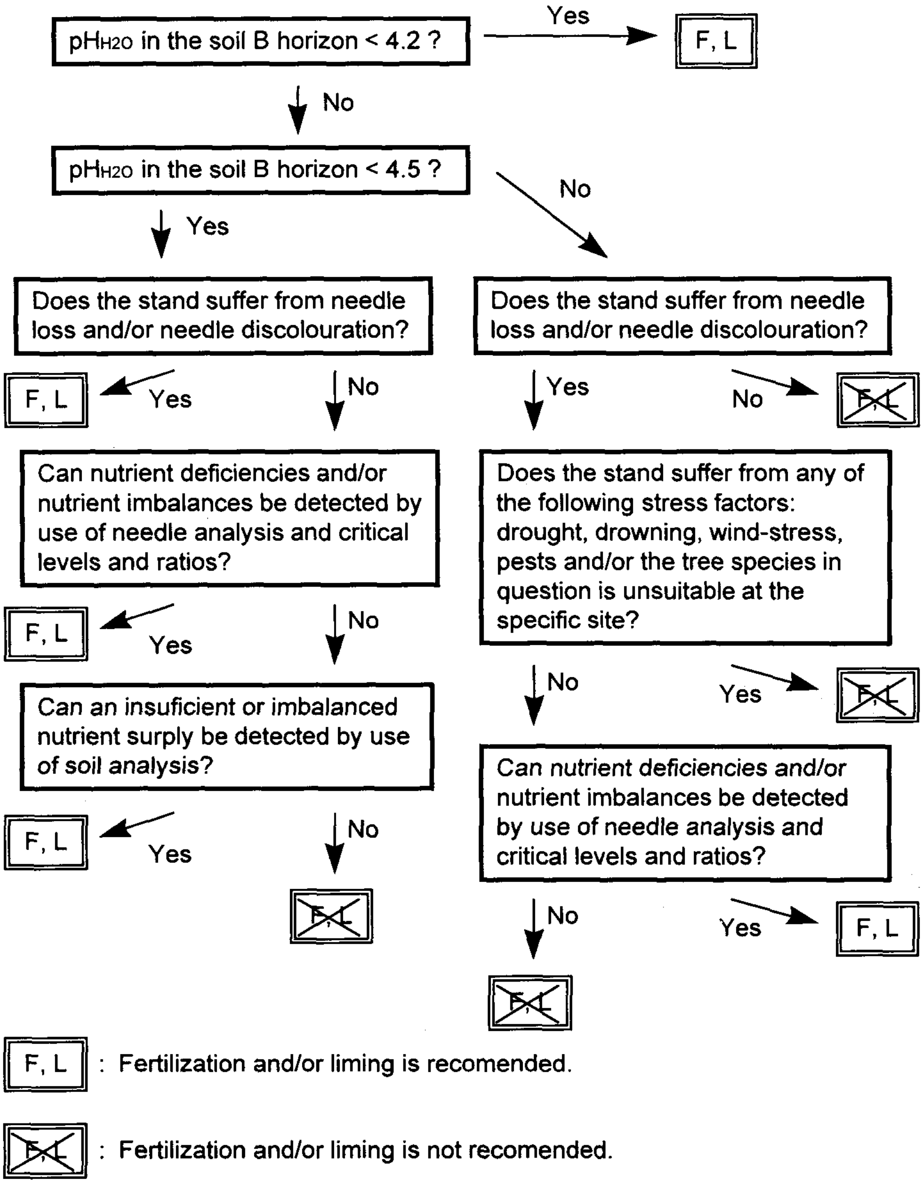


***Figure 4.** A dichotomous system for assessment of the need for fertilization and liming (Liljelund et al., 1990).*

At the Klosterhede site nutritional disorders involving both N and P have been documented. However, since other factors such as drought, sea salt deposition and the current tree species also restricts the growth rate and vitality at this site, fertilization and/or liming can not be unambiguously recommended according to Fig. 4. The water availability is probably the most growth rate and vitality restricting factor at the Klosterhede site. However, fertilization and liming may correct the nutritional disorders and thus limit the overall sum of the tree health restricting factors and enable the trees to withstand drought episodes that otherwise would be fatale.

3. Response to fertilization and liming - concluding recommendations

3.1. Soil and soil solution chemistry, and nutrient leaching

Research results from analysis of the chemical composition of soil and soil solution have proven that fertilization and liming can counteract soil acidification and increase the nutrient availability (Nihlgård and Popovic, 1984; Hallbäcken and Popovic, 1985; Derome et al., 1986; Huettl, 1988; Huettl and Zoettl, 1993; Abrahamsen, 1994; Katzensteiner et al. 1995; Kreutzer, 1995; Meiwes, 1995b; Staaf et al., 1996b; Traaen, et al., 1997; Paper I). In Sweden liming with more than 5 tons ha^{-1} calcite resulted in increased pH and base saturation of the soil, and a decreased Al concentration in the soil solution (Staaf et al., 1996b). This effect was also observed at the Klosterhede site (Paper I). Furthermore, these geochemical changes could be expected to last for a relatively long period of time (Staaf et al., 1996b). The positive and desired effects of fertilization and liming on the chemical composition of soil and soil solution are not further commented on in this chapter. However, fertilization and liming often involve subsequent undesired effects such as nutrient leaching, increased mineralization of organic matter and/or induction of deficiencies of nutrients other than those applied. It is at present difficult to predict how these effects, in the long term, are going to affect the health status of the trees, the forest ecosystem, and the ground water quality.

Increased leaching of nutrients by fertilization and liming was observed at the Klosterhede site (Fig. 5) (Paper I). All the treatments caused increased leaching of ions, although leaching of Mg^{2+}, Ca^{2+} and SO_4^{2-} from the kieserite and calcite treated plots was the most pronounced. The observed leaching of nutrients was presumably due to: i) solute movement of dissolved fertilizer or lime components, and ii) ion mobilization by ion exchange processes (the concentration of some ions, e.g. Na^+, are increased in the soil solution by ion exchange of ions adsorbed to the soil and ions from the dissolved fertilizer and/or lime components) (Paper I). Liming and fertilization with fast dissolving products and products containing easily dissolved and leachable anions (such as Cl^- and SO_4^{2-}) clearly resulted in alterations of the chemical composition of the soil solution, and leaching of notable amounts of essential nutrients (Fig. 5) (Paper I). Many of the treatments caused acidification of the soil solution and increased the concentrations of Al^{3+} in the soil solution. Similar observations of soil solution acidification and nutrient leaching caused by fertilization and liming were made by Nohrstedt (1992), Huettl and Zoettl (1993) and Ponette et al. (1997). Hence, in order to avoid nutrient leaching and soil solution acidification, the dissolution rate and chemical composition, particularly of anions, should be given great attention when products for fertilization and liming are chosen (Paper I). The dissolution rate is recommended to be of a magnitude that corresponds with the nutrient uptake rate of the trees.

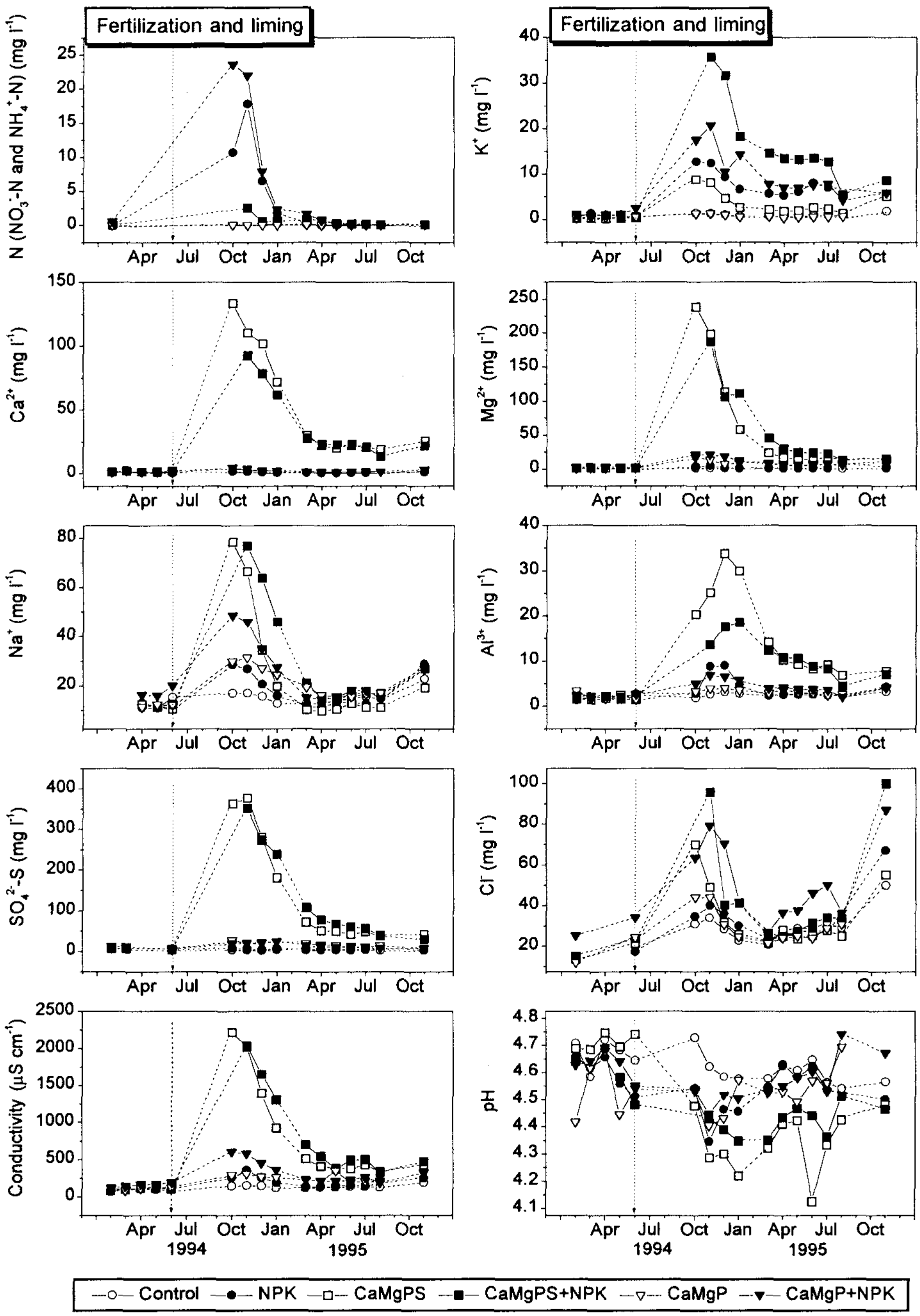


***Figure 5.** The concentration of N (NO_3^--N and NH_4^+-N), K^+, Ca^{2+}, Mg^{2+}, Na^+, Al^{3+}, SO_4^{2-}, Cl^-, and electric conductivity and pH in soil solution at the Klosterhede site from February 1994 to November 1995. Liming and fertilization were carried out in the beginning of June. Dashed lines indicate missing soil solution samples. (Paper I).*

Furthermore, it is recommended that the easily dissolved and leached anions are replaced by less easily leached anions such as PO_4^{3-} or CO_3^{2-}.

Lundberg and Ravnsbæk (1992) investigated the content of nutrients in the soil in a series of Danish fertilization experiments in middle-aged to old Norway spruce stands in western Denmark. They found that the K content in the humus layer was in general significantly decreased from the 1970's to the 1980's in the control and especially in the N applied plots. An increase in the K content in deeper soil horizons could not be detected and the decreased K content in the humus layer could not be explained by K sequestration in the trees. It was concluded that a large amount of K was leached from the forest ecosystem, presumably due to soil acidification and N input from deposition and fertilization.

Liming can increase the mineralization rate of the organic soil compounds and lead to mobilization of N due to increased microbial activity. The amount of mobilized N may subsequently reach levels that exceed the uptake rate of the plants and N leaching may be inevitable (Matzner, 1985; Katzensteiner et al., 1995; Kreutzer, 1995; Meiwes, 1995b; Staff et al., 1996a).

Results from Swedish experiments in spruce stands indicated that the growth response was related to the effect of liming on N mobilization (Staaf et al., 1996a). Liming was found to increase the N mobilization and leaching in soils with a high N content in stands with a high growth rate, whereas the N mobilization and leaching were not notably affected by liming on N poor soils in N limited stands (Staaf et al., 1996a). It was concluded that liming should be avoided on soils with a high N content in Skåne, Halland and Blekinge due to risk of increased N mobilization and leaching (Staaf et al., 1996a). Nilsen (1994) summarized the findings concerning the effects of liming on C and N mobilization in the humus layer in northern European fertilization experiments. He reported that if the C/N-ratio in the humus layer was relatively low (<30), then liming generally led to mobilization of N. However, if the C/N-ratio was relatively high (>30), liming led to immobilization of N. Also German experiments showed that the effect of liming on N leaching varied between different sites (Huettl; 1988; Katzensteiner et al., 1995; Kreutzer, 1995). Kreutzer (1995) discussed different site specific conditions which can influence the effect of liming on N mobilization, such as the C/N-ratio in the humus layer, humus type (mor or mull), N deposition, growth rate of the trees, development of the ground flora, and aeration of the soil. Results from soil and soil solution analysis at the Klosterhede site did not indicate increased mobilization of N within the first eight years of treatment in the limed plots, although the C/N-ratio in the O horizon was below 30 in all the investigated plots (Paper I).

Raulund-Rasmusen (1989) recommended the use of slow-reacting dolomite or limestone (dolomite) at small application rates to avoid increased mineralization. Liming should be carried out at times when the tree uptake is largest, and never within 15 years before clear cutting due to the generally increased risk of nutrient leaching after clear cutting (Raulund-Rasmusen, 1986; 1989). Nitrogen leaching involves leaching of cations in combination with NO_3^- (Reuss and Johnson, 1986; Raulund-Rasmussen, 1989). Therefore it was suggested that liming should be combined with additional fertilization with base cations such as K and Mg (if dolomite is not used) (Raulund-Rasmussen, 1986). If liming is to be carried out on nutrient poor soils in stands which suffer from nutrient deficiencies other than N deficiency, then liming combined with application of the deficient nutrients may have the advantage of balancing the forest nutrition, enabling the trees to take up the possible excess N, and thus counteracting the N leaching.

The availability of nutrients is closely correlated with the pH level in the soil. As liming affects the soil pH, the availability of several nutrients is subsequently affected. The availability of P, Mn, B, Cu and Zn can be restricted by the increased pH in limed forest soils. In Swedish forest liming experiments the availability of P, Mn and B was found to decrease in limed soils (Nihlgård and Popovic, 1984; Popovic and Andersson, 1984; Aronsson, 1985; Nihlgård et al., 1996). It is recommended that liming of stands with a low P, Mn, B, Cu and Zn status is thoroughly considered due to the risk of introducing deficiencies of one or more of these nutrients and liming may preferentially be combined with application of the lacking nutrients (Nihlgård and Popovic, 1984). Liming did not induce deficiency of any of the measured nutrients (N, P, K, Ca, Mg, Mn, Fe and S) at the Klosterhede site (Paper IV).

3.2. Growth response and nutrient status

Fertilization and/or liming, of forests with a declining health status in central Europe, has been shown to effectively counteract diagnosed deficiencies (primarily involving Mg, but also K, Ca, Mn and Zn) and soil acidification (Evers and Hüttl, 1990/91; Huettl and Zoettl, 1993; Katzensteiner et al., 1995; Meiwes, 1995a). The application of dolomite ($MgCa(CO_3)_2$) has especially appeared to improve the vitality and the nutrient status in the foliage, and increase the growth rate of trees suffering from Mg deficiency and soil acidification. However, in some of the German experiments the growth rate was not significantly affected by the altered nutrient supply (Evers and Hüttl, 1990/91; Nohrstedt, 1995).

The situation appears to be different in the Nordic countries where Nohrstedt (1995) has stated that results from fertilization and liming experiments indicated that the health status of Nordic stands is not as impaired by nutritional disorders and acidification of the soil as is the case in Central Europe. In general, fertilization and especially liming has so far not been shown to effectively improve the vitality and/or increase the growth rate of the trees in the Nordic countries, although some of the experiments have documented that the nutrient status in the foliage was improved by the treatments (Popovic and Andersson, 1984; Derome et al., 1986; Nohrstedt et al., 1996; Staff et al. 1996a; Andersson et al., 1997; Paper IV). However, some Swedish fertilization experiments, based on knowledge of the nutrient concentration in the needles and soil, improved the nutrient status in the needles and increased the growth rate of trees by application of the nutrients considered deficient (Rosengren-Brinck and Nihlgård, 1994; Linder, 1995). Binkley and Högberg (1997) concluded that Swedish forests, aside from those located in south-west Sweden, generally do not suffer from N deposition and that the majority of coniferous forests in Sweden still suffered from chronic N deficiency. They also concluded that the forest growth rate in Sweden has increased during recent decades, presumably due to increased deposition of N, and that there is no substantial evidence of a connection between this increased growth rate and a decrease in tree vitality. A large number of liming experiments conducted in Sweden and Finland have shown that liming can affect the growth rate in different ways and that this effect often is linked with N mobilization (discussed in the previous chapter) (Staff et al. 1996a).

Application of N has in some cases been found to increase the risk of relative deficiencies of nutrients apart from those applied such as K and micro-nutrients (Cu and B) (Holstener-Jørgensen and Lauritsen, 1983; Turvey and Grant, 1990; Lundberg and Ravnsbæk, 1992; Rosengren-Brinck and Nihlgård, 1994; Van den Driesche and Ponsford, 1995; Seith et al., 1996).

Conclusions and results from several Danish liming experiments have been evaluated by Matthesen, (1982). In general there seems to be a possibility that liming in plantations on former heathland stimulates growth. However, the experiments seemed to show that this effect is either of a rather short duration or of only modest extent. Matthesen (1982) stated that liming in Danish forests on former heathland was found to increase the amount of nutrients available to the plant in older Danish experiments. These conclusions were based on evaluation of the forest floor flora. The results indicated that liming had enhanced the decomposition of organic material in the soil and increased the mobilization of N. It was also stated that liming with exaggerated amounts of lime can lead to a decline in the growth rate (Matthesen, 1982)

Reviews of the growth responses in Danish fertilization experiments in Norway spruce stands have been presented by e.g. Lundberg and Ravnsbæk (1992), Dralle and Larsen (1995), Vejre (1995). In agreement with Huettl (1988), Vejre (1995) found that the growth response was dependent on the specific stand and site conditions in question. Lundberg and Ravnsbæk (1992) found that N fertilization gave a notably positive growth response in the 1960's, whereas continued N fertilization in the long-term gave no or a negative growth response. The negative growth response has been interpreted as N induced K deficiency (Lundberg and Ravnsbæk, 1992). Danish fertilization experiments, established in the late 1960's, showed that a positive growth response to N fertilization, at some locations, was dependent on simultaneous addition of P and/or K. Dralle and Larsen (1995) concluded that the initial assumption of N being the main limiting factor for tree growth no longer seemed valid and that this might be a result of the increased deposition of atmospheric N during the 1970's and 80's.

At the Klosterhede site the variation in year ring width between the different years clearly exceeds the variation between the treatments (Fig. 6). This may be due to inter-annual differences in the weather conditions, water supply etc. Even though the treatments combining liming with NPK fertilization were found to overcome the detected N and P deficiencies significantly (measured via diagnostic needle analysis in Paper IV), these treatments caused no statistically significant differences in stem growth increment and biomass accumulation (Paper I; III). However, the results indicated that these treatments increased the needle productivity, and the accumulation of above ground biomass, and decreased the defoliation (Paper IV), but these effects were apparently disturbed by considerable within plot variations and could not be proven to be statistically significant. The strongest effect observed was a growth rate reduction caused by the CaMgPS treatment during the first two growing seasons after the applications (Fig. 6). This reduction can presumably be ascribed to stress or even toxicity caused by the increased concentrations of Al^{3+} and SO_4^{2-}, and decreased pH in the soil solution (Paper I). The negative effect of the CaMgPS treatment seemed to be partly compensated by the addition of NPK fertilizer in the CaMgPS+NPK treatment.

This may be explained by Al^{3+} immobilization brought about by phosphorus from the relatively fast dissolving NPK fertilizer (Paper I).

There are various possible reasons for the lack of growth response to the nutritional manipulation: i) the trees do not suffer from severe growth limiting nutrient deficiencies or imbalances, but the growth rate is more restricted by other factors such as e.g. poor water supply, wind stress, fungal infestation or pests (Liljelund et al., 1990), ii) the stand is old and the nutrient supply to the currently growing parts of the trees is largely dependent on nutrient retranslocation rather than nutrient uptake (Miller, 1995), iii) the treatment may have overcome one or more deficiencies but at the same time created other growth limiting conditions (e.g. nutritional imbalances, nutrient deficiencies, impaired nutrient uptake and/or soil solution acidification), which was presumably the case for the CaMgPS treatment at the Klosterhede site (Paper I), and/or iv) only a small part of the applied nutrients are taken up by the trees due to a high leaching rate, a low solubility rate of the applied fertilizer and/or due to sequestrated of the applied nutrients in the ground vegetation or in the humus layer. The most pronounced effects of fertilization and liming should therefore be expected in young nutritional susceptible stands where diagnosed severe nutritional disorders restrict the growth rate and health status of the trees, and where other conditions such as e.g. wind stress or water availability may be of less importance compared to the nutritional disturbances.

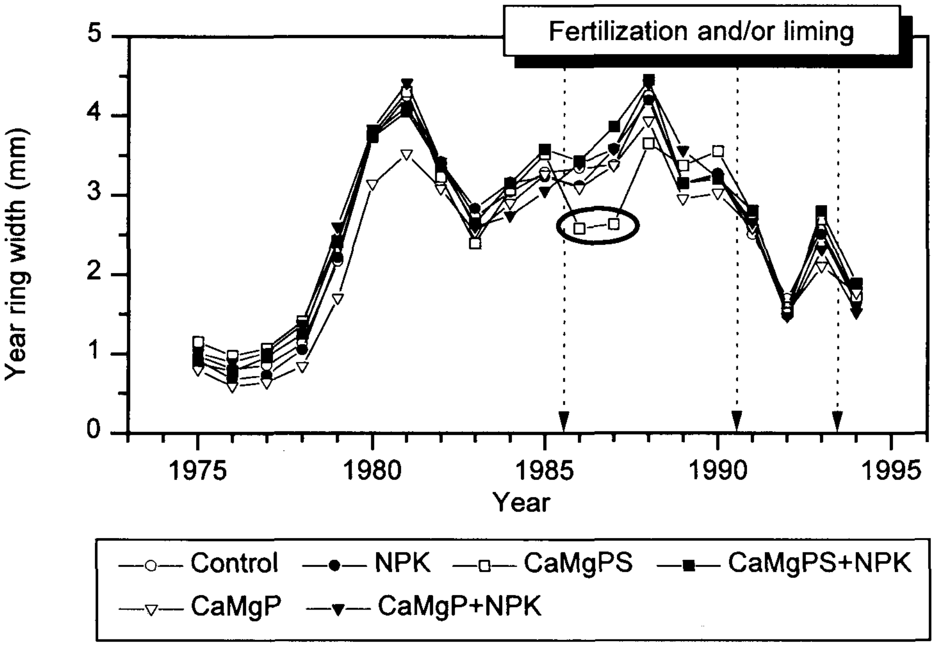


Figure 6. Year ring width from stem cores sampled in autumn 1994 at the Klosterhede site (Paper IV). The encircled observations denote a significant ($P \leq 0.05$) difference from the other treatments.

3.3. Liming and rot infestation

Heterobasidion annosum (formerly know as *Fomes annosus*) causes butt rot in coniferous stands. Economically, it is one of the most important fungi in coniferous forests. *Heterobasidion annosum* is spread via airborne spores or between trees via root contact. Stenlid and Bendz-Hellgren (1996) examined the effects of liming on *H. annosum* infestation in a series of Swedish liming experiments and reviewed several papers on the subject. In Sweden the frequency of *H. annosum* infestation was found to be generally higher on soils containing lime and having a relative high pH level (Stenlid and Bendz-Hellgren, 1996). However, a clear relation between the occurrence of lime and *H. annosum* infestation was not established. They concluded that liming can increase the risk for infestation of *H. annosum* in the long-term. Some of the Danish liming experiments have shown that liming can lead to an increased spread and infestation of *H. annosum* in plantations which have not already been severely attacked, but liming was found to have a minor effect on the spread and infestation of the fungus in plantations which were already infested (Matthesen, 1982).

At present there seem to be a relation between liming and an increased infestation of *H. annosum*. However, this relation has not been clearly established, and further investigations of different liming regimes are recommended before general advise for forest management can be given.

4. Vitality and vitality indicators

Tree vitality is defined by Liljelund et al. (1990) and Naturvårdsverket (1991) as the ability to withstand stress and maintain a healthy and natural life cycle. A vital forest is according to Naturvårdsverket (1991) characterized by: i) the trees can tolerate air pollution and other external stress factors, ii) the damages caused by fungi and pests are limited, iii) the soil has the ability to support a stable forest production in the long-term, iv) the soil is non-toxic to living organisms, and v) the leaching of nutrients in runoff is limited. The ability to a support high stem volume production is thus not necessarily the same as being vital (Liljelund et al., 1990, Helmisaari, 1997). Examination of the Klosterhede site has been mostly focused on examining the vitality of the trees (Paper IV). However, the vitality concept covers the whole forest ecosystem. This fact should be kept in mind when fertilization and liming strategies are considered, since such actions affect the whole forest ecosystem (Paper I). Vitality fertilization is defined as nutrient and/or lime application with the purpose of counteracting both nutritional disorders of the trees and acidification of the soil in the long-term (Liljelund et al., 1990). In the perspective of forest management, vitality fertilization aims at sustaining a stable basis for the continuation of a healthy forest production (Liljelund et al., 1990).

The definitions given above appear closely linked to the concept of sustainable forest management, and the concept of sustainability is likely to consume the vitality concept in the future. The vitality concept will then appear as a part of the overall concept of sustainability rather than appearing as an independent concept.

Vitality indicators provided for the trees can be separated into two classes: i) "general vitality indicators", which provide information concerning the general health status without diagnosing the specific cause of a decline in health status (e.g. needle loss, needle discoloration, accumulation of carbohydrates, needle productivity, "the index of vigour" and growth increment), and ii) "diagnostic vitality indicators" which provide information concerning a specific presumed vitality restricting parameter that acts as a prerequisite for a vital tree (e.g. diagnostic needle analysis, the Ca/Al-molar-ratio in the soil solution and examination of the soil conditions, water supply, wind stress, fungal infestation insect attack etc.). Since terms such as vitality and vitality indicators covers a large area of parameters, these terms need to be defined in the context in which they are used (Nilsson et al., 1995).

The different diagnostic vitality indicators only concern individual prerequisites for a vital tree. Hence, diagnostic vitality indicators may indicate good vitality in cases where the general vitality is clearly impaired. A simple vitality indicator which takes into account the different nutritional disorders is not easily established. However, it is recommended that several diagnostic vitality indicators may be used at the same time to give a better characterization of the vitality (Paper IV). At present the key diagnostic vitality indicators concerning nutritional disorders and soil acidification in Norway spruce stands on nutrient poor soils in western Denmark are: i) diagnostic needle analysis of N, P and K, ii) P/N and K/N-ratios in the needles, iii) base saturation of the soil, iii) Ca/Al-molar-ratio in the soil solution, iv) N-leaching, and v) water availability.

The various vitality indicators may not be able to provide a highly sensitive graduation system which will be suitable for different stand conditions (e.g. geographical location, climatic condition and stand age). However, a reliable and generally usable measuring technique for assessment of tree vitality may be provided by: i) examining parameters that have been documented to be connected with nutritional disturbances or acidic soil conditions, and ii) only classifying trees which have "low vitality" in cases where sever nutritional problems or the acidity of the soil can clearly be considered limiting to the tree vitality (e.g. Ca/Al-molar-ratio in the soil solution < 0.1, the nutrient concentration or nutrient/N-ratio in the foliage shows sever deficiency or imbalance). The Norway spruce stands in Germany in which sever Mg deficiency has been documented to impair tree vitality and growth can, according to this strategy, be taken as an example of stands which should be classified as having "low vitality".

The key diagnostic vitality indicators may change over time because the forest ecosystem is continuously influenced by changing conditions such as e.g. deposition of air pollution components, climate and forest management practice. An example is the above mentioned diagnostic needle analysis of Ca, which is likely to become a key diagnostic vitality indicator in Denmark in the future, if the existing forest management practice regarding Norway spruce plantations in western Denmark is not changed (Vejre, 1995; Pedersen and Beier, 1996).

The fertilization and liming experiment at the Klosterhede site concerned nutritional disorders, soil acidification and possible counteractions. Hence, the examined diagnostic vitality indicators were aimed at clarifying these nutritional problems (Paper IV). Results from the current year needles in the control plot indicated N and P deficiencies when compared to the deficiency threshold values given by Brække (1994). However, the results did not show that the trees were suffering severely from these nutrient deficiencies. Some of the treatments increased the concentration of N and P in the current year needles significantly to a level above deficiency (Paper IV). However, the examined general vitality indicators (defoliation, "index of vigour", needle productivity, needle discoloration, presence of cones, stem volume increment and accumulation of above ground biomass) did not reflect the improvement of the nutrient status in the current year needles significantly (Paper IV). None of the examined trees could be classified as having “low vitality” due to sever nutritional disorders.

5. Concluding remarks

It has been shown in several studies that nutritional disorders, mainly involving N, P and K and soil acidification, may impair the vitality of the Norway spruce plantations in western Denmark. Soil and needle analyses have shown that soil acidity, nutrient availability and tree nutrient status vary between the different stands in western Denmark and general conclusions on which of the mentioned nutrients is the most growth and vitality restricting is not possible to draw. In spite of this, most Danish fertilization experiments have been established without a preceding analysis of the tree nutrient status. Since the need for fertilization and liming obviously differs between various localities, *it is recommended that soil analysis and a diagnostic analysis of the* nutritional status in the trees is carried out to verify the specific need for fertilization and liming at each locality that applications are being considered for. In Sweden, Liljelund et al. (1990) recommend a national and regional survey of the nutrient status of forest trees. Taking into account the lack of information on the nutritional status of forest trees in western Denmark, such a survey is also recommended in Denmark as a usable tool for investigation of the current nutritional status in the trees and the possible need for vitality fertilization. The need for fertilization and liming is likely to change with time as the forest ecosystems is continuously influenced by changing conditions such as deposition of air pollution compounds, climate, forest management practice etc. In Denmark, several fertilization experiments have indicated an effect of increased deposition of air pollution components (mainly N) on the nutritional status of the trees without actually examining the nutritional status. A national survey could reflect these specific effects on the nutritional status of the trees by repeating the diagnostic analysis over time.

Diagnostic needle analysis combined with the use of graphical vector analysis appear to be a suitable and powerful tool for both diagnosing deficiencies, nutritional changes over time and estimating fertilization growth responses.

At the Klosterhede site a diagnostic analysis of the nutritional status of the trees and the acidity of the soil was not carried out prior to establishment of the trial. Such an analysis could have revealed the potential N and P deficiencies and indicated a need for liming at an earlier stage. Thereby a better fertilization and liming strategy could have been applied, focusing more directly on removing the nutrient deficiencies and counteracting the soil acidification, and the application of the harmful kieserite could have been avoided.

Fertilization experiments have documented that the nutritional status of the trees can be manipulated and deficiencies overcome with respect to the nutrient concentration in the foliage. However, this may not necessarily be reflected by increased stem volume increment and/or biomass accumulation. Seen from a forest management point of view, vitality fertilization may thus not in the short-term appear as being economically profitable. However, vitality fertilization may prove profitable in the long-term, since balanced nutrition may enable the trees to withstand stress factors that could otherwise turn out to be lethal.

Even though the input of N through deposition of air pollution compounds is high, N deficiency occur, probably because the incoming N is accumulated in the humus layer without becoming available to the trees. Hence, N fertilization may be required to improve the vitality of the N deficient trees. In cases where N deficiency occurs together with other nutrient deficiencies (e.g. P and K), N fertilization combined with application of other nutrients may turn out to be required to insure a balanced nutrient uptake. Liming and/or application of nutrients apart from N may have the advantage of increasing the N mobilization in the humus layer and subsequently increase the N uptake in the N deficient trees. However, this strategy imply the risk of increasing the N leaching if the mobilization of N exceeds the rate of uptake.

The present study have emphasized the importance of considerations concerning the chemical composition and dissolution rate of available fertilizers before application. To avoid unnecessary nutrient leaching, the dissolution rate should equal the rate of uptake and easily dissolved and leached anions (such as Cl^- and SO_4^{2-}) should be avoided.

Forest management in western Denmark is currently in a phase of change from the traditionally managed Norway spruce plantations to a more sustainable management strategy. This will undoubtedly include changes to other coniferous and broad-leaved species. From this perspective the topic of this dissertation may at first appear to be of decreasing relevance. However, Norway spruce plantations will continue to be present in this area of Denmark for many years to come and N will still accumulate in the forest soils. Consequently nutritional problems in Norway spruce stands will still have to be solved.

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PAPER I

Effects of liming and fertilization on growth, soil chemistry and soil water chemistry in a Norway spruce plantation on a nutrient poor soil in Denmark

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Effects of liming and fertilization on growth, soil chemistry and soil water chemistry in a Norway spruce plantation on a nutrient-poor soil in Denmark

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Abstract

During recent years indications of nutritional imbalances in coniferous forest ecosystems have become more common in southern Scandinavia and central Europe. Deposition of acidifying substances, and relative deficiencies of nutrients, and soil acidification are supposed to be important contributing factors in the picture of forest damage. The need for counteractions such as liming and fertilization is thus pressing. A combined liming and fertilization trial was performed in a 59-year-old Norway spruce stand on a nutrient-poor soil at Klosterhede, Denmark. Two types of lime (calcite and dolomite combined with additional kieserite and phosphorus) were applied alone and in combination with conventional NPK fertilizer to form five different treatments. The treatments were carried out in 1986 and in 1994. All the treatments led to significantly increased leaching of ions from the soil within the first 8 months after treatment. Combined calcite and kieserite applications induced acidification pushes in the first period after the treatments. The magnitude of these changes varied strongly according to the different treatments. The alteration of the chemical composition of the soil water seemed to peak within 8 months following the treatments and it was largely eradicated 8 years after establishment of the trial, and 3 years following the last NPK fertilization. The desired geochemical changes of the soil solid phase regarding the counteraction of acidification were achieved in the upper horizons of limed plots (decreased exchangeable acidity (AC) and concentration of exchangeable Al^{3+}, and increased concentration of exchangeable Ca^{2+} and Mg^{2+}, base saturation (BS), cation exchange capacity (CEC) and pH_{H_2O}). Results from the O horizons (N and C concentration, C/N ratio and horizon thickness) indicate that mobilization of nitrogen did not increase notably within the first 8 years of treatment in the limed plots, even though the pH_{H_2O} in the O horizon of the limed plots was increased and the C/N ratio was below 30. The various treatments caused no significant differences in growth increment. The strongest effect observed was a growth rate reduction caused by application of kieserite and calcite. This reduction can presumably be ascribed to stress or even toxicity caused by the increased concentrations of Al^{3+} and SO_4^{2-}, and decreased levels of pH in the soil water in the first period after the treatment.

Keywords: Liming; Fertilization; Soil water; Acidification; Soil chemistry; Norway spruce

1. Introduction

Air pollution and the subsequent deposition of acidifying substances such as nitrogen and sulphur compounds have enhanced the acidification of forest soils. This acidification can result in an imbalance in the nutrient supply and increasing aluminium toxicity, leading to reduced health conditions for the

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forest trees on nutrient-poor soils (e.g. Ulrich, 1983; Evers and Hüttl, 1990/91).

Revitalization by liming and fertilization has been a success at many locations in Germany (Evers and Hüttl, 1990/91; Huettl and Zoettl, 1993; Meiwes, 1995). The positive effects of the treatments on the forest health condition in Germany have been most pronounced when dolomite has been applied in stands suffering from soil acidification and magnesium deficiency. Therefore, the application of dolomite to declining forests suffering from air pollution, soil acidification or an imbalance in the nutrient supply has become common practice in many areas of Germany (Meiwes, 1995).

In Sweden, a large number of experiments concerning liming and fertilization have been carried out in forests with the purpose of revealing positive or negative ecological effects of various treatments (Hallbäcken and Popovic, 1985; Andersson and Persson, 1988). Some areas, especially in south-west Sweden, are found to be acidified to the extent that liming is recommended (Warfvinge et al., 1993). Decreased growth has been observed in periods of 10–20 years, as a result of liming conducted on nitrogen-poor soils. This has been explained by a decrease in the net nitrogen mineralization caused by liming. However, a period of depressed growth may be followed by a long-lasting period of increased growth (Andersson and Persson, 1988).

Similar soil amelioration experiments have been performed in Norway (summarized by Nielsen, 1994a,b) and in Finland (summarized by Derome et al., 1986). In Finland, liming has been found to increase the amount of organic matter in the humus layer. Accordingly, the amount of organic matter is decreased in the mineral layers. The annual growth was furthermore found to decrease in limed plots. This decrease in growth was avoided when additional nitrogen was applied.

Ongoing acidification of Danish forest soils has been documented by Rasmussen and Hansen (1992), Rasmussen (1988) and Pedersen (1993). Rasmussen (1988) concluded that approximately 60% of the total acidification of different forest ecosystems was caused by air pollution, in relation to acidification caused by forest management and natural biological processes. Pedersen (1993) reached a similar conclusion. He found that 40–65% of the total acidification in the forests in question was caused by air pollution. The extent of forest soil acidification in Denmark has proved to be most serious on the nutrient-poor soils with low acid neutralizing capacity (Rasmussen, 1988; Raulund-Rasmussen, 1989). Counteractions on nutrient-poor sites such as liming and fertilization have been widely discussed, but so far without any general decision for forest management practice. However, due to the supply of magnesium from the sea in Denmark, the problem of magnesium deficiency, even on nutrient-poor sandy soils, is of little concern. Long-term investigations on forest soils in western Denmark do, however, indicate that deficiencies of potassium and to some extent phosphorus may be expected (Lundberg and Ravnsbæk, 1992; Clausen, 1995; Dralle and Larsen, 1995; Pedersen and Bille-Hansen, 1995). Since the atmospheric deposition of nitrogen is 20–40 kg ha^{-1} year^{-1} in this part of the country, it should be more than sufficient to cover the demands of the trees (Pedersen, 1993). However, a major part of the nitrogen input to the forest may be immobilized in the organic layer of the soil and thus be unavailable for the trees (Rasmussen and Hansen, 1992). Liming of Danish forest soils has traditionally been very limited because of the risk of increasing butt rot infestation (Matthesen, 1982). The present knowledge of the effects of soil amelioration in Danish forests is thus limited.

The purpose of this study was to investigate the effects of liming and fertilization on the soil solid phase, soil water and tree growth on a nutrient-poor soil in a Norway spruce stand at Klosterhede in western Denmark.

2. Materials and methods

2.1. Site description

The research site is located at Klosterheden State Forest in western Jutland, Denmark (8°27′E, 56°27′N), 20 km from the North Sea. The site is at 33 m above sea level. The topography is flat, and the parent material consists of glacio-fluvial sand. An organic layer (mor humus) of approximately 10 cm covers the mineral soil. The soil is well drained and classified as a haplic podzol (FAO, 1977). The soil is nutrient poor and consists mainly of coarse sand with low clay content (generally less than 10%). The soil was ploughed prior to planting of the trees. The annual precipitation is 860 mm, only a small percentage of which falls as snow. Annual mean temperature is 9°C, with a mean January temperature of 0.3°C and a mean July temperature of 16°C. Westerly winds from the North Sea, often strong, dominate. Thus throughfall and soil water chemistry is dominated by high inputs of sea salt. The total deposition of nitrogen is approximately 25 kg N ha^{-1} $year^{-1}$ (55% NH_4^+ and 45% NO_3^-) and the deposition of sulphur from sources other than the sea is approximately 25 kg S ha^{-1} $year^{-1}$ (Gundersen and Rasmussen, 1995). The research site is located in a Norway spruce plantation with a stand density of 800 trees ha^{-1}. The stand is even-aged, 59 years old from seed (in 1995) and the average height is 16 m and the stem volume is 225 m^3 ha^{-1}. The stand is second generation after heathland. The trees are planted in rows, and managed for wood production. The stand had been fertilized twice with NPK fertilizers (1977, 1982; see Pretreatment in Table 1) before the trial was established since NPK fertilization has been common practice for Norway plantations in this area of Denmark.

2.2. Treatments and experimental design

The trial was established in 1986 with various combinations of conventional NPK fertilizer, two different liming treatments (calcite and dolomite) and additional phosphorus and sulphur (Table 1). The study includes five different treatment plots repeated in three blocks. The treatments are listed in Table 1. Each plot is 0.15 ha and contains approximately 120 trees. The NPK fertilization was repeated again in 1991 in all the plots where NPK was applied in 1986 (NPK, CaMgPS + NPK, CaMgP + NPK), but this time with a fertilizer with a different chemical composition compared with that used in 1986 (Table 1). The liming and fertilization carried out in 1986 was repeated early in June 1994 (Table 1). Until 1994 the trial contained no true control plots, since the whole forest has been fertilized with NPK fertilizers. However, one earlier NPK-fertilized plot was included as a control plot when the treatments were repeated in spring 1994 for the purpose of investigating the geochemical changes of the soil water, during the period of treatment. Before 1994, this control plot was fertilized with NPK fertilizers in 1986 and 1991 parallel to the NPK-treated plots (Table 1).

Table 1
Applied amounts of nutrients (kg ha^{-1}) in the different treatments. Note that different types of NPK fertilizers have been applied

	Year	N	P	K	Ca	Mg	S	Applications
Pretreatment								
All plots	1977	120	15	35	–	–	–	NPK—23:3:7 [a]
All plots	1982	120	33	80	35	6.7	–	NPK—18:5:12 [a] (incl. Mg, Cu and B)
Treatment								
Control	1986	120	31	140	43	8.5	37	NPK—14:4:17 [a] (incl. Mg, Cu and B)
	1991	120	15	34	40	8.3	21	NPK—23:3:7 [a] (incl. Mg, Cu and B)
NPK	1986, 1994	120	31	140	43	8.5	37	NPK—14:4:17 [a] (incl. Mg, Cu and B)
	1991	120	15	34	40	8.3	21	NPK—23:3:7 [a] (incl. Mg, Cu and B)
CaMgPS	1986, 1994	–	200	–	1710	730	1150	Calcite [b], kieserite [c], 'superphosphate'
CaMgPS + NPK	1986, 1994	120	230	140	1750	740	1190	Combination of NPK and CaMgPS
	1991	120	15	34	40	8.3	21	NPK—23:3:7 [a] (incl. Mg, Cu and B)
CaMgP	1986, 1994	–	200	–	1720	730	–	Dolomite [d], 'raw phosphate'
CaMgP + NPK	1986, 1994	120	230	140	1760	740	37	Combination of NPK and CaMgP
	1991	120	15	34	40	8.3	21	NPK—23:3:7 [a] (incl. Mg, Cu and B)

[a] Conventional agricultural NPK fertilizer containing approximately 50% NO_3^- and 50% NH_4^+.
[b] $CaCO_3$.
[c] $MgSO_4$.
[d] $CaMg(CO_3)_2$.

2.3. Monitoring programme

Basal area, average tree height and stem volume were estimated in spring 1986, 1991 and 1994 from measurements of the diameter at breast height of all the trees, and the tree height of 30 trees per plot. Growth increment was then calculated for all 18 plots for the periods: 1986–91 and 1991–94.

Chemical analyses of soil water and soil solid phase were performed in one block. Soil samples were collected from five pits in each plot in spring 1994, 8 years after the first treatment and just before liming and fertilization was repeated. The upper five pedological horizons (O, A, AE, Bh and Bhs) were sampled in all five pits and the lower three horizons (Bs, BC and C) were sampled in one pit per plot. The A and AE horizons were for practical reasons sampled representatively as one horizon. For each plot, equal amounts (on weight basis) of soil samples from the same horizons but from the five different pits were pooled to form the samples (one per horizon) that were used for chemical analyses. The soil samples were dried at 55°C, sieved (2 mm) and mixed thoroughly before the chemical analyses were carried out. The soil samples were extracted with $BaCl_2$ (0.1 M) (the method is described in UNEP and UN/ECE, 1992) and analysed for exchangeable cations: K^+ and Na^+ by flame emission spectrometry and Ca^{2+}, Mg^{2+}, Al^{3+}, Mn^{2+} and Fe^{3+} by atomic absorption spectrometry. Exchangeable acidity (AC), base saturation (BS) and cation exchange capacity (CEC) were determined at soil pH according to UNEP and UN/ECE (1992). The soil samples were analysed for C and N concentration by a LECO CHN-analyzer.

Soil water samples were sampled each month with five samplers (type: PRENART; pore size: 5–10 μm; material: poly(tetrafluoroethene)/glass) per treatment plot in one block. The soil water was sucked through the sampling cups by continuous suction during each sampling month. Detailed descriptions of samplers and sampling technique are given by Beier et al. (1992). The samplers were installed in the Bs horizon at 45 cm depth in the mineral soil. The soil water samplers were installed in between the tree rows in such a way that they had approximately the same distance (1.5 m) to the two nearest trees. In order to avoid microbial activity during the sampling period, collecting bottles were kept cool and dark in thermo-boxes in soil pits. The soil water samples were analysed for: Cl^-, NO_3^- and SO_4^{2-} by high performance liquid chromatography (ion chromatography), Ca^{2+}, Mg^{2+} and Al^{3+} by atomic absorption spectrometry, K^+ and Na^+ by flame emission spectrometry, NH_4^+ and P by continuous flow colorimetry, pH and electric conductivity. Statistical tests were performed using analysis of variance (SAS system: PROC ANOVA and PROC GLM).

3. Results

3.1. Soil

The results from the chemical analyses of soil samples collected in spring 1994, 8 years after the first treatment and just before liming and fertilization was repeated, are presented in Table 2. The replicated experimental design was not used when soil chemistry was measured. Also the soil sampling method used in this study did not provide information about the variation within the plots. Therefore, the data presented in Table 2 cannot be used to provide statistical evidence for the conclusions, but only to indicate if the soil chemistry will be altered by the treatments and to give an idea as to which chemical processes might have been involved in these alterations. Liming (CaMgPS, CaMgPS + NPK, CaMgP and CaMgP + NPK) increased CEC, BS, pH_{H_2O} and the concentration of exchangeable Ca^{2+} and Mg^{2+}, and decreased AC and the concentration of exchangeable Al^{3+} in the upper horizons (most pronounced in the O horizons) compared with the NPK-treated plot. The concentration of exchangeable Mg^{2+} seemed to increase more under the dolomite liming (CaMgP, CaMgP + NPK) than under the kieserite (CaMgPS and CaMgSP + NPK) treatment. Horizons below approximately 35 cm (under the Bhs horizon) were not notably affected by the different treatments. The combination of liming and NPK fertilization (CaMgPS + NPK and CaMgP + NPK) seemed to have decreased the concentration of exchangeable K^+ in the O horizon compared with

Table 2

Chemical characteristics of the different soil horizons in the various treatments 8 years after establishment of the trial and just before fertilization and liming was repeated. Exchangeable cations (cmol + kg^{-1}), pH_{H_2O}, exchangeable acidity (AC, cmol + kg^{-1}), cation exchange capacity (CEC, cmol + kg^{-1}), base saturation (BS, %), C and N concentration (g kg^{-1}) and C/N ratio on weight basis (g g^{-1}). Note that the A and AE horizons for practical reasons have been representatively sampled as one horizon

Horizons	Depth (cm)	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	Mn^{2+}	Fe^{3+}	pH_{H2O}	AC	CEC	BS	C	N	C/N
NPK															
O	−9–0	1.31	1.03	6.91	4.46	2.01	0.05	0.51	3.65	6.54	20.25	68	478.7	18.73	25.6
A + AE	0–11	0.08	0.08	0.12	0.13	0.95	0.00	0.20	4.04	2.15	2.57	16	24.0	0.43	55.7
Bh	11–15	0.07	0.14	0.12	0.15	10.41	0.00	1.06	3.91	11.16	11.64	4	65.4	2.09	31.3
Bhs	15–30	0.03	0.05	0.05	0.03	4.18	0.00	0.20	4.47	3.80	3.97	4	27.8	0.80	34.8
Bs	30–56	0.01	0.01	0.01	0.00	0.29	0.00	0.02	4.87	0.44	0.46	5	2.06	0	–
CaMgPS															
O	−9–0	1.20	1.06	49.15	7.24	0.07	0.17	0.03	4.76	1.38	60.03	98	437.2	17.54	24.9
A + AE	0–12	0.04	0.06	0.68	0.24	1.02	0.00	0.14	4.21	2.14	3.16	32	24.3	0.35	69.5
Bh	12–15	0.05	0.22	1.44	0.70	7.30	0.00	0.86	4.09	8.38	10.79	22	62.3	2.08	29.9
Bhs	15–39	0.03	0.05	0.08	0.06	3.19	0.00	0.11	4.66	2.91	3.13	7	20.5	0.65	31.5
Bs	39–62	0.01	0.00	0.01	0.00	0.32	0.00	0.01	4.9	0.55	0.56	3	2.6	0	–
CaMgPS + NPK															
O	−10–0	0.90	1.09	41.99	7.34	0.20	0.09	0.08	4.21	1.80	53.12	97	441.7	16.10	27.4
A + AE	0–9	0.04	0.09	0.68	0.48	1.20	0.00	0.28	4.01	2.84	4.13	31	32.33	0.75	43.1
Bh	9–12	0.05	0.13	1.08	0.48	6.23	0.00	0.89	3.97	7.54	9.28	19	54.76	1.90	28.8
Bhs	12–30	0.02	0.09	0.09	0.07	2.91	0.00	0.11	4.65	3.03	3.30	8	27.9	0.92	30.4
Bs	30–48	0.01	0.01	0.00	0.00	0.38	0.00	0.01	4.78	0.68	0.70	3	2.55	0	–
CaMgP															
O	−9–0	1.25	1.08	30.06	22.21	0.09	0.07	0.02	4.55	2.10	56.71	96	427.4	14.77	28.9
A + AE	0–13	0.04	0.06	0.18	0.38	2.13	0.00	0.23	4.02	3.22	3.88	17	31.0	0.74	41.9
Bh	13–17	0.06	0.15	0.17	0.38	10.11	0.00	0.94	4.01	11.37	12.13	6	69.2	2.35	29.4
Bhs	17–33	0.03	0.07	0.04	0.06	3.56	0.00	0.15	4.52	3.82	4.02	5	34.34	1.14	30.3
Bs	33–55	0.01	0.01	0.01	0.01	0.40	0.00	0.03	4.67	0.80	0.84	4	4.48	0	–
CaMgP + NPK															
O	−10–0	0.71	1.18	31.24	20.98	0.12	0.14	0.06	4.64	2.28	56.39	96	447.7	17.06	26.2
A + AE	0–13	0.03	0.06	0.22	0.41	1.33	0.00	0.10	4.17	2.88	3.60	20	31.3	0.58	54.0
Bh	13–17	0.05	0.14	0.18	0.45	9.70	0.00	0.89	4.06	11.39	12.20	7	76.6	2.46	31.1
Bhs	17–36	0.02	0.06	0.22	0.06	2.78	0.00	0.06	4.51	3.19	3.55	10	27.7	0.93	29.8
Bs	36–57	0.02	0.01	0.01	0.00	0.27	0.00	0.01	4.91	0.64	0.68	5	1.9	0	–

the NPK, CaMgPS and CaMgP treatments. The concentrations of exchangeable Mn^{2+} and Na^+ were generally unaffected by the different treatments. Liming (CaMgPS, CaMgPS + NPK, CaMgP and CaMgP + NPK) decreased the concentration of exchangeable Fe^{3+}, most pronounced in the O horizons. The CEC, BS, AC and the concentration of exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} did not change notably by application of NPK fertilizer to either the CaMgPS or CaMgP treatments. The N and C concentrations, the C/N ratio and the thickness of the O horizons were not notably affected by the different treatments.

3.2. Soil water

The concentrations of SO_4^{2-}, Mg^{2+} and Ca^{2+} are presented in Fig. 1 and the electric conductivity, the concentration of Al^{3+} and pH are presented in Fig. 2. The five different soil water samples from each plot are not 'true' replicates but pseudoreplicates in the sense that the replicated experimental design was only used for tree growth measurements and not for soil chemistry. The statistical handling of the soil water concentrations is focused on the situation before and after treatment. Restricted interpretations of the results have been made accordingly. Results from the analyses of soil water from each soil water sampler were pooled (average values were calculated) for the two periods: (a) before the period of treatment in spring 1994 (February–June) and (b) after the period of treatment in autumn 1994 (October–January). A statistical *t*-test (five samplers per plot, $n = 5$) was performed for each chemical element and the two periods to reveal if differences between treated plots and the control plot were significant. The results from these tests are presented in Table 3. The statistical test was performed on logarithmic transformed data for all variables except pH. This was done to obtain homogeneity of the variance.

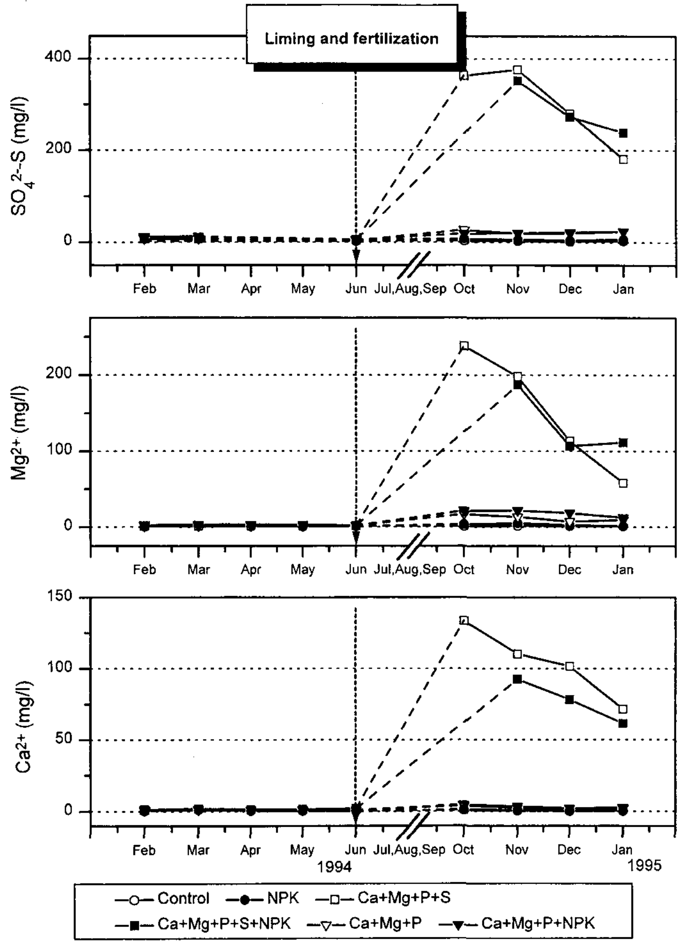

Fig. 1. The concentration of SO_4^{2-}, Mg^{2+} and Ca^{2+} in soil water from February 1994 to January 1995 (five soil water samplers per treatment plot in one block, $n = 5$). Liming and fertilization was carried out in the beginning of June. Note that the *x*-axis is broken at "Jul, Aug, Sep" due to lack of soil water in these dry months. Dashed lines indicate missing soil water samples.

Chemical analyses of soil water samples from February–June 1994, 8 years after the first treatments (preceding the last liming and fertilization in 1994), only revealed minor differences between the different treatments (Figs. 1 and 2, and Table 3). Generally the concentrations of Ca^+ and Mg^{2+} seemed to be higher in all limed plots (CaMgPS, CaMgPS + NPK, CaMgP and CaMgP + NPK) compared with the control plot. This finding was, however, only significant for Ca^{2+} in the case of kieserite and calcite application (CaMgPS and CaMgPS + NPK) (Table 3). The other differences observed for the period before repetition of the treatments can presumably be ascribed to natural variations.

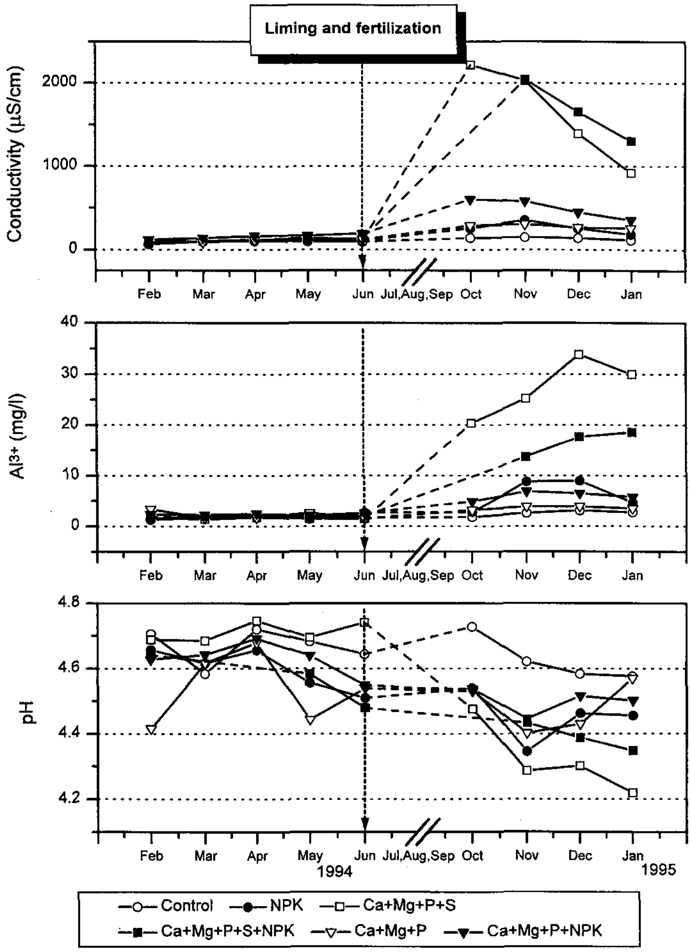

Fig. 2. Electric conductivity, Al^{3+} and pH in soil water from February 1994 to January 1995 (five soil water samplers per treatment plot in one block, $n = 5$). Liming and fertilization was carried out in the beginning of June. Note that the x-axis is broken at "Jul, Aug, Sep" due to lack of soil water in these dry months. Dashed lines indicate missing soil water samples.

Table 3

Average concentration of soil water before and after liming and fertilization in spring 1994. Results from the analysis of soil water from each lysimeter have been pooled (average values were calculated) for the two periods: (a) before the time of treatment in February–June 1994 and (b) after the time of treatment October–January 1994/95. Bold type indicates that the concentration is significantly ($P \geq 0.05$) different from that of the control plot in the period in question (five lysimeters per plot, $n = 5$). No statistical analysis of the SO_4^{2-} concentration has been performed in the period before liming because of too few data

Treatment	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	K^+ (mg l^{-1})	Al^{3+} (mg l^{-1})	SO_4^{2-}-S (mg l^{-1})	NO_3^--N (mg l^{-1})	NH_4^+-N (mg l^{-1})	P (mg l^{-1})	pH	Conductivity (μS cm^{-1})
Before liming and fertilization: January–June 1994										
Control	0.87	0.93	0.63	1.61	–	0.01	0.00	0.000	4.66	93
NPK	0.59	**0.59**	0.80	1.57	–	0.01	0.01	0.000	4.62	85
CaMgPS	**1.60**	1.41	0.28	1.60	–	0.01	0.00	0.000	4.70	101
CaMgPS + NPK	**1.56**	1.16	0.60	1.78	–	0.18	0.01	0.000	4.64	98
CaMgP	1.38	1.30	0.47	**2.96**	–	0.01	0.00	0.000	4.44	129
CaMgP + NPK	1.09	**2.87**	0.95	2.20	–	**0.58**	0.00	0.000	4.64	**145**
After liming and fertilization: October 1994–January 1995										
Control	0.46	1.21	1.10	2.67	2.56	0.01	0.03	0.000	4.62	136
NPK	0.80	2.86	**9.46**	**6.01**	**6.44**	**8.34**	0.37	0.000	4.47	**248**
CaMgPS	**101**	**148**	**6.46**	**27.3**	**296**	0.06	0.03	0.000	**4.30**	**1608**
CaMgPS + NPK	**73.9**	**122**	**31.1**	**16.5**	**256**	0.74	0.14	0.000	**4.37**	**1569**
CaMgP	**3.09**	**11.5**	1.13	3.84	**23.8**	0.01	0.02	0.018	4.46	**299**
CaMgP + NPK	**2.94**	**18.5**	**15.2**	**5.82**	**21.2**	**13.0**	**0.53**	0.004	4.50	**483**

In contrast with analyses of soil water sampled in the periods before repetition of the treatments, soil water sampled in the following period gave different results according to the different treatments (Figs. 1 and 2, and Table 3). The concentration of Ca^+ and Mg^{2+} increased significantly in all limed plots (CaMgPS, CaMgPS + NPK, CaMgP and CaMgP + NPK) in comparison with the control plot (Fig. 1 and Table 3). All treatments caused significantly increased leaching of ions illustrated by the increasing conductivity during the time following the treatment (Fig. 2 and Table 3). At this location the ions are leached by percolating soil water in the period from October to April. Also leaching of SO_4^{2-} was increased significantly in all the treated plots (Fig. 1 and Table 3) in comparison with the control plot. The concentration of K^+ was significantly increased in all plots with NPK fertilizer. The CaMgPS treatment also resulted in significantly increased concentrations of K^+. All the treatments resulted in increased concentrations of Al^{3+} (Fig. 2 and Table 3). However, this was not significant for the CaMgP treatment (Table 3). pH decreased significantly in plots treated with kieserite and calcite (CaMgPS and CaMgPS + NPK). NO_3^- leaching increased in all plots treated with NPK fertilizer. This was significant for the NPK and CaMgP + NPK treatments. The concentrations of NH_4^+ and P were generally unaffected by the different treatments. The most drastic changes in the chemical composition of the soil water were obviously in plots treated with kieserite and calcite (CaMgPS and CaMgPS + NPK) (increased concentrations of Ca^+, Mg^{2+}, Al^{3+} and SO_4^{2-}, increased conductivity and decreased pH).

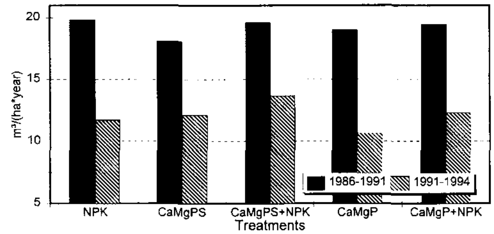

Fig. 3. Stem volume increment in two periods after the establishment of the trial (five plots in three blocks, $n = 3$).

3.3. Growth increment

The differences in stem volume growth between the different treatments were not statistically significant (Fig. 3). The strongest effect observed during the first period was a growth rate reduction caused by the CaMgPS treatment. In the second period (1991–1994) no similar growth response was observed.

4. Discussion

4.1. Soil

The desired geochemical changes regarding the counteraction of acidification were only achieved in the upper horizons of the limed plots. Similar geochemical changes caused by liming have also been reported by Hallbäcken and Popovic (1985) in Sweden, Derome et al. (1986) in Finland and, amongst others, Kreutzer (1995) and Huettl and Zoettl (1993) in Germany. Furthermore, these authors stated that the effect could be expected to last for a period of 20–25 years or more. Many of the treatment-induced changes were presumably caused by ion exchange processes. These changes were most pronounced in the O and Bh horizons where the CEC was highest. CEC was increased almost three fold in the O horizons when lime (CaMgPS, CaMgPS + NPK, CaMgP and CaMgP + NPK) was applied. This increase in CEC caused by liming has also been observed by Hallbäcken and Popovic (1985) in Sweden, Derome et al. (1986) in Finland and Huettl and Zoettl (1993) in Germany. This effect of liming is often ascribed to an increasing amount of organic matter capable of acting as an ion exchange complex in the humus layer. CEC in the O horizon is normally elevated when pH is elevated due to proton dissociation from the carboxylic acids. The condition (N and C concentration, C/N ratio and horizon thickness) of the O horizons seems not to be affected by the different treatments. Nielsen (1994b) summarized the findings concerning the effect on carbon and nitrogen mobilization in the humus layer caused by liming in a large number of liming experiments in northern Europe. It was stated that when pH values increased due to liming, the amount of carbon and nitrogen available to the microorganisms also increased. If the C/N ratio was relatively low (< 30), then liming would lead to mobilization of nitrogen because of increased microbial activity. However, if the C/N ratio was relatively high (> 30), liming would lead to immobilization of nitrogen. The C/N ratios in the O horizons of the treated plots in this study were below 30, which suggests that liming would lead to mobilization of nitrogen. However, the results listed in Table 2 indicate that the microbial activity and thus the mobilization of nitrogen have not been increased notably within the first 8 years of treatment in the limed plots, even though the pH_{H_2O} in the O horizons of the limed plots was increased.

4.2. Soil water

One of the negative effects of all the treatments was increased leaching and loss of essential nutrients. This leaching can presumably be ascribed to: (a) solute movement of dissolved components from the applied lime and fertilizers and (b) ion mobilization by ion exchange processes. The relatively quickly dissolving calcite and kieserite (CaMgPS and CaMgPS + NPK) changed the chemical composition of the soil water drastically. The high concentration of Ca^{2+} and Mg^{2+} in the soil water caused by fast dissolution of kieserite and calcite (CaMgPS and CaMgPS + NPK) presumably led to ion exchange processes, where Ca^{2+} and Mg^{2+} from the soil water exchanged with cations such as K^+, Na^+, Al^{3+} and H^+, resulting in increased concentrations of these ions in the soil water. In the CaMgPS-treated plot, the Al^{3+} concentration reached levels considered to reduce growth of Norway spruce seedlings (Eldhuset and Göransson, 1988), whereas the other treatments had a more moderate effect on the Al^{3+} concentration. Increased leaching of SO_4^{2-} caused by fast dissolution of kieserite (CaMgPS and CaMgPS + NPK) implied an identical equivalent increase in cation leaching. Notable amounts of essential nutrients were lost in the CaMgPS- and CaMgPS + NPK-treated plots. Fertilization on nutrient-poor soils with materials containing easily leached anions such as SO_4^{2-} and Cl^- has the undesirable effect of increasing the leaching of essential nutrients (base cations), but, on the other hand, it also increases the leaching of detrimental acidic cations such as Al^{3+} and H^+. Leaching of Mg^{2+} together with SO_4^{2-} presumably explains why the concentration of exchangeable Mg^{2+} is lower in the upper horizons of CaMgPS- and CaMgSP + NPK-treated plots than in the CaMgP- and CaMgP + NPK-treated plots.

Combined calcite and kieserite application (CaMgPS and CaMgPS + NPK) introduced acidification episodes. Similar acidification episodes introduced by liming and fertilization have been reported from Germany, e.g. Huettl and Zoettl (1993), and Sweden, e.g. Nohrstedt (1992). The CaMgPS + NPK treatment changed the chemical composition of the soil water in a similar manner to the CaMgPS treatment. However, the additional NPK fertilization seemed to have restricted the acidification and the increase in the Al^{3+} concentration. This may be caused by Al^{3+} immobilization brought about by phosphorus from the relatively fast-dissolving NPK fertilizer. The leaching of ions caused by the CaMgP and CaMgP + NPK treatments was relatively small compared with the CaMgPS and CaMgPS + NPK treatments. This was probably due to the leaching of large amounts of SO_4^{2-} from the applied kieserite (CaMgPS and CaMgPS + NPK) (as described earlier) and the relatively slow dissolution rate of the applied dolomite (CaMgP and CaMgP + NPK). It seemed as if the additional NPK fertilization in the CaMgP + NPK treatment enhanced the Al^{3+} concentration more than the CaMgP treatment. This might be due to the fact that the CaMgP + NPK treatment increased the ion strength of the soil water and subsequently the magnitude of ion exchange processes more than the CaMgP treatment. The alteration of the chemical composition of the soil water induced by the different treatments seemed to have peaked within 8 months. It was largely eradicated within 8 years after establishment of the trial, and 3 years following the last NPK fertilization.

4.3. Growth increment

Fertilization trials conducted in Denmark in the 1950s and 60s in Norway spruce plantations suggested that stem volume increment could be expected to increase by 3–4 m^3 (ha^{-1} $year^{-1}$) measured over a 5-year period, when NPK (120 kg N ha^{-1}) fertilizers were applied on nutrient-poor soils every fifth year (Lundberg and Ravnsbæk, 1992). Nitrogen was at that time assumed to be the main limiting factor for tree growth in western Denmark. Later research work from the 1970s and 80s has shown that these expectations could not be fulfilled. NPK (120 kg N ha^{-1}) fertilization applied every fifth year only increased the stem volume increment by 0.76 m^3 (ha^{-1} $year^{-1}$) measured over a 10-year period after the first fertilization had been carried out in this area of Denmark (Dralle and Larsen, 1995). They concluded that the assumption of nitrogen being the main limiting factor for tree growth no longer seemed valid and that this might be a result of the increased nitrogen deposition during the 1970s and 80s. These results also indicated that other nutrients such as potassium and phosphorus might be the main growth-limiting nutrients at present.

The fact that none of the treatments in this study had any significant effect on the stem volume increment indicates that this stand does not suffer from severe deficiency of any of the applied nutrients. Otherwise, the nutrients may be immobilized immediately before the trees are capable of taking them up. Another explanation for the poor growth response to the treatments may be the old age of the trees (according to Danish conditions). Old trees probably retranslocate larger amounts of nutrients in comparison with the amounts taken up from the soil.

The observed reduced stem volume increment in the CaMgPS-treated plots may be ascribed to stress or even toxicity caused by the increased concentrations of Al^{3+} and SO_4^{2-}, accompanied by decreased pH. The negative effect of the CaMgPS treatment seemed to be partly compensated by the addition of NPK fertilizer in the CaMgPS + NPK treatment.

5. Conclusion

The desired geochemical changes of the soil solid phase regarding the counteraction of acidification were only achieved in the upper horizons of the limed plots (increased concentration of exchangeable Ca^{2+} and Mg^{2+}, CEC, BS and pH_{H_2O}, and decreased AC and concentration of exchangeable Al^{3+}).

All the treatments caused increased leaching of ions. Liming and fertilization with fast-dissolving products and products containing easily dissolved and leached anions (such as Cl^- and SO_4^{2-}) clearly resulted in alterations of the chemical composition of the soil water, and leaching and loss of notable amounts of essential nutrients. The dissolution rate and chemical composition, with special respect to anions, should be given great attention when products for fertilization and liming are chosen. Many of the treatments caused acidification and increased concentrations of Al^{3+} in the soil water.

The various treatments caused no significant differences in growth increment. The strongest effect observed was a growth rate reduction caused by application of kieserite and calcite. This reduction can presumably be ascribed to stress or even toxicity caused by the high concentrations of Al^{3+} and SO_4^{2-}, and low levels of pH induced by the treatment.

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PAPER II

Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (*Picea abies*) plantation

Part I. Nutrient concentrations

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Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (*Picea abies*) plantation

Part I. Nutrient concentrations

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Abstract. The spatial variation in the concentration of various plant nutrients in the above ground biomass was examined in a fertilized and limed 59-year-old Norway spruce stand on a nutrient poor soil at Klosterhede, western Denmark. Two types of lime (calcite and dolomite combined with additional kieserite and phosphate) were applied alone and in combination with conventional NPK fertilizer to form five different treatments. Sample trees of different size classes were felled and the nutrient concentrations of N, P, K, Ca, Mg and S were analyzed at various heights from ground level, dividing the biomass in seven compartments (stem wood, stem bark, living branches, dead branches, current year needles, older needles and cones). The nutrient concentrations were generally highest in the actively growing parts of the trees (e.g. needles and stem bark). The concentrations of N, P, K and S were generally higher in current year needles than in older needles, whereas the opposite pattern was observed for the concentration of Mg and Ca. The concentrations of N, P, S and Ca were increased by the treatments, most pronounced in the actively growing parts of the trees. However, the concentration of K and Mg seemed unaffected by the treatments. When N and P were applied, the concentrations in the current year needles were elevated to levels that could be considered above deficiency in all parts of the canopy. The tree size did not affect the nutrient concentration.

Keywords: fertilization, liming, nutrient concentration, nutrient distribution, Norway spruce, *Picea abies.*

1. Introduction

From the beginning of this century and until the 1970's, the main aim of fertilization in Danish forests was to increase production measured in stem volume growth. Since then the aim have changed to revitalization of forests which have lost vitality due to air pollution, forest management, and subsequent imbalanced forest nutrition (Dralle and Larsen, 1995).

It has been shown that soil acidification and imbalanced forest nutrition can be counteracted by liming and fertilization of nutrient poor soils in Norway spruce stands at many locations in Sweden (Rosengren-Brinck, 1994; Svenson et al., 1995) and Germany (Huettl and Zoettl, 1993; Meiwes, 1995). Especially in Germany, fertilization and liming have counteracted ongoing acidification and improved the nutrient status measured by needle analyses (Evers and Hüttl, 1990/91). Before amelioration practices suited for Danish conditions can be achieved it is essential to define and be able to measure parameters such as tree nutrient uptake and status, nutritional imbalance, and nutrient deficiency. Furthermore, it is essential to know the effects of fertilization and liming on these parameters.

The paper focuses on the effect of different fertilization and liming treatments on the concentration of plant nutrients in various parts of the above ground biomass. The spatial variation in the concentration of various nutrients within the canopy in needles, living branches, stem wood and bark is examined. The distribution and accumulation of biomass and nutrient pools were calculated and examined in Ingerslev and Hallbäcken (1997a) (Part II).

2. Materials and methods

2.1. Site description

The research site was located at Klosterhede State Forest, close to Lemvig, in western Jutland, Denmark (8°27'E, 56°27'N), 20 km from the North Sea. The soil was a well drained haplic podzol (FAO, 1977) developed on a glacio-fluvial deposit. It was nutrient poor and consisted of coarse sand with a low clay content (less than 2 %). The site was ploughed prior to the planting of the trees. There was an organic layer (mor humus) of approx. 10 cm. Further details on soil and soil solution chemistry are given by Ingerslev (1997). The annual precipitation was 860 mm. Annual mean temperature was 9 °C, with a mean January temperature of 0.3 °C and a mean July temperature of 16 °C. Westerly winds from the North Sea, often strong, dominated. Thus throughfall and soil water chemistry was dominated by high inputs of sea salt. Total atmospheric deposition of nitrogen was estimated to approx. 25 kg N ha^{-1} year^{-1} (55 % as NH_4^+ and 45 % as NO_3^-) (Gundersen and Rasmussen, 1995).

The research site was located in a Norway spruce (*Picea abies*) plantation, second generation after heathland. The stand was even-aged, 60 years old from seed (in 1996) with a stand density of 800 trees per ha, the average height was 16 m, and the stem volume was 225 m^3 ha^{-1}, stem volume increment varied from 10 to 20 m^3 ha^{-1} year^{-1}. The trees were planted in rows, and managed for wood production by thinning every 3-5 year since c. 1955 (c. 20-35 m^3 ha^{-1} per thinning). The latest thinnings were carried out just before the trial was established in 1986 and before treatment in 1991.

2.2. Treatments and experimental design

Before the experimental trial was established in 1986, the whole stand had been fertilized twice with NPK fertilizers in 1977 and 1982 (Table 1), as part of common management practice in this forest. The trial was established with various combinations of conventional NPK fertilizer, two different liming treatments (calcite and dolomite), and additional phosphorus and sulphur (Table 1). The study included five different treatments repeated in three blocks (A, B and C) (Table 1). Each plot was 0.15 ha and contained approx. 120 trees. In spring 1991 the NPK fertilization was repeated (NPK, CaMgPS+NPK and CaMgP+NPK). However, the NPK fertilizer used in 1991 had a different chemical composition (23:3:7) compared to that used in 1986 (14:4:17) (Table 1). The 1986-treatments were repeated early in June 1994 (Table 1). Until 1994 the trial contained no true control plots since the whole plantation had been fertilized. Three earlier NPK fertilized plots were included as control plots (one in each block, adjacent to the original trial) when the treatments were repeated in spring 1994.

Table 1. *Applied amounts of nutrients in the different treatments. Note that different types of NPK fertilizers have been applied.*

		N	P	K	Ca	Mg	S	Applications
				Kg ha^{-1}				
Pretreatment	Year							
All plots	1977	120	15	35	-	-	-	NPK-23:3:7^a
All plots	1982	120	33	80	35	7	-	NPK-18:5:12^a (incl.: Mg, Cu and B)
Treatment	Year							
Control	1986	120	31	140	43	9	37	NPK-14:4:17^a (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
NPK	1986, 1994	120	31	140	43	9	37	NPK-14:4:17^a (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
CaMgPS	1986, 1994	-	200	-	1710	730	1150	Calcite^b, kieserite^c, 'superphosphate'
CaMgPS+NPK	1986, 1994	120	230	140	1750	740	1190	Combination of NPK and CaMgPS
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
CaMgP	1986, 1994	-	200	-	1720	730	-	Dolomite^d, 'rock-phosphate'
CaMgP+NPK	1986, 1994	120	230	140	1760	740	37	Combination of NPK and CaMgP
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)

a: conventional agricultural NPK fertilizer containing approximately 50 % NO_3^-, 50 % NH_4^+, Cl<2 %, and K as a mixture of KCl and K_2SO_4.
b: $CaCO_3$.
c: $MgSO_4$.
d: $CaMg(CO_3)_2$.

Examination of the stem volume increment was carried out in all plots in a previous study by Ingerslev (1997). Whereas a thorough investigation of chemical parameters was confined to one block (block A). Examination of soil and soil solution chemistry is given by Ingerslev (1997).

2.3. Measurement of the nutrient concentration in the above ground biomass

In autumn 1995 five trees representing different tree sizes were felled in four plots (control, CaMgPS, CaMgPS+NPK and CaMgP+NPK) in order to determine the nutrient concentration in different compartments of the above ground biomass (current year needles (C0), older needles (C1-Cn), living branches, dead branches, stem wood, stem bark (dead and living bark) and cones). A detailed description of the sampling and chemical analysis is given by Ingerslev and Halbäcken (1997a) (part II).

The nutrient concentration was only determined in four plots in one block, which made it impossible to make statistical tests using true replicates. However, in the cases where the tree size did not affect the nutrient concentration, statistical testes were made using the five sampling trees from each plot as replicates. The effect of the treatments, sampling height, and tree size was evaluated using analysis of variance (SAS, PROC GLM). Differences were considered significant at the $P \leq 0.05$ level unless otherwise stated.

3. Results

The N, P, K, Mg and S concentrations were lowest in the stem wood (and in the dead branches for K) (Table 2) and highest in the needles (Fig. 1). The concentration of Ca was lowest in the stem wood and, especially, in the cones, and highest in the stem bark (Table 2) and needles (Fig 1, j and k). Stem bark, living branches and dead branches had intermediate concentrations of N, P, Ca, Mg and S compared to the needles and stem wood (Table 2 and Fig. 1).

The N concentration in the current year needles (C0) increased with height in the control and CaMgPS treated plots and it was significantly higher (15-20 %) in the lower and middle part of the canopy for the plots applied N compared to the control plot (whereas there were no significant treatment effects in the upper part of the canopy) (Fig. 1, a). Similar treatment effects were observed for the older needles (C1-Cn) (Fig. 1, b), although not as pronounced as in the current year needles. The concentration of N in the stem bark was significantly 20-60 % higher in the canopy than at breast height for all the plots (Table 2).

The concentration of P in the current year needles (C0) and older needles (C1-Cn) responded to the P application in a way similar to that of N in the current year needles (Fig. 1, d and e). The P concentration in stem bark in the canopy increased 50-70 % ($P \leq 0.05$) after P application compared to the control plot and the P concentration in the stem bark within the canopy was 40-80 % higher ($P \leq 0.05$) than at breast height for all the plots (Table 2).

The K concentration was not affected by the various treatments and there was no spatial variation with respect to the height of sampling position (Fig. 1, g-i and Table 2).

The Ca concentration in the current and older needles, living branches and stem bark was generally higher (5-250 %) for the Ca applied plots at all sampling heights compared to the control plot (Fig. 1, j-l and Table 2), although the difference was only significant for the living branches, current year needles from the lower and middle part of the canopy in the CaMgPS+NPK treated plot, and for the older needles from the CaMgPS and CaMgPS+NPK treated plots. The Ca concentration in the current and older needles, living branches and stem bark apparently decreased towards the top of the tree (Fig. 1, j-l and Table 2), though this was not significant.

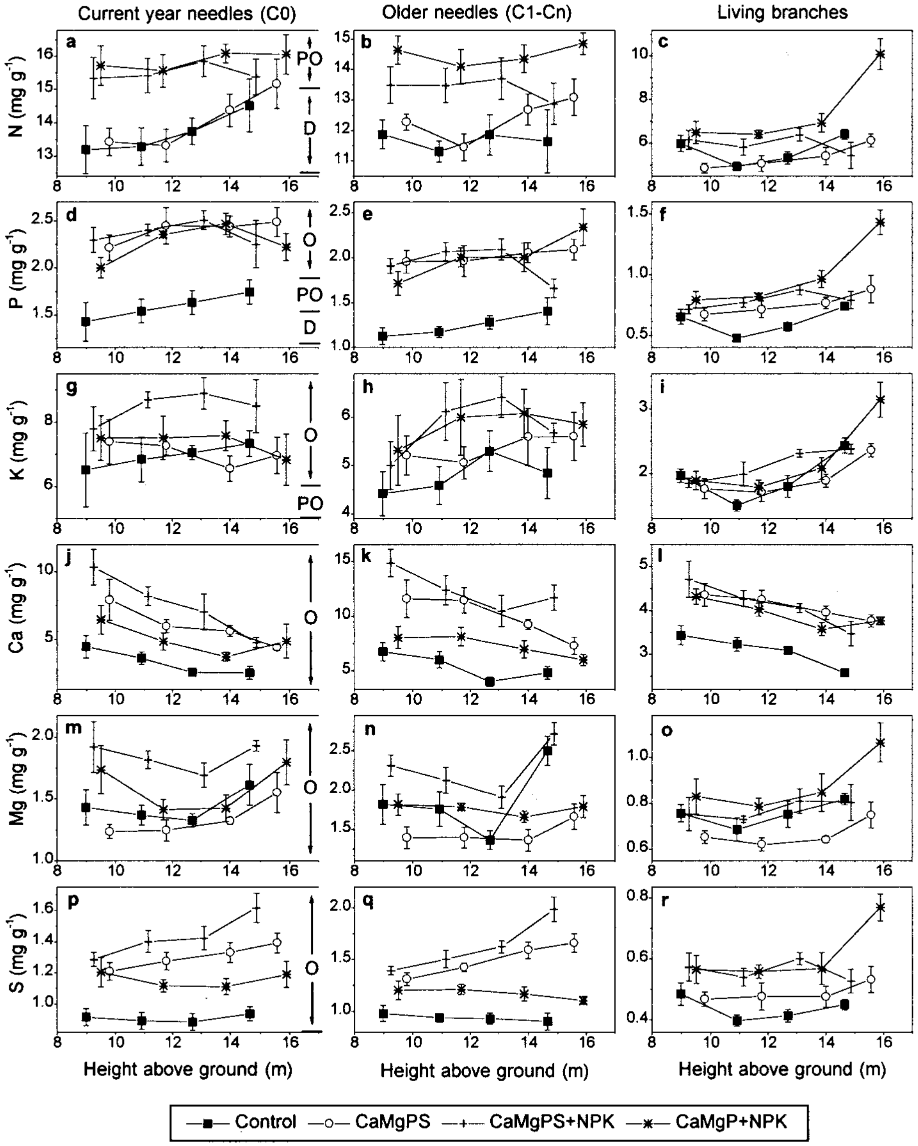

Figure 1. *The concentration of N (a-c), P (d-f), K (g-i), Ca (j-l), Mg (m-o) and S (p-r) in three different biomass compartments at different heights above ground level. Vertical bars represent standard errors of the mean. The figure includes five trees per plot (n=5, N=20). Intervals given at the right side of the figures for the current year needles denotes O=Optimum, PO=Pre-Optimum, D=Deficiency (Brække, 1994).*

Table 2. *Nutrient concentration in stem wood and bark at breast height and in the middle of the canopy, and in cones and dead branches. Different index letters and numbers indicates significant ($P \leq 0.05$) different concentrations between treatments and sampling heights respectively. If no significant differences were found no indexes have been given.*

Tree compartment	N	P	K	Ca	Mg	S
Treatments				mg g^{-1}		
Stem wood at breast height						
Control	0.90	0.094	0.67	0.75	0.181	0.072
CaMgPS	1.01	0.069	0.54	0.69	0.138	0.061
CaMgPS+NPK	1.12	0.095	0.58	0.78	0.148	0.070^{2}
CaMgP+NPK	1.15	0.078^{2}	0.52	0.71	0.157	0.067^{2}
Stem wood in the middle of the canopy						
Control	1.00	0.098^{a}	0.66^{a}	0.73^{ab}	0.191^{a}	0.071^{ab}
CaMgPS	1.28	0.063^{b}	0.46^{b}	0.59^{b}	0.119^{b}	0.056^{b}
CaMgPS+NPK	1.17	0.116^{a}	0.66^{a}	0.83^{a}	0.171^{a}	$0.086^{a\,1}$
CaMgP+NPK	1.30	$0.114^{a\,1}$	0.58^{ab}	0.79^{a}	0.169^{a}	$0.079^{a\,1}$
Stem bark at breast height						
Control	4.4^{2}	$0.50^{c\,2}$	2.8	8.4	1.17	0.46^{c}
CaMgPS	4.6^{2}	$0.60^{bc\,2}$	2.8	9.7^{1}	0.89	$0.52^{bc\,2}$
CaMgPS+NPK	4.8^{2}	$0.70^{ab\,2}$	3.2	8.8	1.08	$0.56^{ab\,2}$
CaMgP+NPK	5.1^{2}	$0.77^{a\,2}$	3.4	10.1^{1}	1.19	0.63^{a}
Stem bark in the middle of the canopy						
Control	$5.5^{b\,1}$	$0.72^{b\,1}$	2.8^{b}	6.3	1.26	0.50^{b}
CaMgPS	$6.3^{b\,1}$	$1.10^{a\,1}$	3.4^{ab}	7.6^{2}	1.12	$0.64^{a\,1}$
CaMgPS+NPK	$6.7^{ab\,1}$	$1.07^{a\,1}$	3.8^{a}	7.2	1.16	$0.70^{a\,1}$
CaMgP+NPK	$8.0^{a\,1}$	$1.20^{a\,1}$	3.5^{a}	6.9^{2}	1.27	0.73^{a}
Cones						
Control	6.8	1.13	6.8	0.089	0.61	0.60
CaMgPS	5.3	1.12	4.9	0.149	0.53	0.52
CaMgPS+NPK	7.6	1.39	7.1	0.152	0.71	0.65
CaMgP+NPK	4.3	1.00	4.3	0.103	0.49	0.40
Dead branches						
Control	8.1	0.39	0.72^{a}	3.0	0.49	0.83
CaMgPS	7.2	0.37	0.44^{b}	3.2	0.53	0.77
CaMgPS+NPK	6.3	0.32	0.43^{b}	2.8	0.46	0.71
CaMgP+NPK	7.4	0.39	0.45^{b}	3.6	0.54	0.79

The Mg concentration was neither affected notably by the various treatments nor the sampling height (Fig. 1, m-o and Table 2). Only in the current year needles from the lower and middle part of the canopy in the CaMgPS+NPK treated plot was the Mg concentration significantly higher (25 %) compared to the control plot.

The S concentration in the current and older needles, living branches and stem bark was generally higher (5-120 %) for the treatments compared with the control plot (Fig. 1, p-r and Table 2). This was significant for the stem bark in the canopy, the current year and older needles at all sampling heights, except for the older needles in the top of the canopy in the CaMgP+NPK treated plot.

4. Discussion

The concentration of the nutrients was generally highest in the actively growing parts of the trees (e.g. needles and stem bark), and lowest in the structural and not actively growing parts (e.g. stem wood). This pattern of nutrient distribution has also been observed by others (e.g. Cromer et al., 1985; Lim and Cousens, 1986; Finér, 1992; Brække and Håland, 1995).

The concentration of N, P, K and S was generally higher in the current year needles than in the older needles (Fig. 1), whereas the opposite pattern was observed for the concentration of Mg and Ca (Fig. 1). Similar nutrient concentration gradients with needle age have also been documented by Cromer et al. (1985), Finér (1992) and Brække and Håland (1995). They can be explained by the nutrient availability in the root zone and the mobility within the trees (Brække and Håland, 1995). N, P, K and S are considered relatively mobile, whereas Mg is less mobile, and Ca is considered rather immobile.

Since only five sampling trees representing different size classes from each plot were used as replicates, it was tested if the tree size affected the nutrient concentrations. The tree size did only in few cases affect the nutrient concentrations significantly. This was most pronounced for K in the older needles (Fig. 2). I have no direct explanation for this relation. The other case which indicated a relation between tree size and nutrient concentration were ascribed to natural statistical variations.

Kimmins et al. (1985) compiled data on dynamics of biomass and nutrients within various forest ecosystems and documented huge variations between stands and sites. When data from other northern European studies of Norway spruce are compared with data from the control plot of the present study they are quite similar. This holds for Sweden (Tamm and Carbonnier, 1961: stand age 52 and 58 years; Nihlgård, 1972: stand age 55 and 60 years) and for Germany (Ulrich et al., 1974: stand age 85 years; Ulrich in Cole and Rapp, 1980: stand age 87 years old). The N concentration was either of the same magnitude or a little higher in the German studies compared to the present study, whereas the N concentration in the trees from the Swedish sites were of the same magnitude as in the present study. The concentration of P, K and Ca was either of the same magnitude or a little higher in Sweden and Germany compared to the present study. But no conclusions concerning extreme low or high concentration of N, P, K and Ca could be made for the present study. However, the concentration of Mg was generally higher in the present study compared to Sweden and Germany, which might be explained by the high input of sea salts from the north sea.

The treatments have increased the concentration of the applied nutrients and thereby affected the nutritional status of the trees, most pronounced for N, P and S in needles and stem bark and for Ca in needles and living branches (Table 2 and Fig. 1). The application of K and Mg did not lead to an additional luxury uptake of any of these nutrients (Table 2 and Fig. 1). These results indicate that fertilization with mobile nutrients coupled to photosynthesis and metabolic processes will influence the nutrient concentration most evidently in the active growing parts of the tree. Furthermore, the trees have only been exposed to these different treatments during the last 10 years, which might explain why the nutrient concentrations in the youngest parts of the trees (needles, living branches and stem bark) have been affected the most.

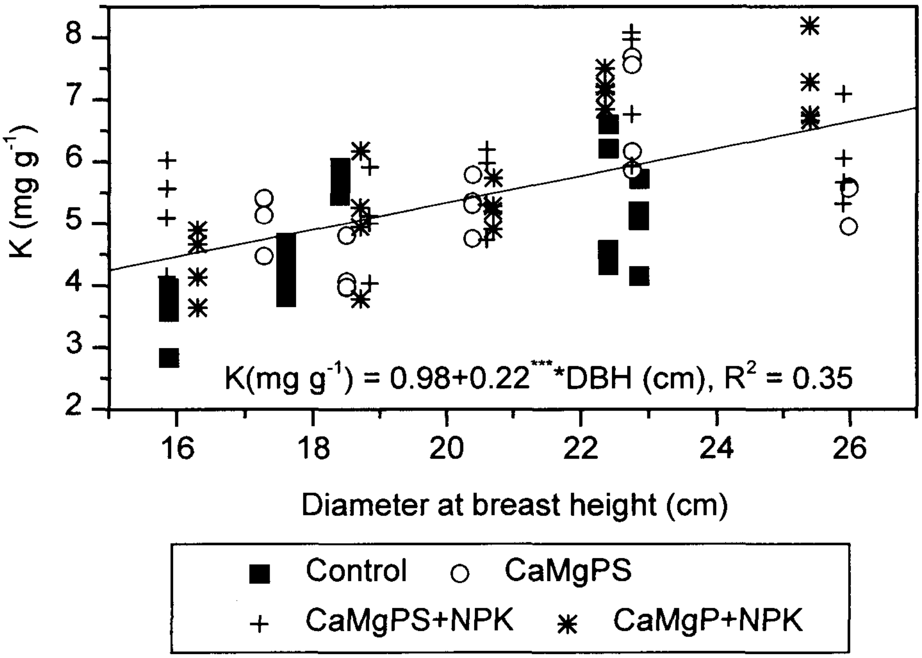

Figure 2. The concentration of K in older needles (C1-Cn) as a function of the diameter at breast height (DBH). The figure includes five trees per plot and four different heights within the canopy for each tree. Results from linear regression is included.
****: The slop was significantly ($P \leq 0.01$) different from 0.*

Diagnostic needle analyses is generally carried out on samples from a south facing branch from the fifth whorl of 10 co-dominant trees per plot, according to UN/ECE (1994). The strategy used in the present study was different and the results could therefore not directly be used for diagnostic comparison with literature values for deficiency. Sampling parameters such as position in the canopy (height and orientation) and social class and size of the tree may influence the results (Raitio, 1994; Rosengren-

Brinck, 1994). A diagnostic needle analysis was carried out in autumn 1995 at the same site following the UN/ECE (1994) protocol (Ingerslev and Hallbäcken, 1997b). The analysis showed that the trees in the control plot suffered from N and P deficiency, and that these deficiencies could be counteracted by application of these nutrients. The needle analysis also showed that the nutrient status of K, Mg and Ca was at optimum in all the plots (Ingerslev and Hallbäcken, 1997b). The nutrient concentrations measured at the upper part of the canopy were of the same magnitude as measured by Ingerslev and Hallbäcken (1997b). However, the concentration of N, P, Mg and Ca were generally higher in the present study compared to Ingerslev and Hallbäcken (1997b). The P deficiency detected by Ingerslev and Hallbäcken (1997b) could not be detected in the upper part of the canopy in the control plot in the present study. The level was within the interval of 'pre-optimum' given by Brække (1994) (Fig. 1). The differences in the concentrations between the present study and the study by Ingerslev and Hallbäcken (1997b) can presumably be ascribed to natural variations and differences in sampling method.

The concentration of N and P in the needles in the control plot was highest in the upper part of the canopy. Vertical N and P concentration gradients have also been observed for *Pinus radiata* by Cromer et al. (1985). The results indicated that the N and P deficient trees preferentially have retranslocated these nutrients to the upper part of the canopy, to maintain a relatively higher concentration in this part of the tree where the photosynthetic activity is highest. When N and P were applied, the concentrations were elevated, most for needles in the middle and lower parts of the canopy, to a level that could be considered above deficiency in all parts of the canopy (Brække, 1994).

The sampling strategy given in the UN/ECE (1994) protocol is suitable for diagnostic comparison with literature values on nutrient status. However, the present study shows that other needle sampling strategies may preferentially be used to obtain additional knowledge concerning the nutrient status of the trees. In the present study vertical concentration gradients of nutrients that are mobile within the trees (e.g. N and P) seem to indicate low nutrient status or deficiency. This can be examined by sampling needles from various heights within the canopy. The same strategy can be used to examine the effect of fertilization on the nutrient status of the trees. Based on the present study fertilization with mobile nutrients in stands suffering from low status or deficiency may show the largest effects on nutrient concentrations in needles from the lower part of the canopy.

The role of Ca in the trees is primarily related to structural linkages, predominantly in the cell walls and the plasma membranes. It could therefore be assumed that Ca fertilization would lead to a general increase in the Ca concentration in all parts of the trees. The present study confirmed this for the needles, living branches and stem bark, but not for the stem wood. A possible reason for this lack of effect on the Ca concentration in the stem wood may again be referred to the fact that the treatments only have been carried out during the last 10 years and most of the wood was thus formed earlier.

The S application generally elevated the concentration of S in the needles, upper living branches and stem bark (Fig 1., p-r and Table 2). However, in the CaMgP+NPK treated plot, the S concentration was also increased in the needles, living branches and stem bark. This finding indicates that the S availability was increased by the K_2SO_4 applied with the commercial NPK fertilizer (Table 1), by increased turnover of organic matter, and/or by ion exchange in the soil due to the salt effect of applied fertilizers (Ingerslev, 1997).

The present study has confirmed that the nutrient concentration in various parts of the above ground biomass can be manipulated by fertilization and liming. However it has also indicated that the effect of such treatments in older stands may be limited to the nutrient concentration in the actively growing parts of the trees. Responses to nutrient additions were most pronounced in the lower part of the canopy for N and P. This knowledge may be used for diagnosing N and P deficiencies.

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PAPER III

Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (*Picea abies*) plantation

Part II. Accumulation of biomass and nutrients

Morten Ingerslev and Leif Hallbäcken
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Part II. Accumulation of biomass and nutrients

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Abstract. Above ground biomass and nutrient distribution were determined in a combined liming and fertilization experiment in a 59-year-old Norway spruce stand on a nutrient poor soil at Klosterhede, Denmark. Two types of lime (calcite and dolomite combined with additional kieserite and phosphate) were applied alone or in combination with conventional NPK fertilizer. Five sample trees of different size classes were felled in each treatment plot. The biomass was divided in seven compartments: stem wood, stem bark, living branches, dead branches, current year needles, older needles and cones. The total above ground biomass and nutrient content in each tree were calculated and referenced to the ground surface area by solving regression equations relating the biomass or amount of nutrients to the tree height and breast height diameter (DBH) for all the trees in a given treatment. The biomass was closely correlated with the tree size (height*DBH^2) for stem wood, stem bark, living branches and older needles ($R^2 \geq 0.70$).

The results show that biomass and stem volume growth were not affected ($P \leq 0.05$) by the different treatments. However, an increase of the above ground biomass caused by NPK fertilization was indicated. The stem wood and living branches contained the main part of the above ground biomass (approx. 80 %, corresponding to 70 t dry weight ha^{-1}). The main part of the N, P, K, Mg and S was in the living branches and needles (>60 %), while stem bark, living branches and needles contained a significant part of the Ca content (>70 %). The accumulation of nutrients in stem bark and needles increased significantly following fertilization and liming, especially in the current year needles. The calculated annual mean accumulation of P in the above ground biomass increased from 2.3 kg ha^{-1} for the control plot to more than 5 kg ha^{-1} for some of the treatments.

Keywords: biomass, fertilization, liming, Norway spruce, *Picea abies*, nutrient accumulation, nutrient distribution, nutrient uptake.

1. Introduction

The main aim of liming and fertilization trials in Danish Norway spruce stands older than 10-20 years has previously been to increase forest production measured in stem volume growth (Lundberg and Ravnsbæk, 1992; Dralle and Larsen, 1995). Nowadays, the aim has changed towards stabilizing a sufficient and balanced nutrient uptake in stands affected by air pollution and increased removal of nutrients by more intensive forest management practices. Based on a series of fertilization trails Dralle and Larsen (1995) concluded that N no longer was the main limiting factor for tree growth in western Denmark, but that K and maybe, P have developed into new minimum factors, limiting production and devitalizing the trees.

In Germany, the most common nutritional disorder in Norway spruce stands is Mg deficiency, but also K and other nutritional disturbances have been documented (Evers and Hüttl, 1990/91). Liming and fertilization experiments have shown that a fast and sustained revitalization and restabilization of declining forest ecosystems can be achieved. This was demonstrated both by chemical and histological foliage analysis and by a visible improvement of the trees (Evers and Hüttl, 1990/91). Amelioration, such as fertilization and liming, may prove necessary in Denmark as well since the health condition of Norway spruce forests expressed as needle loss has declined from 1989 to 1994 (Danish Forest and Nature Agency, 1996), and results from long-term investigations of forest soils and stand growth in western Denmark have indicated that K deficiency, and to some extent P deficiency, may be expected (Lundberg and Ravnsbæk, 1992; Clausen, 1995; Dralle and Larsen, 1995; Pedersen and Bille-Hansen, 1995). Before effective amelioration practices can be achieved it is essential to define and measure parameters such as tree nutrient uptake and status, nutritional imbalance and nutrient deficiency. Furthermore, it is essential to know the effects of fertilization and liming on these parameters.

Vitality of a tree or stand can be defined as the ability to withstand stress and maintain a healthy and natural life cycle (Swedish Environment Protection Agency, 1991). The ability to maintain a high stem volume production does not necessarily imply high vitality. Fertilization and liming have been proven to alter the relative growth of the different biomass compartments of the trees (stem, bark, living branches, current year needles etc.) (Andersson et al., 1995). Growth and nutrient accumulation of the different compartments could be influenced differently by different soil amelioration treatments. Therefore, the nutrient accumulation and growth of the whole tree separated into compartments has to be considered in connection with soil amelioration, instead of just the stem volume growth.

The purpose of this study was i) to measure the above ground biomass and nutrient distribution and accumulation in a Norway spruce stand which was not determined before on nutrient poor soil in western Denmark, and ii) to evaluate effects of fertilization and liming on the measured pools. The spatial variation in the concentration of various plant nutrients in the above ground biomass was measured and examined by Ingerslev (1997b, part I). The accumulation of nutrients in the above ground biomass was compared to the input of nutrients with atmospheric deposition and fertilizers.

2. Materials and methods

2.1. Site description

The research site was located at Klosterhede State Forest close to Lemvig in western Denmark. The soil was nutrient poor coarse sand, with low clay content and an organic layer (mor humus) of approx. 10 cm. The total atmospheric deposition of nitrogen was estimated to approx. 25 kg N ha^{-1} year^{-1} (Gundersen and Rasmussen, 1995). The research site was located in an even-aged, 60 years old Norway spruce (*Picea abies*) stand with a stand density of approx. 800 trees per ha and an average stem volume of 225 m^3 ha^{-1}. More site details are given by Ingerslev (1997a; b, Part I).

2.2. Treatments and experimental design

Prior to the start of the experiment the whole stand was NPK fertilized in 1977 and in 1982 (Table 1). The trial was established in 1986 with various combinations of conventional NPK fertilizer, two different liming treatments (calcite and dolomite), and additional P and S (Table 1). Additional treatments were carried out in spring 1991 and 1994.

***Table 1.** Applied amounts of nutrients in the different treatments. Note that different types of NPK fertilizers have been applied.*

		N	P	K	Ca	Mg	S	Applications
				Kg ha^{-1}				
Pretreatment	Year							
All plots	1977	120	15	35	-	-	-	NPK-23:3:7^a
All plots	1982	120	33	80	35	7	-	NPK-18:5:12^a (incl.: Mg, Cu and B)
Treatment	Year							
Control	1986	120	31	140	43	9	37	NPK-14:4:17^a (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
NPK	1986, 1994	120	31	140	43	9	37	NPK-14:4:17^a (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
CaMgPS	1986, 1994	-	200	-	1710	730	1150	Calcite^b, kieserite^c, 'superphosphate'
CaMgPS+NPK	1986, 1994	120	230	140	1750	740	1190	Combination of NPK and CaMgPS
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)
CaMgP	1986, 1994	-	200	-	1720	730	-	Dolomite^d, 'rock-phosphate'
CaMgP+NPK	1986, 1994	120	230	140	1760	740	37	Combination of NPK and CaMgP
	1991	120	15	34	40	8	21	NPK-23:3:7^a (incl.: Mg, Cu and B)

a: conventional agricultural NPK fertilizer containing approximately 50 % NO_3^-, 50 % NH_4^+, Cl<2 %, and K as a mixture of KCl and K_2SO_4.

b: $CaCO_3$.

c: $MgSO_4$.

d: $CaMg(CO_3)_2$.

The experiment originally included five different treatment plots and no control plots. However, earlier NPK fertilized plots were included as control plots in 1994. The present study focus on examining three treatment plots and one control plot (Table 1). A more detailed description of the treatments and experimental design is given by Ingerslev (1997b, Part I).

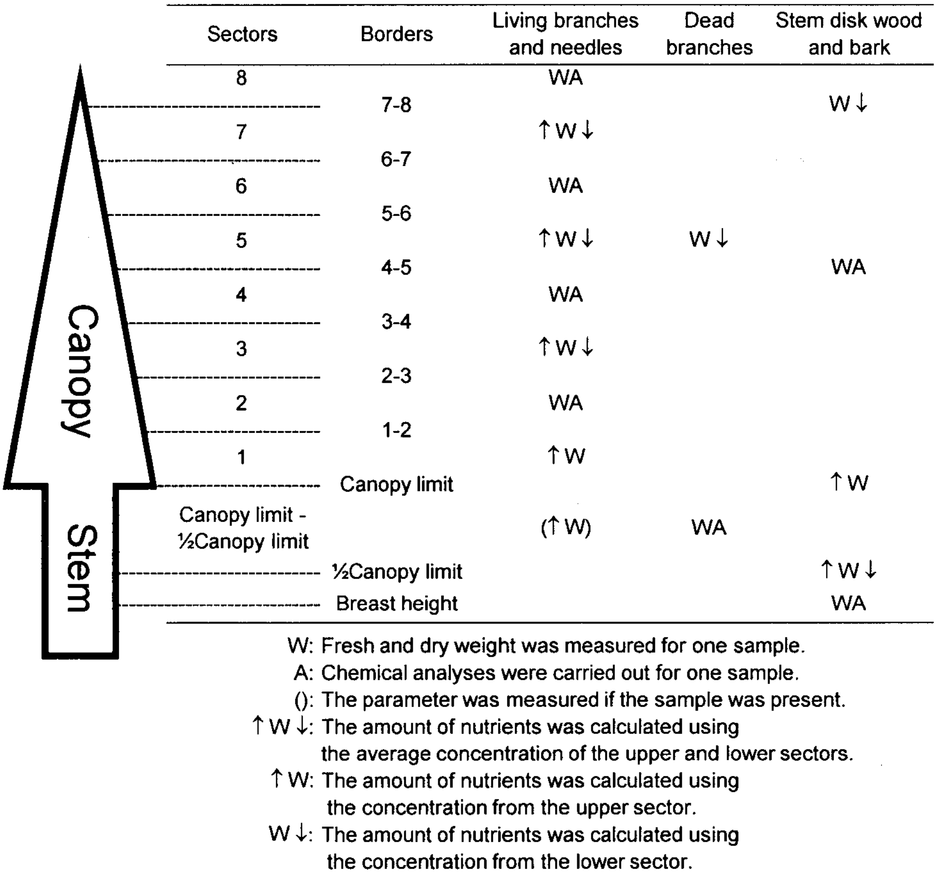
2.3. Biomass and nutrient distribution in above ground biomass

In November 1995 five trees from four plots (control, CaMgPS, CaMgPS+NPK and CaMgP+NPK) in block A were felled in order to determine the biomass and nutrient contents in the different compartments of the above ground biomass. The trees were selected to represent the tree size distribution based on breast height diameter (DBH). Tree height, DBH and height of the canopy limit was measured. The canopy was divided into eight sections of equal length. The different sections were numbered 1-8, starting with 1 at the lowest part of the canopy (Fig. 1).

One living sample branch was selected from a whorl in the middle of each section (Fig. 1). One dead sample branch from within the canopy and one from below the canopy were selected. One sample cone from each section was selected, if cones were present. The total fresh weights of all living and dead branches, and cones from each section were measured (Fig. 1). Each living sample branch was separated into three compartments: i) current year needles (C0), ii) older needles (C1-Cn), and iii) wood and bark. The fresh weight of the stem from base to canopy limit and from canopy limit to the top was measured. Sample disks were taken from the stem at breast height, midway between the stump and canopy limit, at canopy limit, straight between the canopy limit and the top, and at the bottom of the upper most section. Height, diameter and bark thickness of the fresh sample disks were measured. The fresh weight of all samples was measured.

All samples were dried at approx. 75 °C for minimum two days (until constant weight) and weighed (Fig. 1). A subsample from each compartment of the living branches in section 2, 4, 6 and 8 was ground and used for chemical analyses (4 subsamples from each compartment and sample tree) (Fig. 1). A subsample from the dead sample branch from below the canopy was also ground and used for chemical analysis. From each tree with cones, a sample cone was selected from the section that contained the most cones and ground and used for chemical analysis. Each sample disk was separated into a wood and a bark compartment, and weighed. A subsample from each disk compartment from breast height and from the middle of the canopy was ground and used for chemical analysis.

Concentrations of N and C were determined by IR after dry combustion in an oven (LECO-CHN 1000). Following combustion in concentrated nitric acid in a microwave oven (CMC, MDS-2000), the concentration of Ca, Mg, K, Fe, Mn, Na, P and S was determined by ICP-AES (Perkin Elmer, optima 3000 XL).



Sectors	Borders	Living branches and needles	Dead branches	Stem disk wood and bark
8		WA		
	7-8			W↓
7		↑W↓		
	6-7			
6		WA		
	5-6			
5		↑W↓	W↓	
	4-5			WA
4		WA		
	3-4			
3		↑W↓		
	2-3			
2		WA		
	1-2			
1		↑W		
	Canopy limit			↑W
Canopy limit - ½Canopy limit		(↑W)	WA	
	½Canopy limit			↑W↓
	Breast height			WA

W: Fresh and dry weight was measured for one sample.
A: Chemical analyses were carried out for one sample.
(): The parameter was measured if the sample was present.
↑W↓: The amount of nutrients was calculated using the average concentration of the upper and lower sectors.
↑W: The amount of nutrients was calculated using the concentration from the upper sector.
W↓: The amount of nutrients was calculated using the concentration from the lower sector.

Figure 1. *Biomass sampling and calculation strategy.*

2.4. Calculations and statistical analyses

The above ground biomass and the amount of nutrients within the various compartments of each sample tree were calculated by summation over the sectors; illustrated in Fig. 1.

The above ground biomass and the amount of nutrients within the biomass compartments of each tree in the different plots were calculated using simple linear regressions of DBH and tree height versus the biomass or nutrient contents of the various compartments. The regression equations were produced from the sample trees and then applied to all the trees in each plot. These linear regression equations are described by:

$$\ln(\text{kg dry biomass or kg nutrient}) = \alpha + \beta \times \ln(DBH^2 \times H)$$

where:

α is the intercept,
β is the slope,
DBH is the diameter at breast height,
H is the height of the tree.

The linear regressions were produced and tested by use of SAS, PROC REG. Furthermore, the following hypotheses were tested by use of SAS, PROC GLM: i) the regression lines for a specific compartment and component (biomass, N, P, K, Ca etc.) had no slope ($\beta=0$) when differences between the treatments were disregarded, ii) the biomass regression lines for a specific compartment, component and treatment had the same intercept ($\alpha_{treatment}=\alpha_{control}$) and/or slope ($\beta_{treatment}=\beta_{control}$) as the control. The statistical tests and some of the regression equations are presented in Table 2. The results from these tests were used to decide which of the regression equations that gave the best description of the biomass and nutrient amounts. If the treatments did not affect the slope and intercept significantly compared to the control, the differences in treatments were neglected and one general regression equation was used for all treatments to describe the particular tree compartment and component (biomass, N, P, K, Ca ect.) (Table 2). If the treatments did affect the intercept significantly, but not the slope, compared to the control, the general equations listed in Table 2 were not used, but instead individual regression equations for parallel lines were established and used for these treatments. In the cases where only some of the treatments affected the equations new equations containing average slopes and intercepts were established and used for the other treatments. For simplicity the treatment specific equations are not listed in Table 2.

The biomass and nutrient contents were calculated for 1995 and 1991 on a ground surface area basis by solving the equations for all the trees in the four sampled plots (in block A: control, CaMgPS, CaMgPS+NPK and CaMgP+NPK).

The biomass and nutrient contents were calculated for 1986 (time of establishment of the trial) by applying the equations for the control plot to the other plots. The equations for the control plot were chosen because this plot was given nearly the same treatments as all the plots were given prior to the establishment of the trial (Table 1). The biomass and nutrient contents accumulated from 1986 to 1995 were calculated by adding the amounts of biomass or nutrients present in 1995 to the amounts removed by thinning in 1991, and subtracting the amounts present in 1986 (Table 3 and 4).

There were no diameter and height measurements for the thinned trees in the control plot for 1986 and 1991. However, there were no statistical evidence that the average height and diameter varied between treatments at any time of the investigation period. The above ground biomass and nutrient contents in the control plot were therefore calculated for 1986 using the number of trees and average height and diameter from the other plots and for 1991 using the number of thinned trees and the average height and diameter for the thinned trees from the other plots.

The above ground biomass and nutrient distribution was only determined in one block, which made it impossible to make statistical tests of the treatment effects by using the different blocks as replicates. However, the statistical tests, of the regression lines were used to support observations concerning the effects of the treatments. An observation of an increased accumulation of a nutrient in a specific treatment could thus be supported by a significantly elevated intercept for the corresponding regression line compared to the control, presuming that the slope was not significantly affected by the treatment.

Table 2. *Regression equations for calculation of biomass (Bio.) and element contents in different tree compartments, using breast height diameter (DBH in cm) and tree height (H in m), ln(element or biomass, Kg) =* $\alpha + \beta \times \ln(DBH^2 \times H)$*. The equations are based on 20 sample trees, five from each plot (N=20, n=5). P-values for statistical test:* H_0: $\alpha=0$, H_0: $\alpha_{treatment}=\alpha_{control}$, H_0: $\beta_{treatment}=\beta_{control}$. *Bold indicates that the P-value was significant (P≤0.05). Note that the listed equations were not used for biomass calculations when P(*H_0: $\alpha_{treatment}=\alpha_{control}$*)≤0.05 (see text paragraph 2.4.).*

Compartment Element	α	β	R^2 (n=20)	P (n=20)	P (N=20, n=5)	P (N=20, n=5)	Treatments that had an intercept significantly different from
Stem wood							
Bio.	-3.24	0.88	0.96	**0.00**	0.84	0.86	
N	-9.62	0.83	0.70	**0.00**	0.21	0.66	
P	-9.51	0.52	0.37	**0.00**	**0.02**	0.52	CaMgPS$^{\downarrow}$
K	-8.81	0.66	0.59	**0.00**	0.09	0.39	
Ca	-9.21	0.73	0.74	**0.00**	0.15	0.73	
Mg	-8.98	0.53	0.49	**0.00**	0.09	0.76	
S	-11.70	0.75	0.76	**0.00**	**0.01**	0.58	CaMgPS$^{\downarrow}$
Stem bark							
Bio.	-5.51	0.88	0.84	**0.00**	0.74	0.55	
N	-10.93	0.90	0.72	**0.00**	**0.02**	0.52	CaMgP+NPK$^{\uparrow}$
P	-13.08	0.93	0.65	**0.00**	**0.00**	0.81	CaMgPS$^{\uparrow}$, CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
K	-10.70	0.81	0.77	**0.00**	**0.00**	0.57	CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
Ca	-10.30	0.88	0.75	**0.00**	0.25	0.75	
Mg	-10.52	0.68	0.61	**0.00**	0.11	0.87	
S	-13.36	0.92	0.70	**0.00**	**0.01**	0.82	CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
Living branches							
Bio.	-5.88	1.02	0.83	**0.00**	0.45	0.45	
N	-12.02	1.14	0.85	**0.00**	0.09	0.93	
P	-15.03	1.24	0.85	**0.00**	0.44	0.87	
K	-13.35	1.16	0.87	**0.00**	0.21	0.86	
Ca	-12.31	1.12	0.79	**0.00**	0.51	0.47	
Mg	-12.75	0.98	0.80	**0.00**	0.17	0.97	
S	-14.97	1.19	0.86	**0.00**	0.29	0.95	

Dead branches								
	Bio.	-7.75	1.08	0.58	**0.00**	0.08	0.50	
	N	-11.81	0.98	0.52	**0.00**	0.07	0.76	
	P	-14.74	0.97	0.47	**0.00**	0.18	0.74	
	K	-14.44	0.98	0.36	**0.01**	**0.01**	0.35	CaMgPS$^{\downarrow}$, CaMgPS+NPK$^{\downarrow}$ and CaMgP+NPK$^{\downarrow}$
	Ca	-12.96	1.02	0.48	**0.00**	0.34	0.14	
	Mg	-15.05	1.05	0.59	**0.00**	0.26	0.40	
	S	-14.51	1.03	0.54	**0.00**	0.09	0.94	
Current year needles								
(CO)	Bio.	-4.24	0.67	0.46	**0.01**	0.17	0.21	
	N	-9.00	0.73	0.43	**0.00**	**0.03**	0.09	CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
	P	-14.49	1.14	0.76	**0.01**	**0.00**	0.09	CaMgPS$^{\uparrow}$, CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
	K	-10.37	0.81	0.48	**0.00**	**0.04**	0.31	CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
	Ca	-10.69	0.81	0.22	**0.04**	**0.04**	0.10	CaMgPS$^{\uparrow}$, CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
	Mg	-10.16	0.60	0.30	**0.01**	**0.03**	0.07	CaMgPS+NPK$^{\uparrow}$
	S	-11.30	0.70	0.31	**0.01**	**0.01**	0.06	CaMgPS$^{\uparrow}$, CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
Older neeedles								
(C1-Cn)	Bio.	-4.85	0.81	0.74	**0.00**	0.62	0.37	
	N	-10.17	0.92	0.73	**0.00**	0.45	0.31	
	P	-12.23	0.93	0.64	**0.00**	**0.04**	0.65	CaMgPS$^{\uparrow}$, CaMgPS+NPK$^{\uparrow}$ and CaMgP+NPK$^{\uparrow}$
	K	-13.34	1.18	0.86	**0.00**	0.46	0.35	
	Ca	-12.08	1.09	0.55	**0.00**	**0.01**	0.41	CaMgPS$^{\uparrow}$ and CaMgPS+NPK$^{\uparrow}$
	Mg	-12.06	0.91	0.64	**0.00**	**0.01**	0.64	CaMgPS$^{\downarrow}$
	S	-12.31	0.90	0.67	**0.00**	0.10	0.32	

↑: Regression line having an intercept significantly ($P \leq 0.05$) higher than the intercept for the control.
↓: Regression line having an intercept significantly ($P \leq 0.05$) lower than the intercept for the control.

Table 3. *Biomass and nutrient content in the above ground biomass in 1995 in the control plot and the CaMgSP, CaMgSP+NPK and CaMgP+NPK treated plots. Based on the equations listed in Table 2 (with exception from the $\uparrow$, $\downarrow$, $\otimes$ and $\Diamond$ marked figures, see paragraph 2.4.).*

Treatments Biomass compartments	Dry weight	N	P	K	Ca	Mg	Mn	Fe	S	C
	Mg ha^{-1}	----------	--------------	------------	------------	kg ha^{-1}	--------------	--------------	-----------	Mg ha^{-1}
Control										
Stem wood	70	75	6.3	38	49	10	1.2	0.20	5.0	35
Bark	7.3	41	4.1	20	60	7.9	1.2	0.34	3.6	3.7
Stem wood + bark	77	120	10	58	110	18	2.4	0.54	8.6	38
Living branches	19	110	14	36	74	13	1.6	2.1	9.7	9.5
Dead branches	4.8	34	1.7	4.3	15	2.4	0.19	2.1	3.6	2.5
Branches, total	23	140	16	40	89	16	1.7	4.2	13	12
C0 needles	4.0	48	4.9	25	11	5.3	0.49	0.21	2.8	2.0
Older needles	7.7	100	10	44	54	15	1.2	0.63	9.6	3.8
Needles, total	12	150	15	68	64	20	1.7	0.84	12	5.9
Cones	$0.35^{\Diamond}$	$2.3^{\Diamond}$	$0.44^{\Diamond}$	$2.1^{\Diamond}$	$0.055^{\Diamond}$	$0.23^{\Diamond}$	$0.017^{\Diamond}$	$0.008^{\Diamond}$	$0.21^{\Diamond}$	$0.18^{\Diamond}$
Tree biomass, total	110	410	41	170	260	54	5.9	5.6	35	56000
CaMgPS										
Stem wood	70	75	$4.3^{\downarrow}$	38	49	10	$0.79^{\downarrow}$	0.20	$3.9^{\downarrow}$	35
Bark	7.3	41	$5.6^{\uparrow}$	20	60	8.0	1.2	0.35	3.6	3.7
Stem wood + bark	77	120	9.9	59	110	18	2.0	0.54	7.5	38
Living branches	18	110	14	35	73	13	$0.98^{\downarrow}$	2.1	9.6	9.4
Dead branches	4.8	33	1.7	$1.6^{\downarrow}$	15	2.4	$0.12^{\otimes}$	2.0	3.6	2.4
Branches, total	23	140	16	37	88	16	1.1	4.1	13	12
C0 needles	4.0	48	$9.4^{\uparrow}$	25	$25^{\uparrow}$	5.3	0.49	0.21	$5.0^{\uparrow}$	2.0
Older needles	7.7	100	$14^{\uparrow}$	43	$80^{\uparrow}$	$10^{\downarrow}$	$0.85^{\downarrow}$	0.63	9.6	3.8
Needles, total	12	150	23	68	100	15	1.3	0.84	15	5.9
Cones	$0.36^{\Diamond}$	$2.4^{\Diamond}$	$0.45^{\Diamond}$	$2.2^{\Diamond}$	$0.066^{\Diamond}$	$0.24^{\Diamond}$	$0.017^{\Diamond}$	$0.008^{\Diamond}$	$0.22^{\Diamond}$	$0.19^{\Diamond}$
Tree biomass, total	110	410	49	170	300	50	4.4	5.5	36	56

CaMgPS+NPK										
Stem wood	74	80	7.0	42	54	11	$0.93^{\downarrow}$	0.21	5.4	37
Bark	7.8	44	$6.6^{\uparrow}$	$27^{\uparrow}$	64	8.7	1.3	0.39	$4.8^{\uparrow}$	3.9
Stem wood + bark	82	120	14	69	120	20	2.2	0.60	10	41
Living branches	19	110	14	36	76	14	$1.1^{\downarrow}$	2.2	9.8	9.9
Dead branches	5.0	35	1.8	$2.4^{\downarrow}$	15	2.5	0.20	2.0	3.7	2.5
Branches, total	24	150	16	39	91	17	1.3	4.2	14	12
C0 needles	4.4	$77^{\uparrow}$	$12^{\uparrow}$	$42^{\uparrow}$	$39^{\uparrow}$	$8.9^{\uparrow}$	0.54	0.23	$6.9^{\uparrow}$	2.2
Older needles	8.3	110	$16^{\uparrow}$	44	$100^{\uparrow}$	16	1.3	0.68	10	4.2
Needles, total	13	180	28	86	140	24	1.8	0.90	17	6.4
Cones	$0.42^{\Diamond}$	$2.8^{\Diamond}$	$0.53^{\Diamond}$	$2.6^{\Diamond}$	$0.066^{\Diamond}$	$0.28^{\Diamond}$	$0.020^{\Diamond}$	$0.009^{\Diamond}$	$0.25^{\Diamond}$	$0.22^{\Diamond}$
Tree biomass, total	120	460	58	200	350	62	5.3	5.7	41	60
CaMgP+NPK										
Stem wood	83	88	7.2	44	57	12	$1.1^{\downarrow}$	$0.41^{\uparrow}$	5.9	41
Bark	8.7	$44^{\uparrow}$	$8.8^{\uparrow}$	$31^{\uparrow}$	71	9.2	1.4	$0.71^{\uparrow}$	$6.2^{\uparrow}$	4.4
Stem wood + bark	91	130	16	75	130	21	2.5	1.1	12	46
Living branches	22	130	17	44	90	16	$1.1^{\downarrow}$	2.6	12	11
Dead branches	5.9	40	2.0	$2.6^{\downarrow}$	18	2.9	0.23	2.6	4.3	3
Branches, total	28	170	19	46	110	19	1.3	5.2	16	14
C0 needles	4.6	$82^{\uparrow}$	$12^{\uparrow}$	$39^{\uparrow}$	$23^{\uparrow}$	6.0	0.56	0.24	$5.8^{\uparrow}$	2.3
Older needles	9.0	120	$17^{\uparrow}$	53	65	18	$0.70^{\downarrow}$	0.75	11	4.5
Needles, total	14	200	29	92	88	24	1.3	0.99	17	6.9
Cones	$0.37^{\Diamond}$	$2.4^{\Diamond}$	$0.46^{\Diamond}$	$2.2^{\Diamond}$	$0.058^{\Diamond}$	$0.24^{\Diamond}$	$0.018^{\Diamond}$	$0.008^{\Diamond}$	$0.22^{\Diamond}$	$0.19^{\Diamond}$
Tree biomass, total	130	510	65	220	320	64	5.0	7.4	46	67

↑: The used regression line had an intercept that was significantly ($P \leq 0.05$) higher than the intercept for the control.

↓: The used regression line had an intercept that was significantly ($P \leq 0.05$) higher than the intercept for the control.

⊗: The used regression line had an intercept and slope significantly ($P \leq 0.05$) different from the control plot.

◊: The used regression line had no slope.

***Table 4.** Yearly mean accumulated biomass and nutrient content in the above ground biomass from 1986 to 1995 (including the thinned trees from 1991) in the control plot and the CaMgSP, CaMgSP+NPK and CaMgP+NPK treated plots. Based on the equations listed in Table 2 (with exception from the ↑, ↓ and ⊗ marked figures, see paragraph 2.4.).*

Treatments Biomass compartments	Dry weight	N	P	K	Ca	Mg	Mn	Fe	S	C
	kg ha^{-1} year^{-1}									
Control										
Stem wood	3800	3.9	0.24	1.6	2.3	0.35	0.048	0.010	0.25	1900
Bark	400	2.2	0.21	1.0	3.3	0.35	0.065	0.011	0.19	200
Stem wood + bark	4200	6.1	0.45	2.6	5.6	0.70	0.11	0.021	0.44	2100
Living branches	1100	7.2	0.98	2.4	4.9	0.81	0.10	0.15	0.66	590
Dead branches	310	2.0	0.10	0.29	0.90	0.15	0.011	0.16	0.22	160
Branches, total	1500	9.2	1.1	2.7	5.8	0.96	0.11	0.31	0.89	740
C0 needles	170	2.0	0.19	1.2	0.44	0.19	0.021	0.009	0.10	87
Older needles	400	5.7	0.53	2.9	3.3	0.88	0.081	0.035	0.54	200
Needles, total	570	7.7	0.72	4.1	3.8	1.07	0.10	0.044	0.64	280
Tree biomass, total	6200	23	2.3	9.4	15	2.7	0.33	0.37	2.0	3100
CaMgPS										
Stem wood	4200	4.4	-0.006$^{\downarrow}$	2.0	2.7	0.45	-0,003$^{\downarrow}$	0.011	0.13$^{\downarrow}$	2100
Bark	450	2.4	0.45$^{\uparrow}$	1.1	3.6	0.41	0.07	0.014	0.22	230
Stem wood + bark	4700	6.8	0.45	3.1	6.3	0.86	0.070	0.025	0.35	2400
Living branches	1200	7.7	1.0	2.5	5.18	0.88	0.036$^{\downarrow}$	0.16	0.70	630
Dead branches	330	2.2	0.11	-0.044$^{\downarrow}$	0.98	0.16	0.002$^{\otimes}$	0.16	0.24	170
Branches, total	1600	9.9	1.1	2.5	6.2	1.0	0.037	0.32	0.94	800
C0 needles	200	2.4	0.88$^{\uparrow}$	1.4	2.6$^{\uparrow}$	0.23	0.025	0.011	0.45$^{\uparrow}$	100
Older needles	450	6.3	1.2$^{\uparrow}$	3.1	7.2$^{\uparrow}$	0.32$^{\downarrow}$	0.035$^{\downarrow}$	0.039	0.60	220
Needles, total	650	8.7	2.1	4.5	9.7	0.55	0.059	0.050	1.1	320
Tree biomass, total	6900	25	3.6	10	22	2.5	0.17	0.39	2.3	3500

CaMgPS+NPK										
Stem wood	5200	5.5	0.39	2.5	3.4	0.59	0.019$^{\downarrow}$	0.014	0.36	2600
Bark	550	3.0	0.59$^{\uparrow}$	2.1$^{\uparrow}$	4.5	0.53	0.089	0.019	0.38$^{\uparrow}$	280
Stem wood + bark	5800	8.5	0.97	4.6	7.9	1.1	0.11	0.033	0.74	2900
Living branches	1500	9.0	1.2	2.9	6.1	1.1	0.068$^{\downarrow}$	0.18	0.81	760
Dead branches	390	2.6	0.13	0.11$^{\downarrow}$	1.2	0.19	0.015	0.18	0.29	200
Branches, total	1900	12	1.3	3.1	7.2	1.3	0.083	0.36	1.1	960
C0 needles	270	6.4$^{\uparrow}$	1.2$^{\uparrow}$	3.8$^{\uparrow}$	4.5$^{\uparrow}$	0.73$^{\uparrow}$	0.032	0.014	0.70$^{\uparrow}$	130
Older needles	560	7.7	1.5$^{\uparrow}$	3.6	10$^{\uparrow}$	1.2	0.10	0.048	0.73	280
Needles, total	820	14	2.7	7.4	15	1.9	0.13	0.062	1.4	410
Tree biomass, total	8500	34	5.0	15	30	4.3	0.32	0.45	3.3	4300
CaMgP+NPK										
Stem wood	5200	5.3	0.34	2.3	3.2	0.51	0.022$^{\downarrow}$	0.039$^{\uparrow}$	0.34	2600
Bark	540	2.3$^{\uparrow}$	0.84$^{\uparrow}$	2.4$^{\uparrow}$	4.4	0.49	0.088	0.062$^{\uparrow}$	0.52$^{\uparrow}$	280
Stem wood + bark	5700	7.6	1.2	4.7	7.6	1.0	0.11	0.10	0.86	2900
Living branches	1500	9.8	1.3	3.2	6.5	1.1	0.031$^{\downarrow}$	0.20	0.89	790
Dead branches	420	2.7	0.13	0.045$^{\downarrow}$	1.2	0.20	0.015	0.21	0.30	210
Branches, total	2000	13	1.5	3.3	7.8	1.3	0.046	0.41	1.2	1000
C0 needles	240	6.5$^{\uparrow}$	1.2$^{\uparrow}$	2.9$^{\uparrow}$	2.1$^{\uparrow}$	0.27	0.029	0.013	0.51$^{\uparrow}$	120
Older needles	540	7.7	1.5$^{\uparrow}$	4.0	4.5	1.2	0.001$^{\downarrow}$	0.047	0.73	270
Needles, total	780	14	2.6	6.9	6.6	1.5	0.030	0.060	1.2	390
Tree biomass, total	8500	34	5.3	15	22	3.8	0.186	0.57	3.3	4300

↑: The used regression line (1991 and 1995) had an intercept that was significantly ($P\leq0.05$) higher than the intercept for the control.

↓: The used regression line (1991 and 1995) had an intercept that was significantly ($P\leq0.05$) higher than the intercept for the control.

⊗: The used regression line (1991 and 1995) had an intercept and slope significantly ($P\leq0.05$) different from the control plot.

3. Results

3.1. Biomass and nutrient distribution and accumulation

The slopes and intercepts of the regression equations expressing the biomass amounts in the various compartments as a function of DBH and tree height were not affected significantly by the treatments (Table 2). However, the nutrient contents in the different compartments were affected, most pronounced for needles and stem bark.

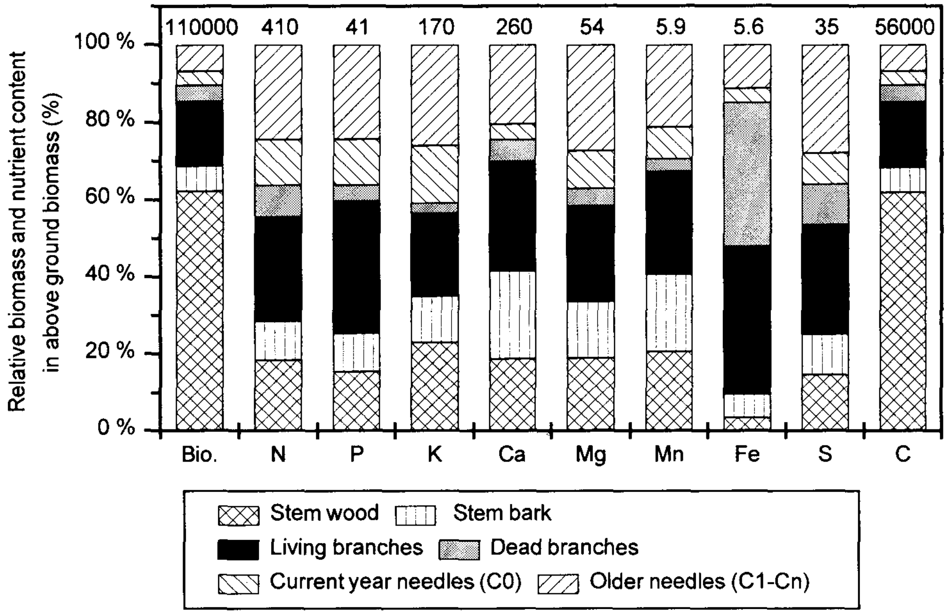


Figure 2. Relative distribution of biomass (Bio.) and nutrient contents of above ground biomass in the control plot. Figures at the top gives the biomass and nutrient content in the total above ground biomass (kg ha^{-1}).

The stem wood made up the main part (>60 %) of the biomass (Fig. 2). The main parts of N, P, K, Mg and S were located in the living branches and needles (>60 %). Ca was mainly located in the stem bark, living branches and needles (>70 %). C made up approximately 50 % of the biomass in all compartments.

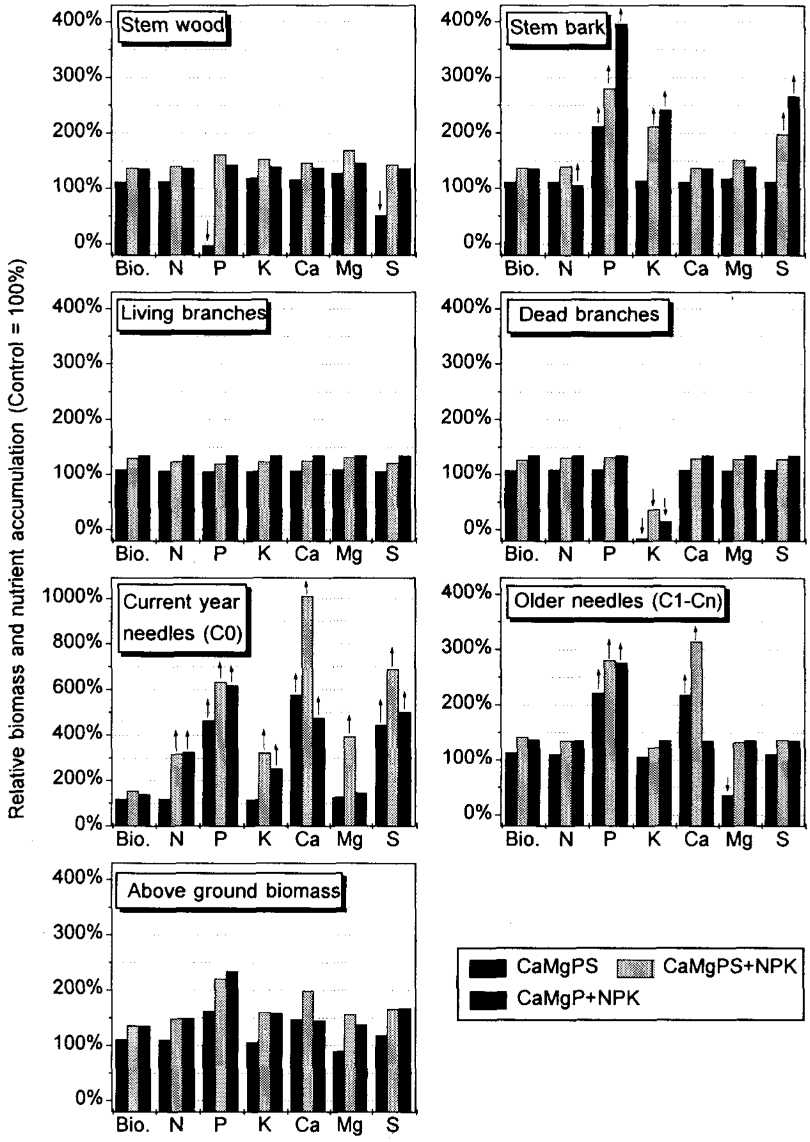


Figure 3. *Relative biomass (Bio.) and nutrient accumulation in various biomass compartments for the investigated treatments (CaMgPS, CaMgPS+NPK, CaMgP+NPK) compared to the control plot (100 %). Note that the y-axis for the current year needles (C0) has a different scale than for the other biomass compartments. Results from the statistical tests of the regression equations are indicated:*

↑: *The used regression line had an intercept significantly ($P \leq 0.05$) higher than the control plot (slope was not significantly affected by the treatment).*

↓: *The used regression line had an intercept significantly ($P \leq 0.05$) lower than the control plot (slope was not significantly affected by the treatment).*

The treatment effect on the accumulation of the biomass in various compartments was relatively small (Fig. 3). Furthermore, the stem volume increment was not affected significantly by the different treatments and there were no significant differences in stem volume increment between the different blocks (examined by Ingerslev, 1997a). However, the stem volume increment and the relative accumulated biomass in the various compartments was generally higher for the CaMgPS+NPK and CaMgP+NPK treated plots, than for the third treatment, most pronounced for the stem wood, bark and older needles (>35 %) (Fig. 3).

The effects of the treatments on the nutrient accumulation was most pronounced in stem bark and needles (Fig. 3). The treatments did not affect the relative biomass and nutrient accumulation in the branches notably. The relative accumulation of nutrients in the branches followed the same pattern for the different treatments as the relative accumulation of biomass. The decreased accumulation of K in the dead branches was an exception.

The relative accumulation of N increased in the above ground biomass (>40 %) and significantly in the current year needles (>200 %) in the N applied plots (Fig 3.). The relative accumulation of P increased notably in the above ground biomass (>50 %), and significantly in stem bark (>100 %), current year needles (>350 %) and older needles (>200 %) for all the treatments, most pronounced in the CaMgPS+NPK and CaMgP+NPK treated plots (Fig. 3). The relative accumulation of K increased in the aboveground biomass (>50 %), and significantly in stem bark (>100 %) and current year needles (>140 %) for the K applied plots (Fig. 3). The relative K accumulation in the dead branches decreased significantly to less than 50 % for all the treatments.

All the treatments increased the relative Ca accumulation in the above ground biomass (>40 %), current year needles (>350 %) and older needles (>30 %), most significantly for the CaMgPS+NPK treated plot (Fig. 3). The relative accumulation of Mg increased in the above ground biomass, stem wood and bark (>30 %) in the CaMgPS+NPK and CaMgP+NPK treated plots, but only significant in the current year needles for the CaMgPS+NPK treatment. The CaMgPS treatment did not affect the Mg accumulation in the above ground biomass, stem wood and bark notably. However, in the older needles the CaMgPS treatment decreased the relative Mg accumulation significantly to less than 50 % compared to the control plot.

The relative accumulation of S increased in the above ground biomass (>50 %), stem bark (>90 %) and in the current year needles (>390 %) in the CaMgPS+NPK and CaMgP+NPK treated plots (Fig. 3). The CaMgPS treatment did not affect the S accumulation in the above ground biomass and stem bark notably. However, in the current year needles the CaMgPS treatment increased the relative S accumulation significantly (>325 %).

3.2. Nutrient input and accumulation

The annual input of K, Mg and S with throughfall clearly exceeded the amounts accumulating in the biomass (Table 5.). The annual input of N with throughfall was of the same magnitude as the amounts accumulating in the above ground biomass in the control plot and in the CaMgPS treated plot, but not in the N applied plots, where the accumulation was higher. If the N accumulation in the below ground total biomass was taken into account too, the accumulation of N in the biomass would exceed the input with throughfall.. The annual flux of Ca with the throughfall was equal to the Ca accumulation in the above ground biomass in the control plot, whereas the Ca accumulation exceeded the flux of Ca in the throughfall for the Ca applied plots. The input of nutrients with fertilization generally exceeded the amounts that were accumulated in the above ground biomass for all the treatments. Furthermore, the applied amounts of Ca, Mg and S by far exceeded the annual accumulation.

The total applied amounts of K and especially Ca, Mg and S (Table 1.) exceeded what was present in the biomass in the control plot in 1995 and the total applied amount of N was approx. half the amount present in the biomass.

Table 5. *Yearly mean nutrient input with fertilization and throughfall from 1986 to 1995. Accumulated biomass and nutrient content from 1986 to 1995 and as total in 1995. Notice the differences in biomass units for the control plot. Throughfall (Beier and Rasmussen, 1993) and below ground biomass (Hansen and Thomsen, 1991) are from a nearby (2 km) Norway spruce stand 17 years older than the stand investigated in this study.*

Treatments	Bio.	N	K	Ca	Mg	S
Control						
Fertilization (kg ha^{-1} year^{-1})		27	19	9	2	6
Accumulated in above ground biomass (kg ha^{-1} year^{-1})	6200	23	9	15	3	2
Above ground biomass in 1995 (kg ha^{-1})	110000	410	170	260	54	35
Below ground biomass in 1995 (kg ha^{-1})	38000	340	54	150	43	37
Biomass in 1995 (kg ha^{-1})	150000	750	220	410	97	72
CaMgPS						
Fertilization (kg ha^{-1} year^{-1})		0	0	380	162	256
Accumulated in above ground biomass (kg ha^{-1} year^{-1})	6900	25	10	22	3	2
CaMgPS+NPK						
Fertilization (kg ha^{-1} year^{-1})		40	35	393	165	267
Accumulated in above ground biomass (kg ha^{-1} year^{-1})	8500	34	15	30	4	3
CaMgP+NPK						
Fertilization (kg ha^{-1} year^{-1})		40	35	396	165	11
Accumulated in above ground biomass (kg ha^{-1} year^{-1})	8500	34	15	22	4	3
Throughfall (kg ha^{-1} year^{-1})		23	28	16	22	36

4. Discussion

In the present study the biomass and nutrient distribution and accumulation was estimated by establishing linear regressions which described the relationship between DBH and tree height on the one hand and the biomass or nutrient contents of the various tree compartments on the other. A similar approach has been used by Nihlgård (1972), Andersson et al. (1995) and Andersson et al. (1997). Nihlgård (1972) noted that DBH^2 x H gave better correlations in the regressions than DBH x H or girth. In the present study it was assumed that the regressions established from trees sampled in autumn 1996 also were valid for the thinned trees in 1991 and that the regressions from control plot could represent all plots at the time of establishment of the trial in 1986. Naturally, this method implies a risk of introducing errors, since the regressions can not be validated for the past.

The regressions described the biomass of stem wood, stem bark and living branches with R^2>0.80. These compartments represented more than 85 % of the above ground biomass. However, the regressions for older needles (R^2=0.74) and especially current year needles (R^2=0.46) and dead branches (R^2=0.58) were weaker (Fig. 4). Nihlgård (1972) examined 8 sample trees and established strong regressions for stem wood (R^2=0.98), stem bark (R^2=0.98) and branches incl. needles (R^2=0.98) in a 55-year-old Norway spruce stand. Andersson et al. (1995) investigated a 55-year-old Norway spruce stand and established regressions with correlation coefficients of the same magnitude as in the present study. Both studies indicate that it may be difficult to establish good regressions for needles and dead branches. The extend of these biomass compartments is presumably largely dependent on the position and sizes of the neighbouring trees. However, the accuracy of the biomass and nutrient content estimations (except from Fe) in dead branches seem to be relatively unimportant when regarding the total above ground biomass (Fig. 2).

General biomass regression equations, relating the dry weight and nutrient content of different biomass compartments with the DBH, the tree height, and other easily measured physical variables have been presented in a number of studies (e.g. Nihlgård, 1972; Carey and O'Brien, 1979; Miller et al., 1980; Cromer et al., 1985; Marklund, 1987, 1988; Andersson et al., 1995; Brække and Håland, 1995; Mitchell et al., 1996). Marklund (1987; 1988) established biomass regression equations for Norway spruce from a large number of trees of different age and from various locations in Sweden. Despite the large variation within the nature and origin of the sample trees the regressions appeared strong (R^2>0.70). The results from the present biomass study of the control plot in 1995 have been compared with the corresponding estimates using Marklund's equations (Fig. 5). The differences between the two methods were small for stem wood and bark. For needles and especially branches, Marklund's equations gave a higher biomass. Presumably this was due to a lower stand density in the Swedish stands investigated by Marklund compared to the Danish stands in western Denmark. It is tempting to use e.g. Nihlgård (1972), Marklund (1987, 1988), or Andersson et al. (1995) for a preliminary investigation of the magnitude of biomass accumulation and distribution in fertilization experiments. However, the use of these equations may introduce serious errors since fertilization has been observed to alter the parameters in the equations (Carey and O'Brien, 1979; Andersson et al., 1995). In contrast, the present study did not reveal any significant treatment effects for the biomass compartments or the stem volume increment.

The treatment effect on stem volume increment (Ingerslev, 1997a) and the accumulated biomass in the various compartments was limited. However, the stem volume increment and accumulation of biomass in all the compartments was highest for both the treatments where liming, Ca, Mg, P and additional NPK were applied

(CaMgPS+NPK and CaMgP+NPK in Fig. 3). This indicates that the untreated stand may have suffered from a relatively low availability of one or more of the added nutrients and/or the stand may have suffered from growth reduction caused by the acid soil condition. However, the stand did not seem to have suffered from severe deficiency of any of the added nutrients since the general treatment response in biomass production was not significant and diagnostic needle analyses did not reveal severe deficiencies (Ingerslev and Halbäcken, 1997).

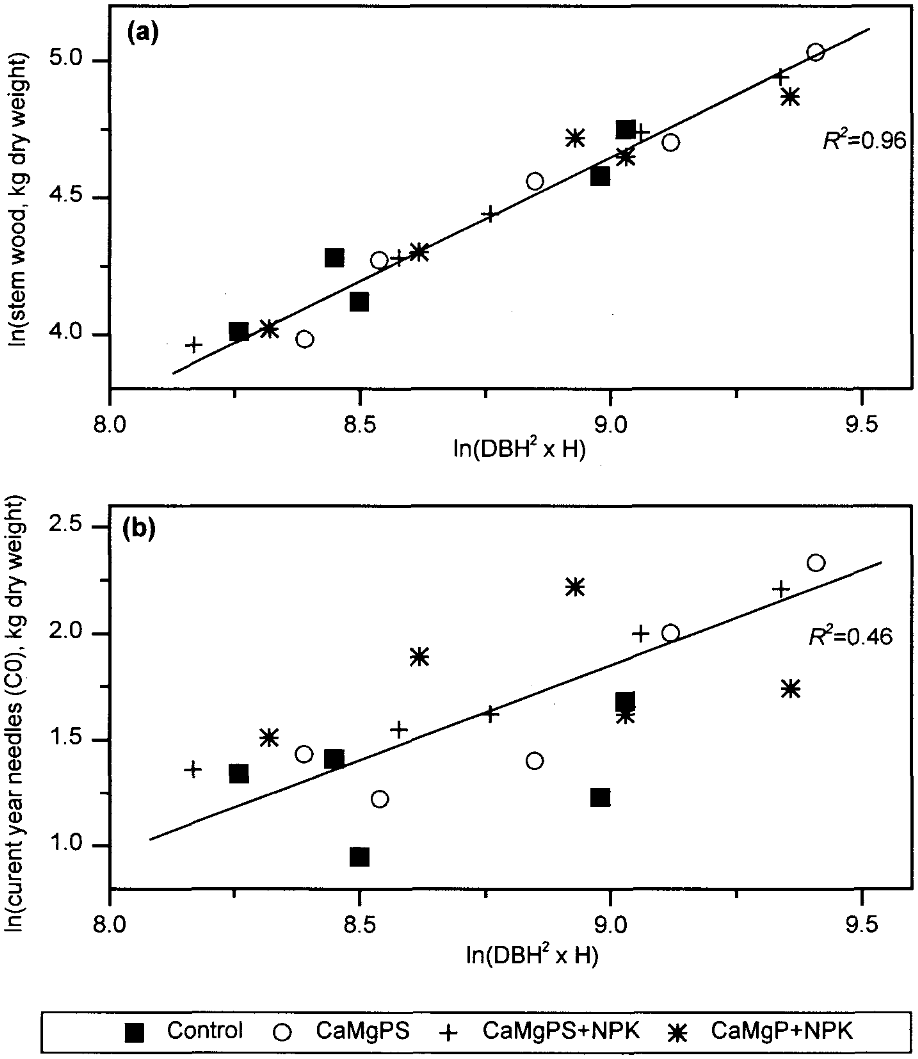


Figure 4. *The logarithm of the stem wood (a) and current year needle (C0) biomass (b) presented as functions for the logarithm of DBH^2 x H (DBH: breast height diameter; H: tree height) for the sample trees.*

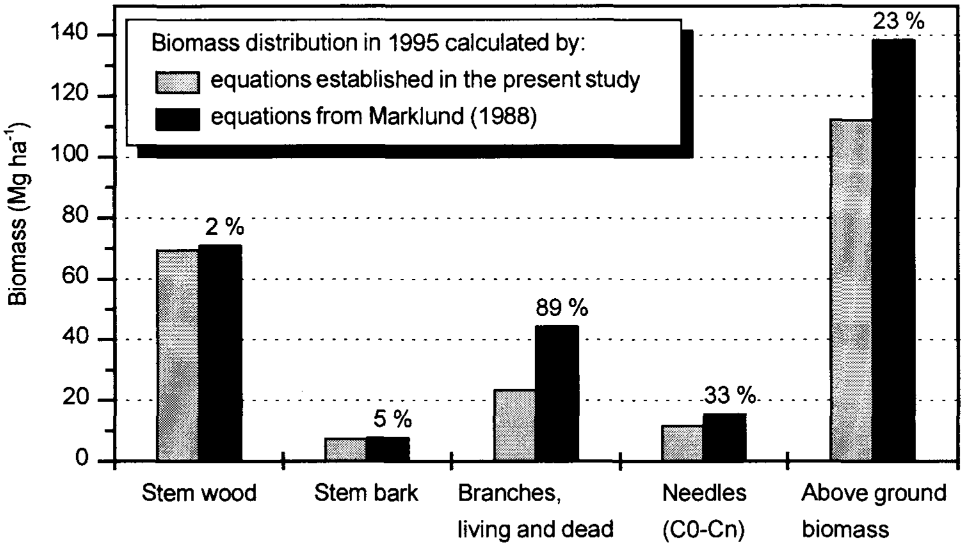


Figure 5. *The biomass in different tree compartments for the control plot calculated by the use of regression equations established in the present study and by the equations given by Marklund (1988). Differences indicated in %.*

The CaMgPS treatment had apparently no effect on the biomass accumulation in the various compartments. This treatment may on one hand have had the positive effect of increasing the availability of the added nutrients, but on the other hand the treatment may have caused acidification stress or even toxicity by inducing high concentrations of Al^{3+} and SO_4^{2-} in the soil solution in a period of time after the treatment was carried out. Indications of temporary growth reduction was observed in the CaMgPS treated plot (Ingerslev, 1997a).

Even though the biomass did not appear to be influenced by the different treatments, the accumulation and concentration of nutrients have evidently been affected. The nutrient accumulation in stem bark and needles, especially current year needles, appeared more sensitive to the treatments than the other compartments. The accumulation of P and Ca seemed to be very sensitive to the treatments. A large part of the Ca uptake can presumably be ascribed to luxury consumption since no indications of Ca deficiencies could be detected by needle analyses. However, P deficiency has been detected in current year needles from the control plot, but this deficiency has been counteracted by the treatments containing a large doze of P (CaMgPS, CaMgPS+NPK, CaMgP and CaMgP+NPK). A detailed description of the diagnostic needle analyses is given by Ingerslev and Hallbäcken (1997) and a description of the treatment effect on the nutrient concentration in the different biomass compartments is given by Ingerslev (1997b, Part I).

The results presented in Table 5 indicate that there might be a need for application of additional N and Ca because the nutrient accumulation in the total biomass exceeds the nutrient input with throughfall in the control plot, assuming that the mineral weathering does not contribute notably to the nutrient input. Other studies of Norway spruce stands on nutrient poor soils in this area of Denmark have also indicated that Ca deficiency may become a problem in the future if intensive removal of biomass through forest management continues and application of additional Ca is neglected (Vejre, 1995; Pedersen and Beier, 1996). The present findings indicated that only a small percentage of the added Ca, Mg and S was accumulated in the aboveground biomass during the investigation period (9 years). However, the added Ca and Mg may have increased the long term availability of these nutrients since a substantial part of the added Ca and Mg was accumulated in the soil (Ingerslev, 1997a).

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PAPER IV

Nutrient status and vitality in a limed and fertilized Norway spruce plantation in Denmark

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Nutrient status and vitality in a limed and fertilized Norway spruce plantation in Denmark

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Abstract. Different strategies for assessing the vitality of the trees were applied in a combined liming and fertilization trial established in a 50-year-old Norway spruce (*Picea abies* (L.) Karst.) stand on a nutrient poor soil. Stem volume increment and biomass accumulation were not significantly affected by the treatments. Needle analysis showed that N and P deficiencies were overcome by the applications. The effect of conventional NPK fertilization on the nutrient status in current year needles had ceased five years after treatment. The variation in the vitality indicators (defoliation, needle discoloration, "index of vigour", needle productivity, presence of cones) was small. Although the N and P status was improved, some of the measured vitality indicators did not reflect this improvement. The reason for this was presumably that the trees at the initiation of the experiment did not have low vitality caused by severe nutrient deficiencies. However, the treatments combining liming with NPK fertilization overcame the N and P deficiency, and increased the "index of vigour", the needle productivity, the accumulation of above ground biomass, and decreased the defoliation notably. With the exception of the nutrient status these effects were noised by within plot variation and could not be proven statistically significant.

Keywords: nutrient status; vitality; index of vigour; fertilization; liming; Norway spruce; *Picea abies*; needle chemistry; nutrient deficiency; nutrient uptake.

1. Introduction

Atmospheric deposition of N and S compounds as well as removal of biomass from the forests may imply soil acidification, imbalanced forest nutrition and eventually a declining forest health status, especially on nutrient poor soils (Berdén et al., 1987; Evers and Hüttl, 1990/91). Nitrogen deposition, soil acidification and leaching of nutrients may lead to relative nutrient deficiency (Ca, Mg, K and other elements) compared to N (Evers and Hüttl, 1990/91). Soil acidification and a subsequent increased Al concentration in the soil solution may cause Al toxicity (Godbold et al., 1988). The increased Al concentration may furthermore lead to P immobilization and potentially P deficiency (Andersson, 1988). Intensive forestry increases the risk of developing nutrient deficiencies by removal of wood and thereby nutrients from the forest ecosystem (Berdén et al., 1987).

Soil acidification and imbalanced forest nutrition are often considered to be among the primary causes of the decline in forest health conditions observed in many forests on nutrient poor soils in Europe during the last decades (Ulrich, 1983; Zoettl and Huettl, 1986; Evers and Hüttl, 1990/91; EC-UN/ECE, 1996). Acidification of Danish forest soils due to atmospheric deposition has been documented by Rasmussen (1988) and Pedersen (1993). The health condition of Danish Norway spruce (*Picea abies* (L.) Karst.) forests expressed as needle loss has declined from 1989 to 1994 (Danish Forest and Nature Agency 1996). Severe nutrient deficiencies have so far only been documented in few Danish Norway spruce plantations. Long-term investigations on forest soils in western Denmark indicated that deficiencies of K, and to some extent P, may be expected (Lundberg and Ravnsbæk, 1992; Clausen, 1995; Dralle and Larsen, 1995; Pedersen and Bille-Hansen, 1995).

Soil acidification and imbalanced forest nutrition in Norway spruce stands have been counteracted by liming and fertilization on nutrient poor soils in Sweden (Rosengren-Brinck, 1994; Svenson et al., 1995) and Germany (Huettl and Zoettl, 1993; Meiwes, 1995). Liming and fertilization of stands on nutrient poor sites in Denmark have been widely discussed, but so far without any general national decision on forest management practice. Liming of Danish forest soils has traditionally been limited because of the risk of increasing butt rot infestation (Matthesen, 82). Previously, the main aim of fertilization in stands older than 10-20 years was to increase the stem volume production. Today the main aim has changed in direction of revitalization of the stands by stabilizing a balanced nutrient supply, improving the nutrient status of the trees, and counteracting ongoing acidification of the forest soil. In this perspective, it is essential that concepts such as tree vitality, nutrient availability, nutrient status, imbalanced nutrition, and nutrient deficiency are properly defined and made measurable.

In this study an old fertilization and liming experiment in Norway spruce was revisited and continued in order to investigate the vitality of the trees. Different strategies and methods were applied to clarify the vitality concept and define how it can be measured. The effects of liming and fertilization on the nutrient uptake, nutrient status, and vitality were examined. The present study was carried out as part of a Nordic project entitled "Imbalanced forest nutrition - Vitality measures" aiming at clarifying the vitality concept (Andersson et al., 1997).

2. Materials and methods

2.1. Site description

The research site was located at Klosterheden State Forest in western Jutland, Denmark (8°27'E, 56°27'N), 20 km from the North Sea, 33 m above sea level. The topography was flat and the soil was well drained. The soil was a nutrient poor coarse sandy haplic podzol (FAO, 1977) with low clay content (<3 %) developed on a glacio-fluvial deposite. A detailed description of the soil and soil solution chemistry is given by Ingerslev (1997a). The annual precipitation was 860 mm, with only a small percentage as snow. Annual mean temperature was 9°C, with a mean January temperature of 0.3°C and a mean July temperature of 16°C. Westerly winds from the North Sea, often strong, dominated. The total deposition of nitrogen was approximately 25 kg N ha^{-1} year^{-1} (55 %

NH_4^+ and 45 % NO_3^-) and the deposition of S from anthropogenic sources was approximately 25 kg S ha^{-1} year^{-1} (Gundersen and Rasmussen, 1995). The examined stand was an even-aged Norway spruce plantation, 59 year old from seed (1995), with a stand density of approx. 800 trees per ha after commercial thinning in 1991. The average height was 16 m, and the stem volume was 225 m^3 ha^{-1} (1996). The stand was second generation after heathland.

2.2 Treatments and experimental design

Liming and fertilization trials were established in 1986 with combinations of conventional NPK fertilizer, two different liming treatments (calcite and dolomite), and additional P and S (Table 1). The design included five different treatment plots replicated in three blocks. Each plot was 0.15 ha and encompassed approximately 120 trees.

Table 1. *Applied amounts of nutrients in the different treatments. Note that different types of NPK fertilizers have been applied.*

		N	P	K	Ca	Mg	S	Applications
		Kg ha^{-1}						
Pretreatment	Year							
All plots	1977	120	15	35	-	-	-	NPK-23:3:7[a]
All plots	1982	120	33	80	35	7	-	NPK-18:5:12[a] (incl.: Mg, Cu and B)
Treatment	Year							
Control	1986	120	31	140	43	9	37	NPK-14:4:17[a] (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7[a] (incl.: Mg, Cu and B)
NPK	1986, 1994	120	31	140	43	9	37	NPK-14:4:17[a] (incl.: Mg, Cu and B)
	1991	120	15	34	40	8	21	NPK-23:3:7[a] (incl.: Mg, Cu and B)
CaMgPS	1986, 1994	-	200	-	1710	730	1150	Calcite[b], kieserite[c], 'superphosphate'
CaMgPS+NPK	1986, 1994	120	230	140	1750	740	1190	Combination of NPK and CaMgPS
	1991	120	15	34	40	8	21	NPK-23:3:7[a] (incl.: Mg, Cu and B)
CaMgP	1986, 1994	-	200	-	1720	730	-	Dolomite[d], 'rock-phosphate'
CaMgP+NPK	1986, 1994	120	230	140	1760	740	37	Combination of NPK and CaMgP
	1991	120	15	34	40	8	21	NPK-23:3:7[a] (incl.: Mg, Cu and B)

a: conventional agricultural NPK fertilizer containing approximately 50 % NO_3^-, 50 % NH_4^+, Cl<2 %, and K as a mixture of KCl and K_2SO_4.

b: $CaCO_3$.

c: $MgSO_4$.

d: $CaMg(CO_3)_2$.

The NPK fertilization was repeated in spring 1991 with a NPK fertilizer slightly different from the one used in 1986 (NPK, CaMgPS+NPK and CaMgP+NPK, Table 1). All 1986 applications were repeated in the spring 1994 (Table 1). Prior to the establishment of the experiment the stand was fertilized with NPK fertilizers in 1977 and in 1982 as part of common practice in this forest district (Table 1).

Since the whole stand had been fertilized in 1977 and 1982, no true control plots could be established. In spring 1994, three earlier NPK fertilized plots were included as control plots. Before 1994, these control plots were treated parallel to the NPK treated plots (Table 1). The full replicated experimental design was used for stem growth measurements only. Other measurements were for resource reasons limited to trees in one block.

2.3. Measurements

Determination of the stem volume increment was carried out and reported by Ingerslev (1997a). Ten co-dominant trees in each of the six plots in one block were selected for needle sampling, determination of defoliation, needle discoloration, and observation of the presence of cones in autumn 1995, two growing seasons after the last treatments were carried out. Defoliation and discoloration were determined by visual inspection and expressed as % defoliation or discoloured needles, according to the ICP Forests Manual (UN/ECE, 1994). Current year (C0) and older (C1-C4) needles from a south facing branch from the 5th whorl were sampled in November 1995. The needles were dried at 55 ^{0}C. Sub-samples were ground and used for chemical analysis. The N concentration was measured by combustion in a LECO-CHN 1000 elemental analyzer. After digestion in concentrated nitric acid in a microwave oven, the concentrations of Ca, Mg, K, Fe, Mn, Na, P and S were measured by ICP-AES (Perkin Elmer, optima 3000 XL).

The above ground biomass and nutrient distribution and accumulation (1986-1995) were determined on a ground surface area basis in studies by Ingerslev (1997b) and Ingerslev and Hallbäcken (1997). This work was carried out in four plots (control, CaMgPS, CaMgPS+NPK, CaMgP+NPK) in one block dividing the aboveground biomass in seven compartments; stem wood, stem bark, living branches (incl. bark and wood), dead branches (incl. bark and wood), current year needles (C0), older needles (C1-Cn) and cones. Furthermore the cross sectional sapwood area at both breast height and at canopy limit was determined for the biomass sampling trees (five trees per plot in four treatments: control, CaMgPS, CaMgPS+NPK and CaMgP+NPK) (Ingerslev and Hallbäcken, 1997)

In autumn 1994, two stem cores were taken at breast height from the east and west side of 15 co-dominant trees per plot in one block (total=180 core samples) in order to estimate the "index of vigour" as defined by Münster-Swendsen (1987). The extent of the sapwood and the current year ring was marked on the cores and the cross sectional sapwood area and current year basal area growth at breast height were estimated.

2.4. Calculations and statistics

Statistical tests were carried out using the examined trees in each plot as pseudoreplicates to reveal treatment related differences within the investigated block. The interpretation of these statistical results was thus limited to this block only.

Statistical tests were carried out by SAS, PROC GLM to determine whether the treatments had affected the chemical composition of the needles and defoliation, and whether there was a difference between the nutrient concentration in the current year needles and older needles.

The relative nutrient uptake (RNU) was calculated for the accumulated needle biomass and the total above ground biomass (accumulated within the period from 1986 to 1995) using the method described by Hallbäcken (1997):

$$RNU_x=(m_{x,\ treatment}/m_{c,\ treatment})/(m_{x,\ control}/m_{c,\ control})$$

Where	RNU	is the relative nutrient uptake.
	x	is the nutrient in question.
	$m_{x,\ treatment}$	is the amount of the nutrient (x) accumulated in the needle biomass or in the above ground biomass in the treated plot.
	$m_{c,\ treatment}$	is the amount of carbon (C) accumulated in the needle biomass or in the above ground biomass in the treated plot.
	$m_{x,\ control}$	is the amount of the nutrient (x) accumulated in the needle biomass or in the above ground biomass in the control plot.
	$m_{c,\ control}$	is the amount of carbon (C) accumulated in the needle biomasss or in the above ground biomass in the control plot.

The size of the biomass and nutrient pools was determined by Ingerslev and Hallbäcken (1997).

Plotting of the RNU along with the C accumulation (Fig. 2) provides information concerning which nutrients that will be the most plausible growth limiting elements in relation to the control plot, when a specific treatment is carried out (Hallbäcken, 1997). The horizontal line in Fig. 2 indicates the *iso-concentration line* in relation to the control plot and the vertical line in Fig. 2 indicates the *iso-biomass production line* in relation to the control plot. The treatment effects on the long-term net accumulation of a specific nutrient compared to the control may be categorized in 4 groups (A, B, C and D, see N in Fig. 2) by separating the treatment response according to the *iso-concentration* and *iso-biomass production lines* (Hallbäcken, 1997):

Group A Both the relative C accumulation and the RNU is decreased, indicating a treatment induced deficiency of a main limiting nutrient (probably the nutrient in question).

Group B	The relative C accumulation is increased, whereas the RNU is unchanged or decreased, indicating that the treatment has led to a higher efficiency of the trees to utilize the nutrient taken up for carbon accumulation. Decreased RNU may indicate an increased risk of deficiency of the nutrient in question at a future stage.
Group C	Both the relative C accumulation and the RNU are increased, indicating that the nutrient in question initially (before treatment) restricted the accumulation of C and that the nutrient status has been improved by the application.
Group D	The relative C accumulation is decreased, whereas the RNU is increased, indicating a possible treatment induced deficiency of an other nutrient than the one in question.

Linear regressions between the needle biomass and cross-sectional sapwood area ((needle biomass, kg)=$\alpha+\beta$*(sapwood area, cm^2)) were established from data of the sapwood area both at breast height and at canopy limit for the biomass sampling trees. The linear regressions were calculated using SAS, PROC REG and the following hypotheses were tested by SAS, PROC GLM using the five trees from each plot as pseudoreplicates: i) the lines had no slope ($\beta=0$), ii) the line for the sap wood area at breast height had the same intercept and/or slope as the line for the sapwood area at canopy limit ($\alpha_{\text{breast h.}}=\alpha_{\text{canopy l.}}$, $\beta_{\text{breast h.}}=\beta_{\text{canopy l.}}$) when differences between the treatments were disregarded, and iii) the line for a specific treatment and height of sap wood area measurement had the same intercept and/or slope as the control ($\alpha_{\text{treatment}}=\alpha_{\text{control}}$, $\beta_{\text{treatment}}=\beta_{\text{control}}$).

The "index of vigour" was calculated for each tree as the ratio between the current year basal area growth and the sapwood area at breast height using the core samples. Statistical tests were carried out using SAS, PROC GLM to determine if the treatments had affected the "index of vigour" and whether the "index of vigour" or defoliation was dependent on the stem volume increment within the treatment period (1986-1994) or on the tree size measured as total stem volume.

The ratio between the forest production (expressed as e.g. stem volume increment, or stem biomass or above ground biomass accumulation) and the needle biomass is often referred to as the needle productivity (Andersson et al., 1995; Hallbäcken, 1997). The needle productivity expresses the same ratio as the "index of vigour" by means of other parameters. The needle productivity was calculated as the ratio between the average accumulated above ground biomass from 1986 to 1995 and the needle biomass present in 1995 from data for the biomass sampling trees examined by Ingerslev and Hallbäcken (1997).

Statistical differences were considered significant at the $P \leq 0.05$ level unless otherwise stated.

3. Results

3.1. Diagnostic needle analyses

The nutrient concentrations in the current year needles were compared to the nutrient status threshold values given by Brække (1994) and Linder (1995) (Fig. 1a and b and Table 2). Concentrations of N, K and P were generally higher in current year needles than in older needles, (Fig. 1a) whereas the opposite pattern was observed for Mg, Ca and Mn (Fig. 1b).

The concentration of N was within the range of deficiency, but reached pre-optimum levels with added N (Fig. 1a). The concentration of N in current year needles from the control plot was significantly lower than that in any of the treated plots. The concentration of P was significantly higher in the treated plots compared to the control plot (deficiency) and the NPK treated plot (pre-optimum) compared to the other treatments (optimum) (Fig. 1a). The concentrations of K, Ca, Mg and Mn were within the range of optimum in all plots (Fig. 1a and b). The concentration of Ca was significantly higher for the Ca addition plots compared to the other plots (Fig. 1b).

The interpretation of the nutrient/N-ratios was difficult since N concentrations in needles were below optimum in all the plots. The K/N, Ca/N, Mg/N and Mn/N-ratios were above the suggested optimum values for all the treatments (Table 2). The P/N-ratio was close to optimum in the control plot and in the NPK treated plot, and significantly above optimum for the other treatments, particularly for the CaMgPS and CaMgP treatments. The K/N-ratio was significantly higher in the control plot than in any of the other treatments. The P/N, Ca/N and Mg/N-ratios were lowest for the NPK treatment.

Tabel 2. *N concentration and nutrient/N-ratios in current year needles. Suggested optimum threshold values are included. Small letters denotes significant differences between the treatments ($LSD_{0.95}$-test).*

	N (mg g^{-1})	P/N	K/N	Ca/N	Mg/N	Mn/N
Optimum Brække (1994)	18	10	39	4	4	0.08
Optimum Linder (1995)	18	10	35	2.5	4	0.05
Control	13 ^{d}	11 ^{c}	55 ^{a}	18 ^{b}	9.0 ^{ab}	0.95 ^{ab}
NPK	17 ^{a}	9 ^{c}	49 ^{ab}	13 ^{c}	7.0 ^{c}	0.60 ^{c}
CaMgPS	14 ^{c}	16 ^{a}	51 ^{ab}	35 ^{a}	9.2 ^{ab}	0.93 ^{ab}
CaMgPS+NPK	16 ^{ab}	14 ^{b}	53 ^{ab}	32 ^{a}	8.9 ^{ab}	0.80 ^{b}
CaMgP	15 ^{bc}	17 ^{a}	51 ^{ab}	30 ^{a}	9.5 ^{a}	1.00 ^{a}
CaMgP+NPK	16 ^{a}	13 ^{b}	48 ^{b}	22 ^{b}	8.1 ^{b}	0.51 ^{c}

1a.

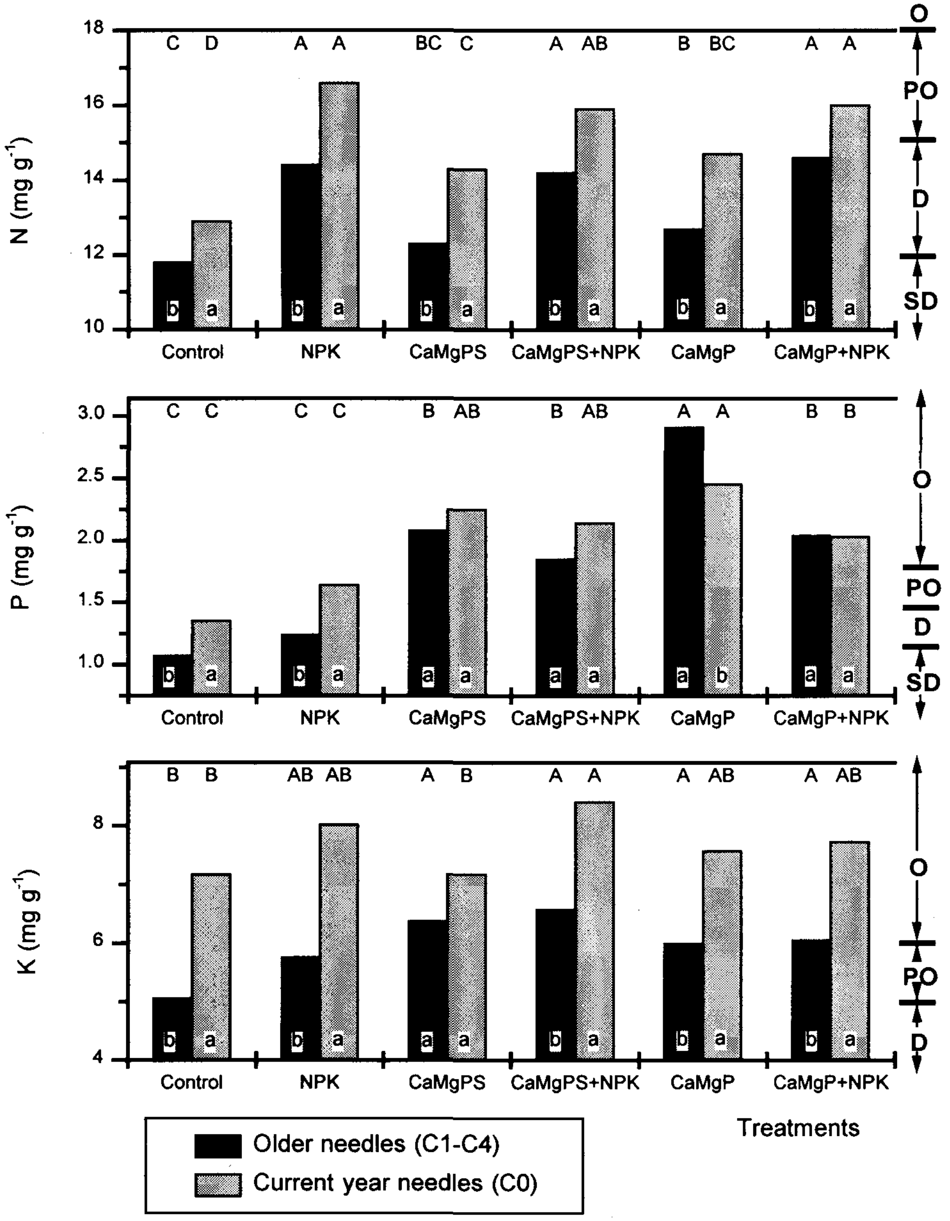
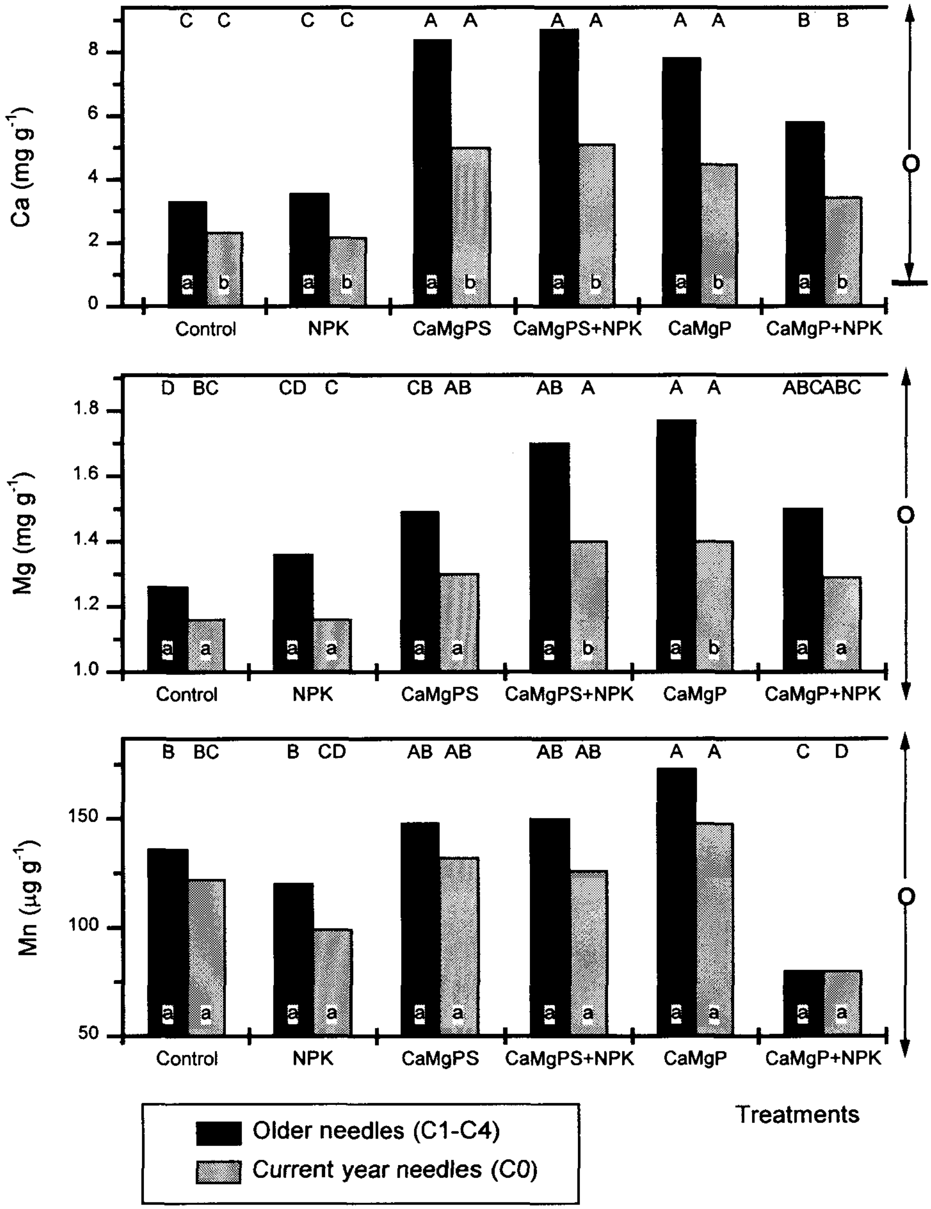


Figure 1a and b. Concentration of N, P, K, Ca, Mg and Mn in current year needles (C0) and older needles (C1-C4) (10 trees per plot). Different small letters denotes significant differences between the two needle age classes ($LSD_{0.95}$-test). Different capital letters denotes significant differences between the treatments ($LSD_{0.95}$-test). Intervals given at the right side of the figure denotes O=Optimum, PO=Pre-Optimum, D=Deficiency, SD=Strong deficiency for current year needles (Brække, 1994).

1b.



C C C C A A A A A A B B
Ca (mg g-1)
0
2
4
6
8
a b a b a b a b a b a b
O
Control
NPK
CaMgPS
CaMgPS+NPK
CaMgP
CaMgP+NPK
D BC CD C CB AB AB A A A ABCABC
Mg (mg g-1)
1.0
1.2
1.4
1.6
1.8
a a a a a a a b a b a a
O
Control
NPK
CaMgPS
CaMgPS+NPK
CaMgP
CaMgP+NPK
B BC B CD AB AB AB AB A A C D
Mn (µg g-1)
50
100
150
a a a a a a a a a a a a
O
Control
NPK
CaMgPS
CaMgPS+NPK
CaMgP
CaMgP+NPK
Older needles (C1-C4)
Current year needles (C0)
Treatments

3.2. Relative nutrient uptake and C accumulation

The C accumulation in the above ground biomass was not significantly affected by any of the treatments. The results however indicated that the C accumulation in the above ground biomass was increased approximately 35 % in the CaMgPS+NPK and CaMgP+NPK treated plots compared to the control (Fig. 2).

The RNU in the needles followed the same pattern of change with treatment as the RNU in the above ground biomass (Fig. 2). However, the treatments affected the RNU in the needles much stronger than that in the above ground biomass (Mn was an exception). The RNU_N, RNU_K and RNU_{Fe} were not affected notably by the different treatments, whereas RNU_{Mg}, RNU_S and RNU_{Mn} were affected moderately and RNU_P and RNU_{Ca} were affected strongly (Fig. 2).

None of the nutrients were found in group A and D in Fig. 2. None of the treatments appear to have induced a risk of N, P, K, Ca, S and Fe deficiency. However, Fig. 2 indicates that there may be a risk of Mg deficiency in the CaMgPS treated plot and of Mn deficiency in all the treated plots in the future. However, at present the concentration of Mg and Mn in the needles is at optimum according to Fig. 1b.

3.3. Sapwood area and needle biomass

Needle biomass was correlated with the sap wood area at canopy limit (Fig. 3 and Table 3), whereas for the sap wood area at breast height, three of the treatments had a slope that were not significantly different from 0 (Table 3). There was a significant difference between the lines (slope and intercept) for the sap wood area at breast height and at canopy limit, when differences between the treatments were disregarded. The needle biomass was better correlated with the sap wood area at canopy limit (R^2=0.68) than at breast height (R^2=0.37) when disregarding differences in treatments. There were no significant differences between the lines for the control plot and the treated plots for neither the sap wood area at breast height nor at canopy limit. However, the test of a treatment effect on the correlation was very close to being significant (P=0.057) for the intercept (Table 3).

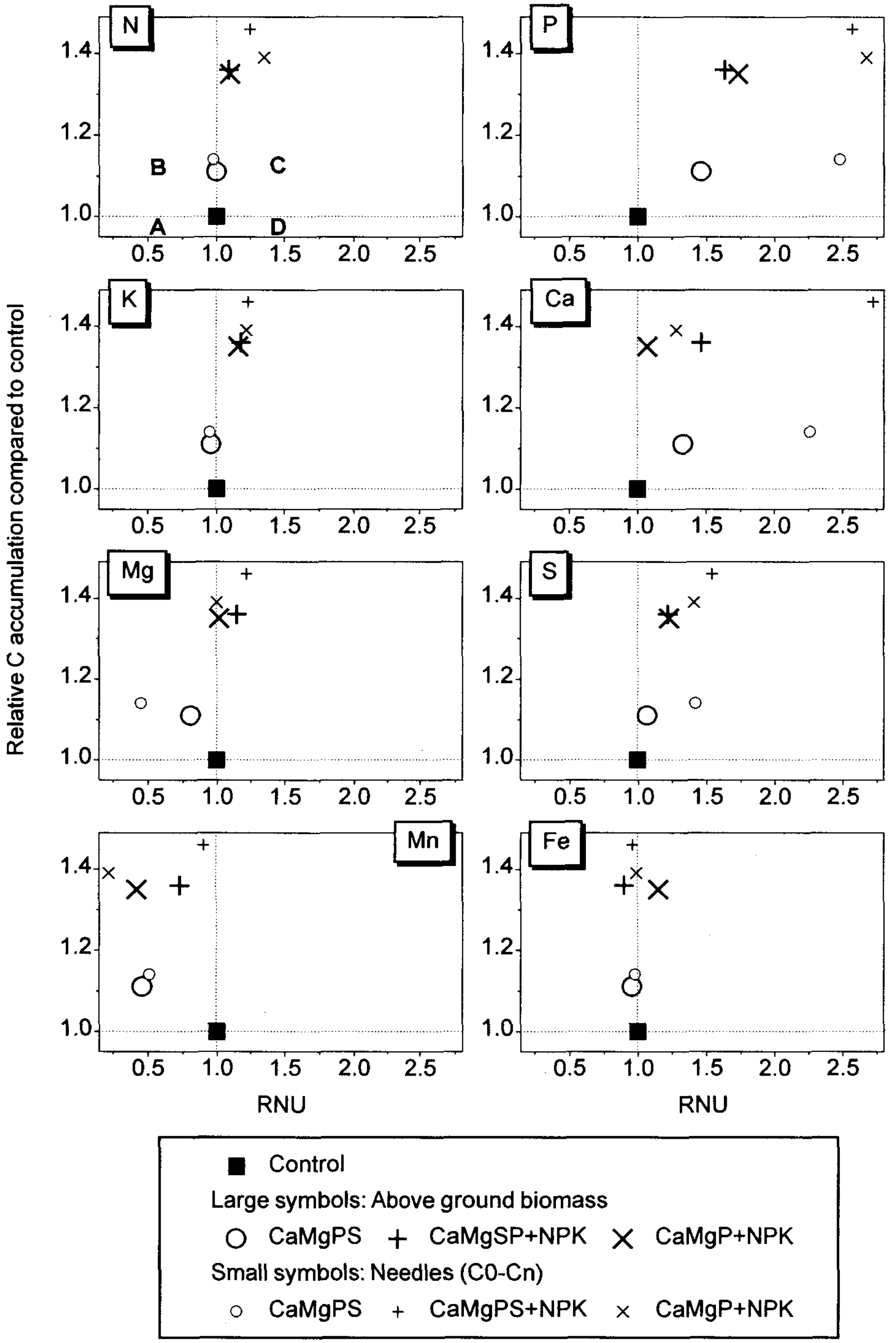


Figure 2. *The relative C accumulation in the above ground biomass as a function of the relative nutrient uptake (RNU) of N, P, K, Ca, Mg, S, Mn and Fe in the above ground biomass and needles. Group A, B, C and D are explained in the text.*

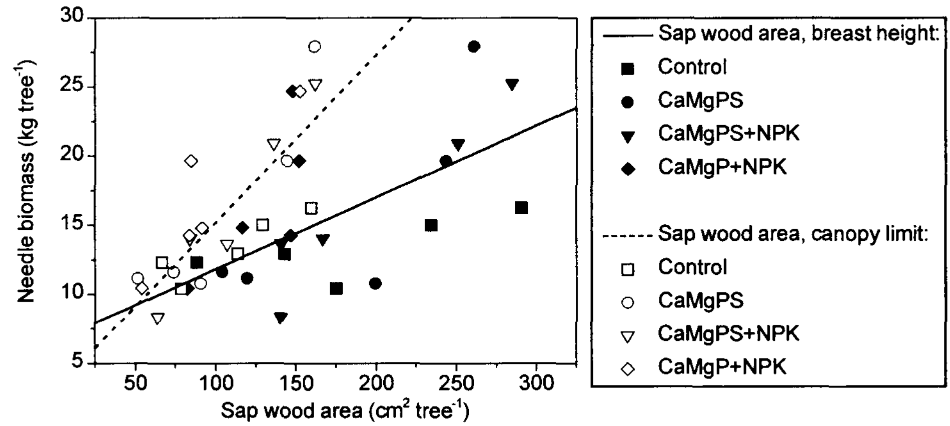


Figure 3. *Needle biomass presented as functions of the sapwood area at breast height (130 cm) and at canopy limit for 20 trees (5 trees per plot, from three treatments and control). Regression equations are presented in Table 3.*

Tabel 3. *Linear regression: (needle biomass, kg)=$\alpha+\beta$*(sap wood area, cm^2). The equations are based on 20 sample trees, five from each plot (N=20, n=5). P-values for statistical test: H_0: $\beta=0$, H_0: $\alpha_{breast\ height}=\alpha_{canopy\ limit}$, H_0: $\beta_{breast\ height}=\beta_{canopy\ limit}$, H_0: $\alpha_{treatment}=\alpha_{control}$, H_0: $\beta_{treatment}=\beta_{control}$ Bold and underlining indicates that the P-value was significant ($P\leq 0.05$).*

	α	β	R^2	*P* $\beta=0$	*P* $\alpha_{\text{breast h.}}=\alpha_{\text{canopy l.}}$	*P* $\beta_{\text{breast h.}}=\beta_{\text{canopy l.}}$
All observations (*n*=40)	9.06	0.0475	0.30	**0.0001**	**0.0041**	**0.0148**
Treatments	α	β	R^2	*P* $\beta=0$	*P* $\alpha_{\text{treat.}}=\alpha_{\text{cont.}}$	*P* $\beta_{\text{treat.}}=\beta_{\text{cont.}}$
Breast height						
All treatments (*n*=20)	6.63	0.0519	0.37	**0.0004**	0.11	0.15
Canopy limit						
All treatments (*n*=20)	3.08	0.121	0.68	**0.0001**	0.057	0.19
Breast height						
Control (*n*=5)	9.38	0.0216	0.55	0.15		
CaMgPS (*n*=5)	0.472	0.0848	0.65	0.10		
CaMgPS+NPK (*n*=5)	-2.28	0.0950	0.92	**0.011**		
CaMgP+NPK (*n*=5)	-1.27	0.139	0.56	0.14		
Canopy limit						
Control (*n*=5)	7.43	0.0545	0.81	**0.038**		
CaMgPS (*n*=5)	0.901	0.146	0.84	**0.028**		
CaMgPS+NPK (*n*=5)	-1.74	0.163	0.95	**0.005**		
CaMgP+NPK (*n*=5)	3.93	0.137	0.82	**0.035**		

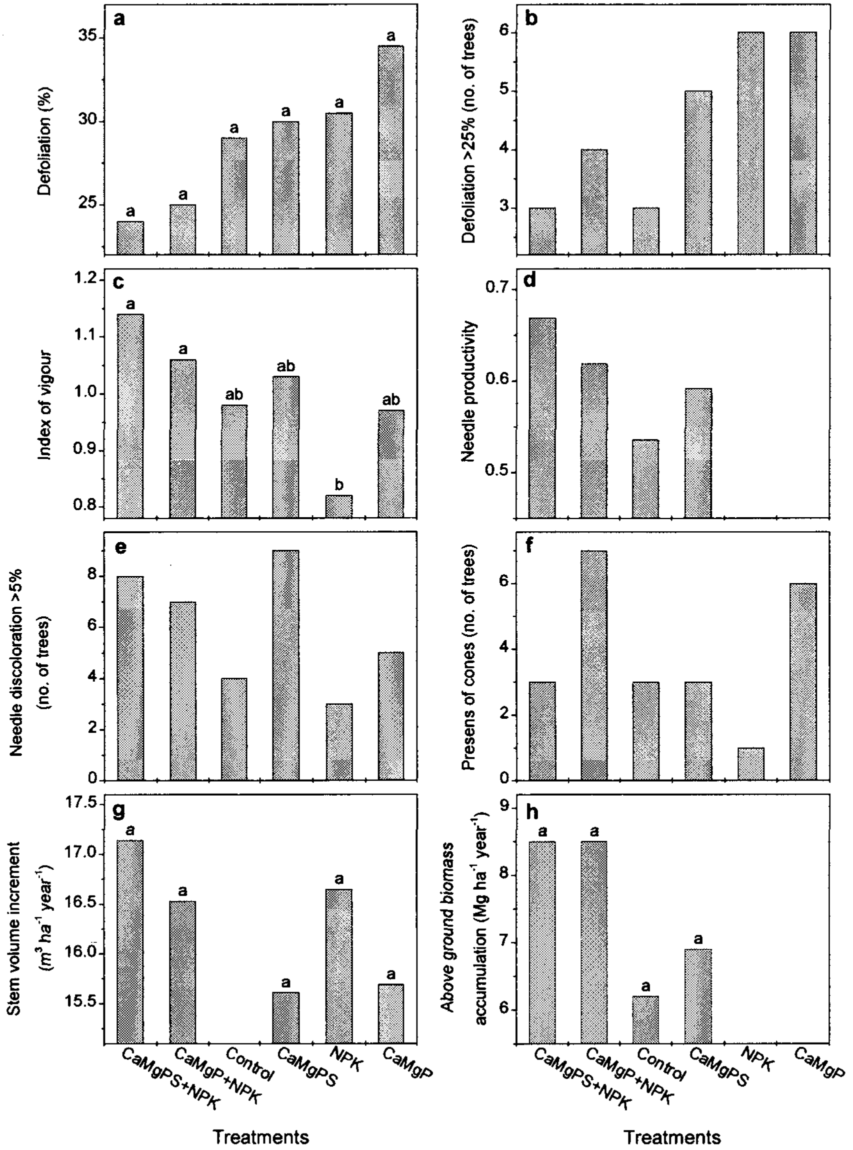


Figure 4. *Vitality indicators: a) defoliation (10 trees per plot in one block), b) number of trees with defoliation above 25 %, (10 trees per plot in one block), c) "index of vigour" (two stem core samples per tree from 15 trees per plot in one block), d) needle productivity (the ratio of the mean accumulation of above ground biomass to the needle biomass; 5 trees per plot, from four plots in one block), e) needle discoloration (10 trees per plot in one block), f) presence of cones (10 trees per plot in one block), g) mean stem volume increment given by Ingerslev (1997a) (stem volume was not measured in the control plot before 1994), and h) Above ground biomass accumulation given by Ingerslev and Hallbäcken (1997). Different small letters denotes significant differences between the treatments (LSD$_{0.95}$-test).*

3.4. Vitality indicators

Trees with defoliation and/or discoloration above 25 % (Fig. 4b) are considered "damaged" according to the ICP Forests Manual (UN/ECE, 1994). According to the degree of defoliation, the lowest number of damaged trees was observed for the CaMgPS+NPK and CaMgP+NPK treated plots and the control plot (Fig. 4b). None of the trees were considered damaged according to the results concerning discoloration.

Vitality indicators such as defoliation, "Index of vigour", needle productivity, needle discoloration, presence of cones, stem volume increment, and above ground biomass accumulation were generally not found to be significantly affected by the different treatments (Fig. 4). The results indicated, however that the CaMgPS+NPK and CaMgP+NPK treated plots had the lowest defoliation (Fig. 4a), the highest "index of vigour" (Fig. 4c) and needle productivity (Fig. 4d), as well as a relatively higher stem volume increment (Fig. 4g) and above ground biomass accumulation (Fig. 4h). On the other hand these plots also contained a relatively high number of trees with discoloured needles (Fig. 4e). The number of trees with cones apparently increased in the calcite applied plots (Fig. 4f).

No statistically significant relationships between the indicators were found although increasing defoliation seem to correspond with decreasing "index of vigour", needle productivity, and stem volume increment. As expected the "index of vigour" followed the same treatment related pattern as the needle productivity. Since not all indicators were measured on the same trees correlations could only be tested for a few of the indicators: defoliation and "index of vigour" was not significantly dependent on the stem volume increment within the treatment period nor on the total stem volume.

4. Discussion and conclusions

4.1. Stem volume and biomass production

None of the examined treatments affected the stem volume increment (Ingerslev, 1997a) and above ground biomass accumulation to a statistical significant extend. Thus indicating that the investigated stand did not suffer from severe growth restriction due to lack of any of the applied nutrients. Other factors such as poor water supply, wind stress, fungal infestation etc. may be more limiting. Another explanation for the poor treatment response of biomass production may be the relative old age of the trees. Old trees presumably retranslocate larger amounts of nutrients in comparison with the amounts taken up from the soil (Miller, 1981). However, the results indicated that the accumulation of above ground biomass, stem wood and bark biomass and current year needle biomass, was highest for the treatments where NPK had been applied in combination with additional liming (more than 30 % compared to the control plot) (Ingerslev and Hallbäcken, 1997).

4.2. Nutrient status and uptake

The relevance of the control plot, established for the latest treatments in 1994, was tested with respect to the chemical composition of the needles by comparison with a similar unfertilized stand nearby (Gundersen, 1997). No significant differences in the chemical needle composition between the stands were found. Thus current year needles from the control plot in the present study had a nutrient status which may represent a "true control" plot. This also indicated that the effect on the nutrient status in the current year needles of the NPK applications in the control plot (1977, 1982, 1986 and 1991) had ceased five growing seasons after the last application. Therefore, a long term effect from conventional NPK fertilization on the chemical composition of the current year needles may not be expected.

The nutrient concentration gradients found with needle age (Fig. 1) are well known (Cromer et al., 1985; Finér, 1992; Brække and Håland, 1995). They are explained by the nutrient availability in the root zone and the mobility within the trees, where N, P and K are considered relatively mobile, Mg intermediate, and Ca and Mn relative immobile.

The nutrient status of trees has been investigated by means of chemical needle analyses in a large number of studies and values for deficiency and optimum levels have been suggested (Van den Burg, 1985; 1990; Hüttl, 1986; Brække, 1994; Rosengren-Brinck, 1994; Linder, 1995). A large variation can be found in the presented values depending on the age of the trees and needles, the position of the needles in the canopy, and the definition of nutritional characteristics such as deficiency, optimum and toxicity (Van den Burg, 1985; 1990).

The concentration of N in current year needles in the control plot and in the CaMgPS and CaMgP treated plots was within the deficiency range given by Brække (1994). Other studies suggest that the deficiency level is below 12-13 mg g^{-1} and that the optimum level is above 14-15 mg g^{-1} N (Hüttl, 1986; Van den Burg, 1990). Even though the N concentration in current year needles increased by the NPK fertilization, the optimum level given by Brække (1994) was not reached. Optimum levels given by Van den Burg (1990) was reached. P fertilization increased the P concentration to the optimum level given by Brække (1994). Results from the current year needles in the control plot indicated that the N and P status were low or deficient when compared to the deficiency levels given by both van den Burg (1990) and Brække (1994). It could not be assessed which of the two nutrients was growth limiting. The N status appeared to be low even though the input of N through deposition of air pollution compound was high (c. 25 kg N ha^{-1} $year^{-1}$), probably because the incoming N was sequestrated in the humus layer without becoming available to the trees. The N concentration in the current year needles was significantly increased by the CaMgPS and CaMgP treatments compared to the control, indicating that these treatments increased the N availability, presumably by increasing the decomposition of the humus layer and thus the mobilization of N. Aiming at a relatively high optimum level for the concentration of N in the current year needles, such as the one given by Brække (1994) (18 mg g^{-1} N), may prove to be sensible for optimizing the growth rate, but at the same time imply a risk for increasing the N leaching. At 15 mg g^{-1} N in the current year needles excesses N leaching often occurs in forest ecosystems (Tietema and Beier, 1995).

The results showed that both the nutrient concentration in the current year needles and the RNU in the above ground biomass could be increased for N, P and Ca by addition of fertilizers. Even though several of the treatments improved the N and P status, the risk of other nutrient deficiencies may at the same time have been increased by these treatments such as shown in Fig. 2 where the risk of Mn deficiency was increased by all treatments and the risk of Mg deficiency was increased by the CaMgPS treatment.

Fertilization experiments conducted in Norway spruce stands on nutrient poor soils in western Denmark from the start of this century until the 1970's have shown that N was the main growth limiting nutrient (Lundberg and Ravnsbæk, 1992). Dralle and Larsen (1995) found that this assumption no longer seemed valid, and that due to increasing N deposition, K and maybe P now have become the new growth limiting nutrients. However, their study did not include chemical needle analyses. The current study indicates that at present not only the N status in the trees is low, but also the P status seems to be at a level that can be considered as deficient.

At many locations in central Europe, chemical needle analyses and fertilization experiments have shown that Norway spruce stands are suffering from soil acidification, nutrient leaching, and nutrient deficiencies involving K, Ca, Mn and Zn, but mainly Mg deficiency (Huettl et al., 1990; Huettl and Zoettl, 1993; Katzensteiner et al., 1995). Fertilization and liming experiments in central Europe have proven that the nutrient deficiencies and soil acidification can be effectively counteracted. Especially, application of dolomite $MgCa(CO_3)_2$ has appeared to increase both growth and vitality of stands suffering from Mg deficiency and soil acidification (Katzensteiner et al., 1995).

The ecological conditions on the nutrient poor soils in western Denmark differs from those of central Europe, although reduced forest health conditions in Danish Norway spruce plantations have been widespread too. Especially, Mg deficiency is not considered a major problem in this area of Denmark, since deposition of large amounts of sea salts contributes a notable input of Mg. The present study may indicate that the nutrient status of the investigated trees is changing from N limiting conditions to a condition where other nutrients such as P may become the main growth and vitality limiting nutrient.

4.3. The correlation between sapwood area and needle biomass

Several studies have established linear regressions between the cross-sectional sapwood area and leaf area and/or needle biomass (Grier and Waring, 1974; Waring et al., 1977; Snell and Brown, 1978; Whitehead, 1978; Kaufmann and Troendle, 1981). The present study indicates that the sapwood area should preferably be measured at canopy limit to give a good correlation between sapwood area and needle biomass, rather than at breast height and that fertilization and liming treatments may affect the correlation between sapwood area and needle biomass (Fig. 3 and Table 3). The use of a general correlation between the sapwood area and the needle biomass does consequently not seem appropriate for investigations of fertilization and liming experiments. In these cases the correlations between sapwood area and needle biomass should be established for each treatment.

4.4. Vitality

Vitality of a tree can be defined as the ability to withstand stress and maintain a healthy and natural life cycle (Naturvårdsverket, 1991). Having a high stem volume production is thus not necessarily the same as being vital. Furthermore, Andersson et al. (1995) showed that fertilization and liming may change the relative growth of the different biomass compartments of the trees (stem, bark, living branches, current year needles, etc.). This means that the proportions between the different compartments may be altered in the fertilized plots compared to the control plots. Growth of the different biomass compartments can be influenced differently by the different treatments. Therefore, it must be recommended to assess the growth of the individual tree compartments when the biomass production and nutrient uptake and accumulation is to be measured in connection with fertilization experiments.

When vitality of a tree is to be measured in connection with nutrition improving actions, the main aim is to determine a well defined health criteria in relation to nutrient availability, uptake, nutritional status or balance of the tree (Andersson et al., 1997). Vitality can be defined and measured in different ways based on different health criteria. Some of these vitality measuring strategies can give contradictory results. In the present study we could not find a simple indicator of vitality. Preferentially several vitality indicators should be used at the same time to give a better characterization of the vitality.

Diagnostic analyses of current year needles are a useful tool for assessing information concerning the nutrient status. Furthermore, the chemical composition of the needles was in the present study found to give a distinct respond to the nutrient applications. Thus diagnostic needle analyses can provide information, basic for accessing tree vitality in connection with nutritional disorders.

Brække et al. (1997) defined three vitality classes related to the diagnostic needle analyses of current year needles described by Brække (1994):

Good:	The concentration of N is above 12 mg g^{-1} and the nutrient/N-ratios of all other nutrients are higher than the critical ones; or all other nutrient concentrations are in the pre-optimum or optimum range and not in the toxic range.
Reasonable:	The concentration of N is between 9 and 12 mg g^{-1} and the nutrient/N-ratios of all other nutrients are higher than the critical ones; or the concentration of one or more of the other macro nutrients is within the range of deficiency and is growth restricting according to the nutrient/N-ratios (below the critical level).
Low:	The concentration of N is below 9 mg g^{-1} and the ratios of all other nutrients to N are higher than the critical ones; or the concentration of one or more of the other macro nutrients is within the range of strong deficiency and is growth restricting according to the nutrient/N-ratios (below the critical level); or the concentration of one or more of the

micro nutrients is within the range of deficiency and is growth restricting according to the nutrient/N-ratios (below the critical level).

These vitality classes are based on the following assumptions (Brække et al., 1997): i) Norway spruce has adapted to low N availability within the natural geographical distribution area over a very long time period, probably by genetic adaptations. The trees can thus grow quite well at low N concentrations in their biomass without loosing their vitality, ii) the trees can not tolerate low concentrations of other nutrients so well as low concentrations of N, and iii)) trees with a N concentration in the current year needle above 9 mg g^{-1} are rather vital.

According to these definitions trees in the control plot and NPK treated plot of the present study were classified as having a "good" vitality close to a "reasonable" vitality. The low P concentration in current year needles indicated that P was the vitality restricting nutrient in these plot. The trees in the other plots were classified as having a "good" vitality.

The aim of revitalization by fertilization and liming may, according to the principles of the vitality classification system (Brække et al., 1997), be to reach a nutrient status, where N is either at optimum or pre-optimum and the other nutrients are at optimum. In this perspective the vitality of trees in the CaMgPS, CaMgPS+NPK, CaMgP and CaMgP+NPK treated plots was elevated, compared to the control.

The RNU may prove to be a useful tool when nutrient disturbances and decreasing vitality occur after fertilization and possible measures for correcting the nutritional imbalances are to be discussed. However, it should be kept in mind that the interpretation of the RNU uses the control plot as point of reference, when carried out as in the present study. This might not be ideal if the nutrient status (deficiency, optimum, luxury uptake) in the control plot is not known. Diagnostic needle analyses may therefore provide a valuable supplement to the interpretation of the RNU.

In the present study, the nutrient concentration in current year needles was clearly affected by the treatments, whereas the stem volume production, needle productivity and defoliation was not notably altered. The nutritional status was thus improved, but some of the measured vitality indicators did not reflect this improvement (needle discoloration, presence of cones) and some of the indicators gave contradictory conclusions. The reason for this is probably that the trees from the start did not suffer from low vitality caused by severe deficiencies of any of the applied nutrients.

Even though the variation of the measured vitality indicators was rather small, it appears as if the treatments containing lime combined with NPK fertilizer (CaMgPS+NPK and CaMgP+NPK) have overcome the N and P deficiency, increased the "index of vigour", the needle productivity, and the accumulation of above ground biomass, and decreased the defoliation.

The hypothesis behind the "index of vigour" postulates that a vital tree uses a large part of its energy resource for growth and only a small part for repairing damages and withstanding stress, whereas a not vital tree will use a larger part of its energy resource for repairing damages and withstanding stress and thus a smaller part is used for growth. The "index of vigour" (Waring et al., 1980; Münster-Swendsen, 1987) expresses the ratio between growth (current year basal area growth at breast height) and the potential energy resource (sapwood area at breast height, assuming that there is a general proportionality between this sapwood area and the leaf area and needle biomass). In accordance with Waring et al. (1980) we found that defoliation and "index of vigour" was not statistically dependent on the stem volume increment within the treatment period or total stem volume. Even though correlations between the different vitality indicators could not be examined further in the present study, future research work should focus on this subject.

Many health criteria and monitoring strategies may be established to obtain information on tree vitality. The ones mentioned in this study are restricted to the vitality of the trees, but the vitality of the whole ecosystem should be considered in connection with fertilization and liming, since this affects the soil chemical conditions and leaching of nutrients from the root zone. A fertilization and liming strategy should improve the nutritional status and vitality of the trees, and at the same time not lead to nutrient leaching and subsequently groundwater pollution.

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APPENDICES

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1997-10-27

Appendix I

Co-author declaration from Leif Hallbäcken

As co-author on the papers entitled: 'ABOVE GROUND BIOMASS AND NUTRIENT DISTRIBUTION IN A LIMED AND FERTILIZED NORWAY SPRUCE (*PICEA ABIES*) PLANTATION' (submitted to Forest Ecology and Management) and 'NUTRIENT STATUS, AND VITALITY IN A LIMED AND FERTILIZED NORWAY SPRUCE (*PICEA ABIES*) PLANTATION IN DENMARK' (submitted to Canadian Journal of Forest Research), I hereby declare that:

- I have mainly acted as an supervisor concerning the calculations of the accumulation of dry mass/ carbon and nutrients in above-ground biomass. The methods and approach used for calculation and interpretation of effects on tree functioning and nutrient dynamics by long-term fertilisation are according to findings and developments made during a joint Nordic project 1992-96 (Andersson et al. 1997) involving 11 forest experiments. This has been my area of responsibility. The material from the Klosterheden experiment has been processed and further analysed by Morten Ingerslev who also has conducted the preparation of the articles.

- None of the papers have been used for the acquisition of any other academic degrees.

Leif Hallbäcken

Andersson, F., Braekke, F. and Hallbäcken, L. (eds.), 1997. Imbalanced forest nutrition - vitality measures. A SNS project 1993-1996. Final report. Internal report, Section of Systems Ecology, Swedish University of Agricultural Sciences. 277 pp. Uppsala.

Appendix II

Documentation and presentation of the present study; not included in the dissertation

1. Final reports from connecting research programs

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