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Nutrient imbalance in Norway spruce

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Gunnar Thelin
FM

Dissertation
Lund 2000

Att våga är att förlora fotfästet ett tag
Att inte våga är att förlora sig själv

S. Kierkegaard

och här var det skugga och här var sol
och här var det gott om nattviol
den dungen är mig kär
min barndom susar där

G. Fröding

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FM

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Title and subtitle

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Abstract

The studies presented in my thesis indicate that growing Norway spruce in monoculture does not constitute sustainable forest management in a high N and S deposition environment, such as in southern Sweden. The combination of N-induced high growth rates and leaching due to soil acidification causes soil reserves of nutrients to decrease. This will increase the risk of nutrient imbalance within the trees when nutrient demands are not met. The development of nutrient imbalance in Scania, southern Sweden, was shown as negative trends in needle and soil nutrient status from the mid-80s to the present in Norway spruce and Scots pine stands. This imbalance appears to be connected to high levels of N and S deposition. Clear negative effects on tree vitality were found when using a new branch development method. Today, growth and vitality seems to be limited by K, rather than N, in spruce stands older than 40 years. However, younger stands appear to be able to absorb the deposited N without negative effects on growth and vitality. When investigating effects of nutrient stress on tree vitality, indicators such as branch length and shoot multiplication rate, which include effects accumulated over several years, are suitable. Countermeasures are needed in order maintain the forest production at a high level. Positive effects on tree nutrient status after vitality fertilization (N-free fertilization) was shown in two micronutrient deficient stands in south-central Sweden. In addition, tree vitality was positively affected after the application of a site-adapted fertilizer to the canopy. Site-adaption of fertilizers will most likely improve the possibilities of a positive response on tree growth and vitality in declining stands. In a survey of Norway spruce in mixtures with beech, birch, or oak compared to monocultures it was shown that spruce nutrient status was higher in mixtures with deciduous species than in monocultures. By using mixed-species stands the needs for nutrient additions are most likely decreased. Nutrient imbalance may be counteracted by changed forest management and nutrient compensation. However, in the long term N deposition to the forest ecosystems must be decreased in order to maintain the productivity of the forest soils in southern Sweden.

Key words	sustainability, conifers, *Picea abies*, *Pinus sylvestris*, long-term studies, pollution, potassium, boron, copper, pH, base saturation, nitrogen saturation, deficiency, multiple limitation, vitality assessments, vitalization, mixed-species stands	
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Näringsobalans hos gran

Studierna som presenteras i min avhandling visar att granmonokultur inte är uthålligt skogsbruk i en miljö med högt nedfall av kväve och svavel, som i södra Sverige. Markens näringskapital minskar p g a onaturligt hög tillväxt, orsakad av den höga kvävetillgången, och utlakning p g a markförsurning. När den begränsade tillgången på näring inte motsvarar trädens näringsbehov, ökar risken för näringsobalans.

I skånska gran- och tallbestånd har näringsstatus, hos såväl barr som mark, försämrats gradvis från mitten av 80-talet och framåt. Utvecklingen av näringsobalans verkar i stor utsträckning bero på högt nedfall av kväve och svavel. Idag begränsas tillväxt och vitalitet av kalium, snarare än kväve, i granbestånd äldre än 40 år. Yngre bestånd, å andra sidan, verkar kunna ta emot högt kvävenedfall utan negativa effekter på tillväxt och vitalitet. Granens vitalitet bedömdes med en s k grenutvecklingsmetod. När man studerar effekter av näringsstress på vitalitet är indikatorer som grenlängd och skottutvecklingshastighet lämpliga, eftersom de kan mäta effekter som ackumulerats i flera år.

Det är nödvändigt med motåtgärder för att skogsproduktionen på sikt ska kunna upprätthållas i södra Sverige. I två bestånd med mikronäringsbrist i Mellansverige ledde vitatilitetsgödsling till förbättrad barrnäringsstatus. I ett av bestånden, där gödslingsmedlet beståndsanpassats och spridits från helikopter, påverkades även trädens vitalitet positivt. Det är mycket troligt att beståndsanpassning av vitaliseringsmedel förbättrar möjligheterna till positiva effekter av vitalitetsgödsling.

I en undersökning av gran i blandning med bok, björk, eller ek jämfört med monokultur visade sig granens näringsstatus vara högre i blandbestånd än i monokultur. Behoven av näringstillförsel, för att kompensera för näringsförluster, är sannolikt lägre i blandbestånd med lövträd än i granmonokulturer.

Det är möjligt att motverka näringsobalans genom förändrad skogsskötsel och näringstillförsel. Men, på sikt måste kvävenedfallet minska, om skogsmarkens långsiktiga produktionsförmåga ska kunna upprätthållas i södra Sverige.

A doctoral thesis at a university in Sweden is produced either as a monograph or as a collection of papers. In the latter case, the introductory part constitutes the formal thesis, which summarises the accompanying papers. These have either already been published or are manuscripts at various stages (in press, submitted or in ms).

Contents

This thesis is based on the following papers which are referred to by their Roman numerals.

I.   Thelin, G., Rosengren-Brinck, U., Nihlgård, B., and Barkman, A. 1998. Trends in needle and soil chemistry of Norway spruce and Scots pine stands in South Sweden 1985-1994. *Environmental Pollution*, 99: 149-158.

II.   Jönsson, U., Rosengren, U., Thelin, G., and Nihlgård, B. Acidification induced chemical changes in coniferous forest soils in southern Sweden 1988 – 1999. *Submitted to Environmental Pollution.*

III.   Thelin, G., Znotina, V., and Rosengren, U. Nutrient Imbalance effects on Norway Spruce Vitality as Assessed through a Branch Development Method. *Manuscript.*

IV.   Thelin, G., Rosengren-Brinck, U., and Nihlgård, B. 1999. Can graphical vector analysis be used to identify micro nutrient deficiency? *Water Air and Soil Pollution*, 116: 383-388.

V.   Thelin, G. and Nihlgård, B. Site-Adapted Vitality Fertilization of a Declining Conifer Stand. *Submitted to Forest Ecology and Management.*

VI.   Thelin, G., Rosengren, U., Callesen, I., and Ingerslev, M. The nutrient status of Norway spruce in pure and in mixed-species stands. *Submitted to Forest Ecology and Management.*

Introduction

Forest decline has been an issue of great concern in Europe during the last decades. Tree vitality, as indicated by crown condition assessments, has deteriorated for the seven most frequent tree species, including Norway spruce (*Picea abies* L. Karst.), since the beginning of large-scale monitoring in the 1980s (Müller-Edzards et al., 1997). Several explanations to decreasing forest health have been suggested and the focus has shifted from direct effects of gaseous air pollutants like SO_2 (Schulze, 1989; Darrall, 1989), to soil acidification and Al toxicity to roots (Ulrich, 1983; Schaedle et al., 1989; Andersson, 1993), to effects of enhanced N deposition. There is a growing concern about the role of N in forest decline (Nihlgård, 1985; Van Breemen and Van Dijk, 1988; Skeffington and Wilson, 1988; Aber, 1992; Hornung and Sutton, 1995). In addition, elevated concentrations of ground-level ozone may, in combination with nutrient imbalance, affect tree vitality negatively (Skärby, et al., 1999).

In southern Sweden there appears to be a connection between deteriorating forest condition, as indicated by increasing needle loss, and air pollution (Rosengren-Brinck, 1998), although the levels of deposition are not extremely high. However, the bedrock is to a large extent dominated by granite. This means that the buffering capacity to acid input is limited and that soil nutrient pools are relatively small. It has been questioned whether intensively managed Norway spruce monocultures constitute sustainable forest management with the current levels of N and S deposition. If the present management is not sustainable, then alternative management practices must be applied in order to maintain the long-term productivity of the forest soils.

The forests in southern Sweden have changed from mixed deciduous at 1500 B. P., to beech (*Fagus sylvatica* L.) domination in large parts at 500 B. P., to domination by Norway spruce at present (Björse and Bradshaw, 2000). Driving forces have been a combination of climatic change and former land use (Björse and Bradshaw, 2000). Norway spruce, migrating southwards, did not reach its natural southern border until the late 19th century. During the 20th century the landscape was completely changed since large areas were planted with Norway spruce. This created a landscape very different from that experienced by Linnæus (1751).

Objectives and approach

The objectives of the studies presented in this thesis have been to *i)* investigate the sustainability of Norway spruce monocultures in an N and S deposition environment and *ii)* evaluate countermeasures to tree nutrient imbalance and declining vitality. Four basic issues have been addressed:

1. Trends in the nutrient status of Norway spruce forests in southern Sweden (papers I and II).

2. The effects of nutrient imbalance on Norway spruce vitality (paper III).

3. Vitality fertilization as a countermeasure to tree nutrient imbalance and declining tree vitality (papers IV and V).

4. The effects of mixed-species stands on the nutrient status of Norway spruce (paper VI).

The studies include the evaluation of long-term data on soil and tree nutrient status (papers I and II). These data were also used, together with additional field data, in the evaluation of effects on tree vitality (paper III). Effects of vitality fertilization were investigated in two field experiments: a Norway spruce stand (paper IV) and a mixed Norway spruce/Scots pine stand (paper V) in southcentral Sweden. Finally a survey was performed to compare existing Norway spruce monocultures and Norway spruce/deciduous mixtures in southern Sweden and eastern Denmark (paper VI). All studies have been performed on data collected in the field.

Deficiency

There is a general relationship between plant growth and the concentration of nutrients in the plant tissue. Nutrient deficiency has been defined as a 10 % growth reduction (Walker, 1991) (Figure 1). However, the strength of the connection between the concentration of a nutrient and plant growth response differs between nutrients. Whereas, deficiency of N or P leads to immediate growth-reductions, other nutrients, especially micronutrients, are not as closely related to growth (paper IV). Hence, symptoms of micronutrient deficiency,

e. g. impaired apical dominance at B-deficiency, may appear without immediate growth reductions. The use of a 10 % growth reduction as a criterion for deficiency is questionable since growth reductions are usually identified on a short-term basis. Symptoms related to micronutrient deficiency may lead to growth reductions only in the long term.
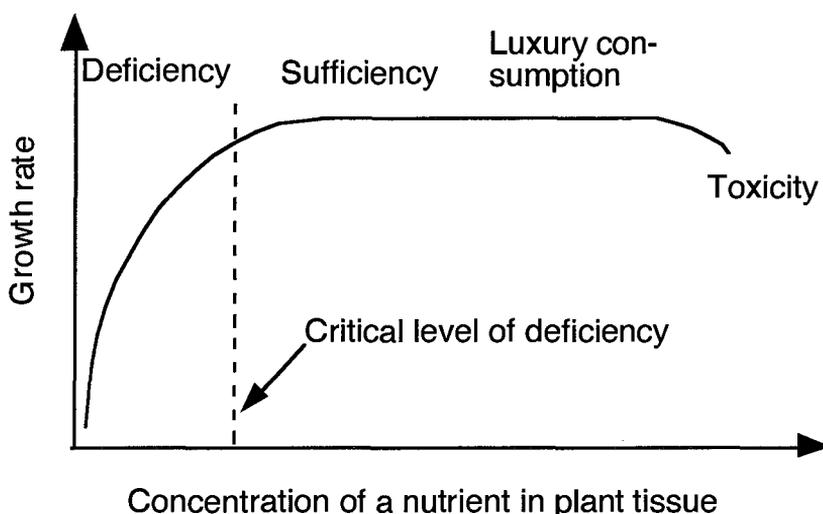
Figur 1. Relationship between growth and foliar nutrient concentration (adapted from Walker, 1991)

The Liebigs law of the minimum states that growth is limited by the nutrient in least supply. However, according to the multiple resource limitation hypothesis, it is not self-evident that the amelioration of a deficiency, or a growth limitation, will lead to increased growth (Chapin et al., 1987; Gleeson and Tilman, 1992). Immediately after a deficiency is alleviated another nutrient or growth factor may become growth-limiting and, thus the growth will not increase. Increased concentration of one of two growth-limiting nutrients may not affect the growth, but if they are both increased the effect on growth may be synergistic (Gleeson and Tilman, 1992). The apparent conflict between the Liebigs law of the minimum and the multiple resource limitation hypothesis arise since the timing of sampling and analyses does not permit us to distinguish between a single- or

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multiple-factor limitation to growth. Hence, e. g. an alteration between two growth factors as limiting to growth may appear as a multiple limitation, although, at every specific moment in time, only one factor limits growth.

A nutrient concentration below an empirical critical level of deficiency may be termed absolute deficiency. Relative deficiency, on the other hand, may appear when the proportion between nutrients is disrupted, e. g. if there is too much N in relation to K. This may occur although the concentration of the nutrient in relative deficiency is above the critical level of deficiency (Ingestad, 1979).

Common deficiency symptoms on spruce/coniferous trees are needle yellowing and premature shedding of needles (Walker 1991). Symptoms of deficiency of different nutrients are related to their physiological function; elements that are mobile within the plant (N, P, K, Mg) can be translocated from old to young needles producing deficiency symptoms in older needles, whereas deficiency of nonmobile elements (Ca, B, Cu, Fe and Zn) appear first in young needles (Marschner 1986).

When investigating tree nutrient status and growth it should be expected to find the Michaelis-Menthen type of relationship seen at the left side of Figure 1. However, the investigated material, e. g. needle samples, frequently covers only a small portion of the range of nutrient concentrations. In such cases the relationship between the needle status of the growth-limiting nutrient and growth may appear linear.

Micro nutrient deficiency

Deficiency of micronutrients has received much less attention than macro nutrient deficiency. In part this is due to the difficulties involved in an analysis of very small amounts of an element. Consequently, there is little reference material on micronutrients compared to the vast amount of available material on macro nutrient deficiency and dynamics.

Both B deficiency (Möller, 1982; Braekke, 1983) and Cu deficiency (Turvey and Grant, 1990) affect apical meristems and may lead to dieback of leading shoots. Cu deficiency may also cause stems and branches to turn permanently bent and twisted (Turvey and Grant,

1990). B is taken up through mass flow (Brady 1990), and the availability is largely governed by water status. Cu, on the other hand, must first be adsorbed to organic complexes before the roots (McLaren et al., 1990) can take it up.

Micro nutrient deficiencies may arise on leached sandy soils (Adriano, 1986; Brady, 1990; McLaren et al., 1990; Stone, 1990), although more commonly on organic or calcareous soils. In addition, fertilization with N has been shown to induce deficiency of B (Möller, 1982; Braekke, 1983; Hopmans and Clerehan, 1991) and Cu (Turvey, 1984; Turvey and Grant, 1990). A continuous supply of both B and Cu is needed since they are not readily retranslocated within the tree (Marschner, 1986).

Vitality

Tree vitality has been defined as the ability of the tree to survive, grow normally, and produce viable seed (Andersson, 1995), and the ability of the tree to resist stress (Liljelund, 1990; Walker, 1991). Trees depend on a balanced nutrient status to stay healthy, maintain a high growth rate, and resist abiotic and biotic stress.

Trees are naturally exposed to stress like short-term weather fluctuations and parasite attack. E. g. pathogenic fungi often kill trees with decreased vitality. However, the risk of infection is lower in vital trees. The multiple stress hypothesis - the idea that several kinds of stress work in concert to produce observed damage - may be the best explanation to the forest decline observed in Europe (Manion, 1981; Nihlgård, 1985; Schulze, 1989; Nihlgård, 1997). Stress factors have been divided into predisposing, triggering, and mortal (Larsen, 1995; Nihlgård, 1997). Pathogens, drought, frost, or short term weather fluctuations may be secondary or triggering stress factors while air pollutants, and associated disturbances in the tree nutrient status, are regarded as predisposing factors (Nihlgård, 1997). For example, plants suffering from nutrient deficiency or imbalance have an increased sensitivity to frost (Alden and Herman, 1971; Klein, 1989; Jönsson, 2000a). High N amounts predisposes trees to frost injury (Nihlgård, 1985; Skeffington and Wilson, 1988) and increase the frequency of bark lesions on beech (Jönsson, 2000b).

Methods

Here I present the methods used to evaluate foliage and soil data and tree vitality. For more detailed information on chemical analyses etc. please see the material and methods sections in the attached papers.

Foliage nutrient status

The leaves of trees can be viewed as bioindicators of the nutritional status of the ecosystem, since tree nutrition naturally is closely related to concentrations and availability of nutrients in the soil (Tomlinson 1991). Important metabolic activity takes place in leaves and needles and they are the organs most likely to show deficiency symptoms (Walker 1991).

Needle nutrient status is often evaluated using critical levels of deficiency (Foerst et al., 1987; Hüttl and Fink, 1988; Nihlgård, 1990; Braekke, 1996). The use of critical levels has been questioned due to differences in soil substrate, climate etc. between investigated and reference stands (Timmer and Morrow 1984). Nutrient levels vary with species, age, season, year, site, and position in the tree (Leyton 1948, Rosengren-Brinck 1994, Raitio 1995). Non-nutrient factors, growth dilution effects, element interactions, and provenance differences can further complicate the interpretation (Van den Driesche 1979).

By using nutrient ratios (Ingestad, 1979; Linder, 1995; Braekke, 1996) problems with annual and spatial variations, and dilution effects are reduced (Van den Driesche 1979; Rosengren-Brinck and Nihlgård, 1995). The basis for using nutrient ratios as a diagnostic tool is that the proportion of a nutrient relative to N may be at least as important to tree vitality as the concentration of the nutrient (Linder, 1995). In addition, ratios are more reliable than concentrations when evaluating samples collected at different times of the growing season since seasonal differences in the carbohydrate content of needles affect ratios less than concentrations (Linder 1995).

The use of ratios has been criticized since excess N may be stored as arginine in needles (Näsholm and Ericsson, 1990; Edfast et al., 1990). N in arginine is removed from the metabolism and thus detoxified. However, there is a cost involved for the tree in storing excess N as

arginine and the ratios have been shown to perform well as indicators in the studies presented in this thesis.

A more complex method to evaluate foliage nutrient status is the graphical vector analysis (Timmer and Stone, 1978; Timmer and Morrow, 1984; Weetman, 1989; Valentine and Allen, 1990; Swift and Brockley, 1994; paper IV). This method can be used to evaluate the pre-treatment status of nutrients by examining tree response to a treatment, e. g. fertilization, in terms of effects on needle mass and needle nutrient concentrations relative to a control (see Figure 1 in paper V). The addition of a deficient nutrient is assumed to cause both increased concentration of the nutrient in the needles and increased growth measured as current year needle mass.

However, the applicability of the graphical vector analysis appears to be limited to primarily growth-promoting nutrients (paper IV). The application of deficient elements, which are less closely related to growth, e. g. micronutrients, may yield inappropriate interpretations. In addition, after a change in nutrient availability there may be a time lag before the trees are able to respond optimally since they first must adjust their allocation of internal resources to the new environment (Gleeson and Tilman, 1992). Without a quick response in needle mass in combination with improved needle nutrient status the technique can not be used to identify nutrient deficiencies.

Interpretations based on this technique may be more reliable in single nutrient fertilization trials than in treatments involving the addition of combinations of nutrients (Valentine and Allen, 1990). Luxury uptake of a nutrient may be interpreted as a pre-treatment deficiency if the needle mass increases compared to a control due to an alleviated deficiency of another nutrient (paper V).

The graphical vector analysis is a very useful method for diagnoses of tree nutrient status. However, the method is best used in combination with other diagnostic tools such as critical levels of deficiency and optimum nutrient ratios in order to arrive at sound interpretations of the tree nutrient status.

Soil chemistry

There are, at present, few reference values for extractable amounts of nutrients in the mineral soil. There is a very large natural variation in

soil nutrient content both between and within sites depending mostly on the parent material, e. g. soils derived from granite or sandstone are naturally poor. This means that reference values are largely limited to specific soil types, as are critical levels of deficiency to species. However, based on empirical data from several forest stands in southern Sweden Nihlgård (1999) suggested chemical minimum and maximum values for the exchangeable phase in productive, sustainably managed, boreal coniferous or mixed forest soil in southern Sweden. These values have been used to assess soil nutrient status in papers II and V. Studies of changes of soil chemistry over time or as a response to a treatment, e. g. liming or the inclusion of deciduous species in a spruce stand (mixed-species stand, paper VI), give more information, e. g. concerning the sustainability of different types of management.

Vitality indicators

Vitality defined as reproductive performance or stress resistance is not easily assessed in the short-term. Instead, indicators of tree vitality are used for this purpose. These have been divided into general indicators, e. g. needle loss, shoot growth etc., and specific indicators, e. g. needle nutrient status (Ingerslev, 1998). However, the term vitality indicators usually - as in this thesis - refer to the general indicators.

Needle loss or crown defoliation is one of the most common vitality indicators used (Innes, 1993). There is a strong positive relationship between needle mass and subsequent growth (Timmer and Stone, 1978); consequently a loss of needles will lead to growth reductions (Björkdahl and Eriksson, 1989; Salemaa and Jukola-Sulonen, 1990; Horntvedt, 1993). However, the use of needle loss as a vitality indicator has been questioned (paper III). Since needle loss is estimated rather than measured there is always a risk for over- or underestimation. Horntvedt (1993) found that trees with an estimated needle loss of 10 % in fact had 17 % less needle biomass than a fully foliaged tree. In addition, although some trees in a stand have high needle loss, most trees will frequently have moderate needle loss. The distribution of needle loss in a stand will be strongly skewed to the left. The large proportion of relatively healthy trees hamper the possibility of detecting relationships with tree or site variables (Rosengren-Brinck, 1998). Several alternative ways of assessing vitality have been used, e. g. discoloration of foliage (Innes,

1996), the incidence of stress shoots and dwarfed shoots (Liedeker et al., 1988), and a damage index including the number of needle age classes, discoloration, shoot length, and the amount of dead branches (Tichy, 1996).

In paper III another method is proposed: the branch development method. This method uses branches in the top part of the crown to represent the whole tree. The method is based on the fact that the allocation of dry matter in branches is influenced by tree nutrition (Madgwick and Tamm, 1987; Flower-Ellis, 1993). Hence, decreased vitality related to nutrient stress could be identified with indicators reflecting allocation within branches. The studies in paper III showed surprisingly strong relationships between spruce branch length and the needle nutrient status several years earlier (approximately at the onset of growth of investigated branches). Branch length can be seen as the accumulated shoot length over several years on the main axis of the branch. Shoot length has frequently been used in vitality assessments (Tichy, 1996; Salemaa and Jukola-Sulonen, 1990). It is probable that a shortage in nutrient supply has a long-term negative effect on shoot development, whereas e. g. drought in one year undoubtedly will restrict shoot growth and bud development in that particular year. In coming years, however, increasing shoot development and growth may repair the damage done in the drought year, provided e. g. that the nutrient supply is sufficient. This suggests that branch length, as well as the shoot multiplication rate, may be appropriate vitality indicators in the assessment of nutrient stress effects.

The negative relationship between tree age and defoliation (Hendriks et al., 1994; Nelleman and Frogner, 1994; Landman et al., 1995) is a general feature which complicates the evaluation of anthropogenic and other influences on tree vitality. By including stands of different age in studies of tree vitality relationships with nutrition may be hidden by the dominating age factor. This is shown in paper III in which a separation of Norway spruce stands into age groups below or above 40 years old lead to the disappearance of correlations between vitality indicators and stand age (paper III).

Since, symptoms of deficiency differ between nutrients negative effects on vitality from deficiency of a specific nutrient may be identified using vitality indicators adapted to the deficiency symptoms in question. Evaluating leader shoot health and top shoot

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growth (paper V) could identify effects of alleviated B and Cu deficiency.
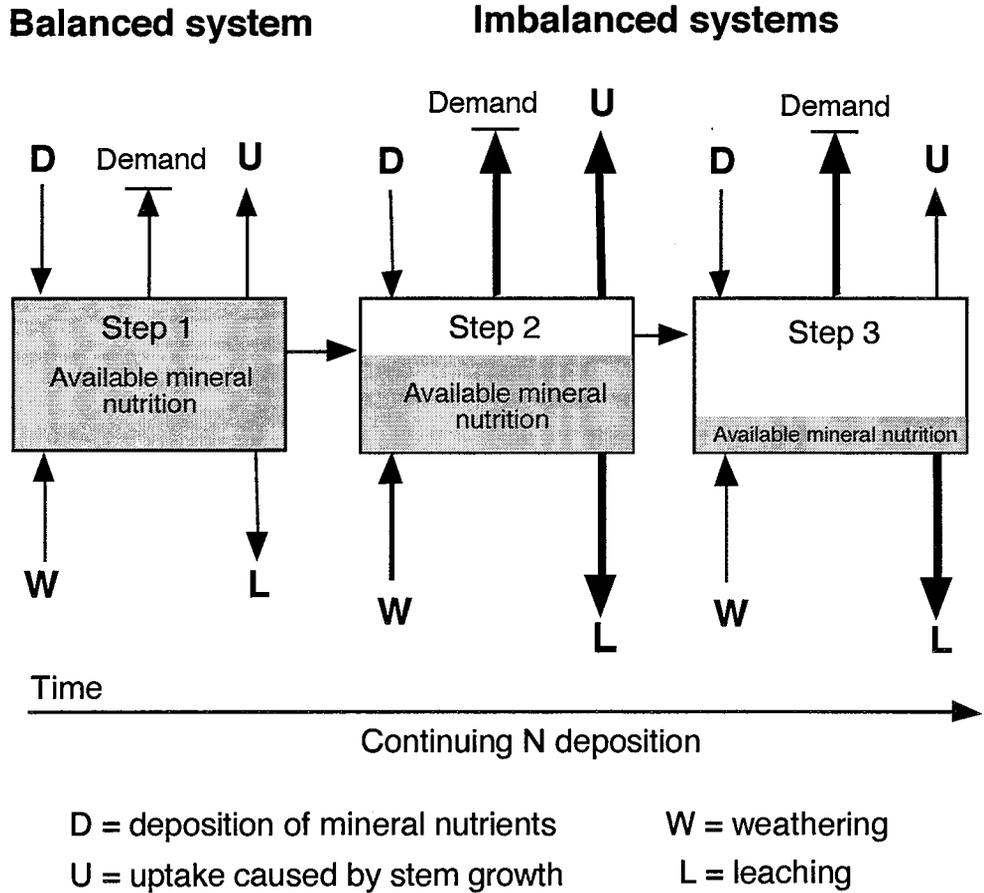
Balanced system   Imbalanced systems

Figure 2. The development of nutrient imbalance in a forest stand. The length of the arrows indicate the magnitude of each factor in relation to the other factors. For further comments, see the text.

Nutrient imbalance

The loss of nutrients through leaching and an increased removal of harvested biomass respectively due to a higher growth induced by N, may lead to an imbalance between nutrients in soil and/or trees. The term nutrient imbalance may be used to describe:

A. An imbalanced nutrient situation within a tree (paper I). This is manifested as an absolute or relative deficiency of one or more nutrients.

B. Nutrient depletion of the soil (paper II), i. e. when concentrations of nutrients decrease below what would be sustainable for long-term forest production.

C. A deficit of mineral nutrients within the forest ecosystem due to an imbalance between inputs and outputs of nutrients. This may be described as:

$$W+D < L+U$$

where W is weathering, D is the deposition of base cations, L is leaching, and U is uptake caused by stem growth (Sverdrup and Rosén, 1998).

C may be seen as the precursor to A and B. Deficits may be the case for a long period of time before soil or tree nutrient imbalance develop. However, Aronsson (1985) found decreasing P concentrations concomitant with increasing N concentrations in Norway spruce needles during a 20-year period in south-western Sweden. In Scania the needle K status decreased by 40 % from 1985 to 1994 (paper I).

The development of nutrient imbalance within a forest ecosystem in response to enhanced N deposition is illustrated in Figure 2 and may be described as follows: The available pool of e. g. base cations will decrease over time if leaching (L) + uptake caused by stem growth (U) exceed weathering (W) + deposition of base cations (D). In this example, stems are harvested and no compensatory nutrient additions are made. In step 1 inputs and outputs are balanced, the tree demand for nutrients is satisfied, and the system is in balance. In step 2 N deposition has lead to increased growth which boosts uptake rates and leaching through growth-driven acidification.

Weathering increases due to acidification, but not as much as the leaching does. The rate at which cations are replenished from the parent material is often insufficient compared to increased leaching losses (Chapin, 1991). In step 2 nutrient pools are still sufficient to satisfy the tree demand. As the pool of available mineral nutrition decrease further it will be increasingly difficult for the trees to satisfy their nutrient demand. In step 3 the tree demand exceeds the uptake and this will lead to nutrient imbalance within the tree. This is seldom the case on normal forest soils as long as N is growth-limiting. However, when N is no longer in short supply, growth is increased – increasing the demand for other nutrients and water. The high uptake will continue until growth is limited by another nutrient than N.

In the above equation internal nutrient cycling within the system, e. g. uptake into foliage - litterfall – decomposition, is not included. The net effect of internal cycling is assumed to be negligible compared to weathering, deposition, leaching, and stem uptake (and subsequent removal through harvest). In the mineralization process nutrients may in fact be lost through the formation of recalcitrant organic matter (Sverdrup et al., 200x).

Since branches and foliage contain large amounts of nutrients whole-tree harvesting will substantially increase the losses of nutrients from the forest ecosystems (Mälkönen, 1976). Decreased nutrient pools in the soil after whole-tree harvesting have been shown after both clearcuts (Olsson et al., 1996) and thinnings (Olsson, 1999). According to modeling of weathering rates and calculations of mass balances, the risk of nutrient imbalances and associated negative effects on tree vitality are dramatically increased when whole-tree harvesting is applied in a system where N deposition and soil acidification already lead to depletion of soil nutrient pools (Thelin et al., 200x).

In addition to a limited supply there are other limitations to nutrient uptake. High Al concentrations in the soil solution may impede plant uptake of essential ions by ion competition for negative charges on soil colloids and for uptake positions on plant root membranes (Schaedle et al., 1989; Blamey and Dawling, 1995; Godbold and Jentschke, 1998). High Al-concentrations may also insolubilize inorganic P (Schaedle et al., 1989). However, P availability most likely depend on species-specific mechanisms for solubilization and uptake of P (Fransson, 2000). Nutrient uptake may also be limited by

a lowered root/shoot-ratio (Boxman et al. 1991; Gundersen, 1991), decreased external mycorrhizal mycelium (Wallander, 1995), and changes in the mycorrhizal community (Kårén and Nylund, 1997) due to high N availability.

However, in the Scanian Norway spruce stands it appears probable that the development of nutrient imbalance and K limitation is due to a low supply of available K (paper I). Mass balances for the base cations in the Scanian Norway spruce stands; calculated using the weathering rate calculated by PROFILE (Warfvinge and Sverdrup, 1992), deposition and climatic data; indicated that in a long-term perspective there is a high risk of K becoming deficient in the soil solution (Barkman and Sverdrup, 1996). In addition, root bioassay studies performed on root material from twelve of the Norway spruce sites indicated a very high tree demand for K (Rosengren-Brinck et al., 1997).

Deposition and soil acidification

The solubility of Al and the base cations K, Mg, and Ca increase as a consequence of increasing acidity (Bergkvist, 1986; Tyler et al., 1992; Norton et al., 1994, Adams, 1997). The increased solubility implies a temporary increase in availability of nutrients for the vegetation. However, the ions are also easily leached down through the soil profile, especially at high sulfate or nitrate concentrations. When these anions are leached from the soil profile they take cations with them (Morrison 1983, Chapin 1991). The partitioning between nutrients absorbed into biomass and nutrients leached depend partly on tree species, but also on the extent of acidification of the soil (Bergkvist and Folkesson, 1995).

In southern Sweden atmospheric deposition of N and S decreases from the southwest to the northeast (Westling et al., 1995). Whereas deposition of S tends to be decreasing over time, N deposition seems to be constant (Anon., 1991; Lövblad et al., 1995). In the south and south-west total (wet + dry) deposition of N and S may be as high as 25 kg ha^{-1} yr^{-1} respectively (Westling et al., 1995). Locally, e. g. close to large animal farms, deposition levels of N may be substantially higher (Nihlgård, 1988; Duyzer et al., 1994).

Several investigations have shown increases in soil acidity and decreasing pools of base cations in the forest soils of southern

Sweden during the last decades (Falkengren-Grerup, 1986, Hallbäcken and Tamm, 1986; Falkengren-Grerup et al., 1987; Tamm and Hallbäcken, 1988). Similar changes have also been documented in England and Germany (Kuylenstierna and Chadwick, 1991; Wesselink et al., 1995, Adamson et al., 1996).

In paper II it is shown that acidification of coniferous forest soils in southern Sweden continues and is extensive, despite a decreasing deposition of acidifying compounds during the last decade (Lövblad et al., 1995). Pools of available base cations in Scanian coniferous forest soils are now very small. In 1999, 81% of the plots had a base saturation below 10% and a majority of the plots had values below 5%. The leaching process could be identified through a decrease of base cations in the 0-10 cm part of the mineral soil and an increase at 20-30 cm depth in 1993 (paper I). The accumulation of these ions in the 20-30 cm part of the mineral soil was temporary, however (paper II). As the leaching progresses, nutrients disappear into deeper layers or out into surrounding water systems. Consequently, nutrient concentrations in 1999 were lower than in 1988.

It has been argued that pH changes may largely be attributed to increased ionic strength of the soil solution and increases in soil organic matter (Binkley and Högberg, 1997). However, it has been shown that the changes in soil acidity are mainly due to the extensive deposition of acidifying and eutrophying substances (S and N compounds) (Falkengren-Grerup et al., 1987; Tamm and Hallbäcken, 1988). In addition, dynamic modeling showed that the deposition of acid substances is the most significant acidity input to the soil and the greatest cause of chemical change (Sverdrup and Warfvinge, 1995). However, soils do acidify naturally and acidification increases as growth increases. In this context it should be emphasized that increasing acidity will increase leaching losses of nutrients regardless of cause. Even if a large part of the observed acidification of forest soils may be explained by increased growth it is important to remember that this growth-induced acidification is of anthropogenic origin, as is the deposition of acid substances.

Reports on forest decline symptoms have been most common in southwestern Sweden. Large-scale field trials have been located in this region, at Skogaby (Bergholm et al., 1995) and at Gårdsjön (e. g. Moldan et al., 1995), in order to investigate the effects of e. g. artificially increased deposition, removal of deposition, and counteractions, e.g. compensatory fertilization.

Excess nitrogen

The growth in European forests increased from 1970 to 1990 (Kauppi et al., 1992). Various causes have been suggested, e. g. improved forest management (Elfving and Tegnhammar, 1996) and/or enhanced N deposition (Eriksson and Johansson, 1993). Furthermore, increased concentration of CO_2 in the atmosphere may influence plant growth positively (Ceulemans and Mosseau, 1994; Amthor, 1995). Considering the well documented deterioration of forest health and increasing soil acidity, increased forest productivity may be seen as a paradox. However, when this paradox is examined more closely, it becomes evident that it is reasonable to expect both growth and acidification to increase when N availability is increased in a system where N is growth-limiting. High growth rates can be maintained as long as no other limitation to growth replaces nitrogen limitation. This will not appear until the pools of available mineral nutrients become too small to satisfy the tree nutrient demands or the tree nutrient uptake is otherwise impaired.

Nitrogen is normally the nutrient most limiting to forest growth in temperate forest ecosystems (Tamm, 1991; Gundersen and Bashkin 1994). However, enhanced deposition of N in large parts of Europe has greatly increased the N availability to plants and in many ecosystems today N is in excess. Levels of N-deposition are in many parts of Europe well above calculated critical load levels (Gundersen 1991, Rosén et al. 1992). The resulting increased demand for mineral nutrients may very well result in nutrient deficiencies in trees. Deficiencies related to N deposition has been shown for e. g. P (Mohren et al., 1986), Mg and K (Hüttl, 1990b), Ca and Mg (Katzensteiner et al., 1992), P and Mg (Houdijk and Roelofs, 1993), and K (paper I). Depending on e. g. soil properties the nutrient for which the supply becomes insufficient will differ between stands.

The development of forest growth in response to increasing N supply is shown in Figure 3. In northern Sweden N deposition levels are low and fertilization with N compounds normally increase forest production. In Holland N deposition levels are locally very high due to a high density of large animal farms. At Ysselsteyn, Holland, growth in a Scots pine stand was increased compared to the control a few years after the installment of a roof removing much of the N deposition (Boxman et al., 1998). In Scania growth and vitality in Norway spruce stands older than 40 years are no longer N-limited (paper III). This implies that growth now has reached a maximum

level. Probably this is true also for other parts of southern Sweden with deposition levels similar to Scania.
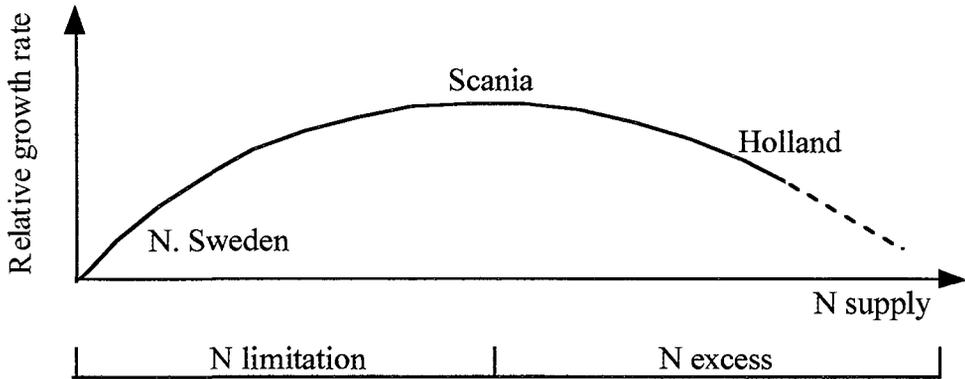

Figure 3. Relative growth rate in a forest stand in relation to N supply (adapted from Rosén et al., 1992). The position of forest stands in northern Sweden (N. Sweden), Scania, and Holland are indicated.

The term N saturation has been used to define the N status of ecosystems in several ways, e. g. as the absence of a growth response after addition of N (Nilsson, 1986); as an ecosystem where N losses equal or exceed N inputs (Ågren and Bosatta, 1988); and as an ecosystem where N availability exceeds the total combined N-demand from plants and microorganisms (Aber, 1989). The definitions by Nilsson (1986) and Ågren and Bosatta (1988) both allow high levels of N-leaching (although it may be argued that they are technically correct (Binkley and Högberg, 1997)). This is unfortunate since leaching of N is a threat to the water quality in other ecosystems and in water reservoirs. The definition by Aber (1989) does not allow leaching of more than minute amounts of N; if leaching is substantial then N availability exceeds the total demand and hence the system is N-saturated. This is thus the most legitimate definition. However, it is emphasized that N-induced nutrient imbalance in a forest stand may develop before N leaching appears,

e. g. if soil reserves of one or more nutrients are intrinsically low (paper V). Problems associated with N excess are not restricted to N-saturated systems, regardless of definition.

Analysis of a number of European forest ecosystems has shown a strong correlation between nitrate leaching and the C/N-ratio in the humus layer (Gundersen et al., 1998). According to Gundersen et al. (1998), a C/N-ratio less than 25 implies a high risk for considerable nitrate leaching. In the Scanian Norway spruce forests the humus C/N-ratio was below 25 at approximately half of the investigated stands in 1999 (paper II). Hence, it is probable that these stands leach N and that they are N saturated according to the Aber (1989) definition. However, the age of the stands is most likely a factor of importance for the extent of the leaching. Young stands have a high growth rate and may probably have relatively low C/N-ratios without leaching, whereas in older stands and stands with a low vitality and consequently lower growth rate, leaching may probably occur in considerable amounts even at relatively high C/N-ratios.

Stand age

It appears from paper III that the Scanian Norway spruce stands that are younger than 40 years old do not suffer from excess N, in contrast to older stands, at the current levels of N deposition. This is in conjunction with results after N addition experiments in southwestern Sweden. At Skogaby (Nilsson and Wiklund, 1992) and Mästocka (Salih and Andersson, 1999) N addition did not result in a shift of growth-limitation from N to another nutrient. This has been used to argue that N deposition does not pose a threat to forest growth and vitality in Sweden (Binkley and Högberg, 1997). After five years with repeated N additions the Norway spruce stands at Skogaby still showed increased growth compared to the control (Nilsson and Wiklund, 1995), although there were clear signs of tree nutrient imbalance (Rosengren-Brinck and Nihlgård, 1995). However, recent analyses (1999) indicate that growth in the N addition treatment is now lower than in the control (Nilsson, pers. comm.).

The stands in both the Skogaby and the Mästocka experiments were young - approximately 20 years old – when the experiments were initiated (Bergholm et al., 1995; Salih and Andersson, 1999). Hence, at the current deposition levels N limitation to growth should not be

surprising in such young stands (paper III). However, there were no indications of increased growth after N addition in older stands (approx. 50 and 60 years old) in the same area (Nohrstedt and Sikström, 1999) and leaching of nitrate was high at one of these sites (Nohrstedt et al., 1997).

Nohrstedt et al. (1993) found increased growth after N addition in four fertilization experiments in southeastern Sweden. Stand age ranged from 45 to 70 years. However, in southeastern Sweden deposition levels are lower than in southwestern Sweden (Hallgren-Larsson, 1999). Persson et al. (1995) found no effect of N addition on ten sites of differing age distributed along a southwest - northeast diagonal in southern Sweden. However, an examination of separate sites indicates decreased growth at the southern sites and increased growth at the northern sites in response to N addition (data in Persson et al., 1995).

These studies indicate that N limitation to forest growth in south Swedish Norway spruce forests is likely in *i)* areas with relatively low N deposition levels and *ii)* stands younger than approximately 40 years, even if deposition levels are high. In addition, it is evident that conclusions from N addition experiments in young stands can not be used to predict the effects of N addition in older stands.
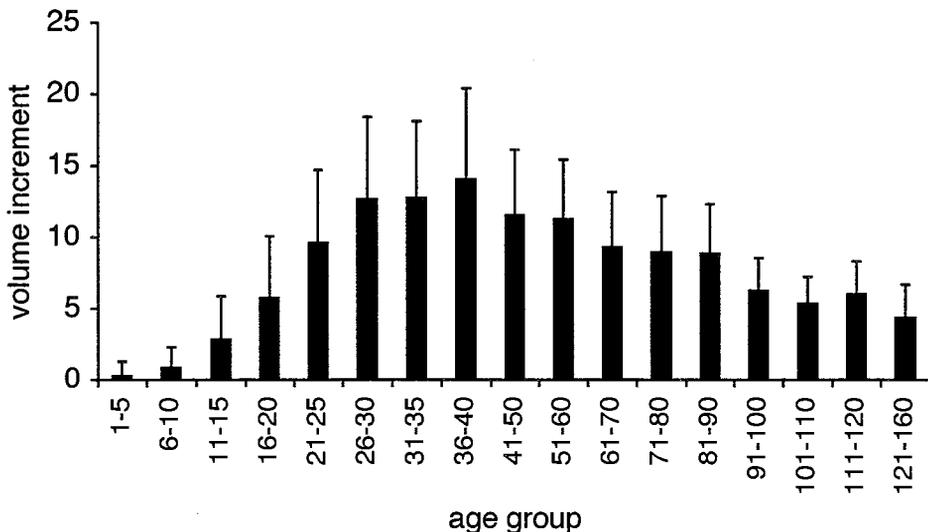

Figure 4. Annual volume increment m^3 ha^{-1} yr^{-1} (stem growth) in Norway spruce stands in different age groups in southern Sweden (data from the national Swedish forest inventory).

Young stands appear to be able to receive high amounts of N before any restrictions on growth, e. g. limitation by another nutrient, appear. In Norway spruce stands in southern Sweden, the annual growth rate increases to approx. 40 years, depending on site conditions, and then declines (Figure 4). It appears as the fast-growing young stands are able to efficiently absorb all deposited N. The growth rate as well as the nutrient requirements change with time as a stand develops (Miller, 1995; Kimmins, 1997). As shown in paper III stands below 40 years old appear to behave quite differently from younger stands.

According to Miller (1995), nutrient deficiencies are most likely to appear in young stands, when crowns are being constructed, since fast-growing young stands depend on soil reserves of nutrients to a greater extent than older stands, in which a large share of the nutrient demand is satisfied through retranslocation (Miller, 1986). Miller (1995) adds that "if deficiencies are rectified prior to canopy closure there is then unlikely to be any further nutritional problems providing that nothing occurs to disrupt one or more of the nutrient cycles".

This is probably what has happened in the Norway spruce stands in southern Sweden which have received enhanced N and S deposition for decades. Apparently, when stands reach the age of approximately 40 years soil pools of nutrients can no longer sustain the N-induced high growth rates.

It should be emphasized that although N additions may increase forest growth in large parts of southern Sweden in the short run, this is clearly not sustainable in the long run.

Countermeasures

Countermeasures to nutrient imbalance in Norway spruce may be divided into preventive, e. g. lower harvest intensities, and compensatory, e. g. fertilization. The purpose being to either remove less nutrients from the system or add more nutrients to the system in order to balance a deficit.

Among the preventive measures a decrease of S and N deposition is critical to long-term biogeochemically sustainable forestry. However, there are at present, few indications of substantial reductions in N

deposition and it should not be expected unless governmental policies are altered concerning e. g. the combustion of fossil fuels and large-scale animal farming. In addition, even if N deposition is decreased countermeasures will be needed to restore the nutrient capital at depleted sites.

The use of monocultures, whole-tree harvest, soil scarification, and deforestation of large areas increase leaching losses and remove nutrient capital (Rosén and Lundmark 1990). The removal of nutrients per time unit will be lowered if rotation periods are extended (Kimmins, 1997). This is, however, seldom an option due to financial demands. Whole-tree harvesting, or slash removal will, as mentioned before, remove large amounts of nutrients.

After clearfelling the leaching of nutrients will be high until a new vegetation cover has been established. Recent studies have shown dramatic decreases in the amount of leached nutrients in shelterwoods with 150 stems ha^{-1} compared to clearfellings (Karlsson et al., 2000). Hence, shelterwoods may work as both natural regeneration and nutrient conservation. Another possible way to lower losses and improve resource utilization is the use of mixed-species stands (see separate section). An increased use of deciduous species instead of fastgrowing Norway spruce monocultures is seen as a prerequisite for sustainable forestry in southern Sweden if compensatory nutrient additions are not made (Sverdrup and Stjernquist, 200x).

The compensatory countermeasures may be divided into general amendments, i. e. the recirculation or the compensation of nutrients lost at harvest or through leaching, and the treatment of specific deficiencies or imbalances in trees, i. e. vitality fertilization (see separate section). Among general amendments liming has been mostly used. However, in liming the objective is usually the counteraction of soil acidity and further leaching losses, rather than the addition of Ca (and Mg if dolomite is added). Liming with 5000 kg ha^{-1} may prevent soil acidification for 25 years (Nihlgård and Popovic, 1984). However, high availability of Ca in calcareous soils, or excess of Ca after liming, can reduce the tree uptake of K (Tomlinson, 1991; Ljungström and Nihlgård, 1995).

The recirculation of wood ashes (Bramryd and Fransman, 1995) would be a natural way of returning nutrients removed at harvest. However, logistic systems for the handling of ashes are yet to be

implemented and the development is restricted by the contamination of heavy metals in ashes (Bramryd et al., 1996). The comparison with agriculture is striking.

On farms in southern Swedish the production of cereals amounts to between 4 and 8 tons ha^{-1} yr^{-1} (SCB, 1997). In order to sustain such a production level substantial amounts of fertilizer are added to the system including 80-130 kg N, 25-35 kg P, and 75 to 110 kg K ha^{-1} yr^{-1} in manure and commercial fertilizer combined. In agriculture it is obvious that fertilization with N only will induce nutrient imbalances and restrict production. Hence, fertilizers are dominated by N, P, and K, but substantial amounts of Ca, Mg, S, and micro nutrients are added as well, where needed. In comparison, highly productive Norway spruce forests in southern Sweden produce approximately 4 tons harvestable stem biomass ha^{-1} yr^{-1} in average for one rotation. Considering that the atmospheric input of N is very high compared to the deposition of most other nutrients in forests in southern Sweden it appears self-evident that soil reserves of nutrients will eventually be depleted if nutrients are not added to compensate for losses at harvest at the present levels. Of course, nutrient contents of stemwood are low compared to cereals and it has been argued that weathering may compensate for losses at harvest (Binkley and Högberg, 1997). However, calculations of mass balances for base cations show that the present rates of leaching and uptake caused by stem growth exceed inputs from weathering and base cation deposition in a vast majority of the forest stands in southern Sweden (Sverdrup and Rosén, 1998; Thelin et al., 200x). The problem with nutrient deficits in high-production forestry is further increased with the introduction of whole-tree harvesting or slash removal.

Vitality fertilization

Vitality fertilization has been 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, 1990). However, the concept focuses on the effects on tree nutrient status and tree vitality. Since N is not normally included at vitality fertilization it has also been termed N-free fertilization.

Positive effects of vitality fertilization on tree nutrient status and tree vitality are shown in many European studies (Hüttl 1990a, Hüttl

1990b, Katzensteiner et al. 1992, Boxman, et al. 1994, Flückiger and Braun 1995, Katzensteiner et al. 1995). Until recently, positive response on growth and vitality after treatment with N-free fertilizers in Sweden has not been documented (Nohrstedt, 1990; Nohrstedt et al., 1993; Johansson et al., 1999). However, fertilizers have generally not been adapted to the treated stands. Increased growth or improved vitality after treatment should not be expected after addition of nondeficient nutrients.

Vitality fertilization was found to have positive effects on oak (*Quercus robur* L. and *Quercus petraéa* (Matt.) Liebl.) crown development (Sonesson, 2000) and frost resistance in bark (Jönsson, 2000a). As shown in paper V, site-adaption of the fertilizer will most likely improve the possibilities of a positive response on tree growth and vitality. This was clearly demonstrated by the positive treatment effects on needle B and Cu status, needle mass, and several vitality indicators in pine 18 months after treatment. In addition, site-specific application has proven successful in reducing Mg and K deficiency (e. g. Hüttl, 1990a; Evers and Hüttl, 1991).

The form in which nutrients are added may play an important role for their uptake, e. g. nutrients applied in an organic form were found to improve the nutrient status and growth of beech seedlings (Thelin and Nihlgård, 1998). In nurseries, nutrients are often added as foliar spray, but foliar application to mature stands have not been much investigated (paper V). It appears from a comparison between the vitality fertilizer experiments presented in papers IV and V that foliar application may improve the uptake of Cu in Cu-deficient trees. The amounts of Cu added were of the same magnitude in both experiments. The inclusion of a low dose of N in vitality fertilization was found only to have an effect if the needle nutrient status of N was low prior to treatment (paper V).

Further studies are needed to optimize treatment forms. Site-adapted vitality fertilization of nutrient deficient stands in the high-deposition areas in southern Sweden may prove effective in counteracting nutrient imbalances.

Mixed-species stands

The possibilities of achieving increased production by using mixed-species stands instead of monocultures was understood by forest

managers in the early 19th century. Af Ström (1837) notes that site production will increase in mixtures consisting of one species with a deep root system and one species with a shallow root system. The appreciation of mixed-species stands as a high-production management type has been lost since then in large-scale forestry. However, there has been a revival for shelterwoods of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) as frost protection for Norway spruce saplings since the 1980s.

The inclusion of deciduous species in Norway spruce stands has been suggested as a possible countermeasure to soil acidification and tree nutrient imbalances. There are several studies showing higher pH and/or base saturation in conifer/deciduous mixtures compared to conifer monocultures (Troedsson 1983, Liljelund 1986, Klemmedson 1987, Frank 1994). The total production in conifer/deciduous mixtures may exceed the production in monocultures (Kelty 1988, Tham 1988, Debrinyuk 1990, Mård 1996, Man and Lieffers 1999) (although there are many examples of the opposite as well, see Burkhart and Tham, 1992). One reason for the higher production may be increased nutrient availability for one or more of the species in the mixtures. Increased foliage N and P concentrations and increased growth have been reported in mixtures with Sitka spruce and Scots pine or larch in Great Britain (Carlyle and Malcolm 1986, Brown 1992, Morgan et al. 1992), but studies on conifer nutrient status in mixtures with hardwoods are scarce.

In paper VI positive effects on the needle status of K and P in Norway spruce in stands mixed with beech, birch, or oak compared to spruce monocultures were found. The positive effect on needle K and P status is interesting since studies have indicated declining trends of Norway spruce K and P in southern Sweden (Aronsson 1985; paper I). However, in paper VI the nutrient status of Norway spruce was found to be similar in monocultures growing on fertile soils and in mixtures growing on poor soils. Thus, it appears that the inclusion of deciduous species in Norway spruce stands can make up for poor soil conditions. This supports the idea of using mixed-species stands to counteract nutrient imbalances in Norway spruce.

Improved Norway spruce nutrient status in mixtures compared to monocultures is most likely the result of a combination of factors (Figure 5):

Figure 5. Effects on tree nutrient balance in mixed-species stands compared to Norway spruce monocultures in an N and S deposition environment. An increased deciduous share of the trees in the mixture will affect Norway spruce nutrition positively. See comments in the text.

- Litter quality is higher in Norway spruce/deciduous mixtures than in monocultures. Deciduous litter is generally more nutrient-rich than spruce litter (Mikkola 1985, Liljelund et al. 1986, Man and Lieffers 1999). Understorey litter, largely absent in Norway spruce monocultures, may further promote litter quality (Tappeiner and Alm 1975). The mixing of litters increase the mineralization rate and nutrient availability (Chapman 1988, Taylor and Parkinson 1988, Briones and Ineson 1996, McTiernan et al. 1997). Higher quality litter provides a more suitable environment for soil fauna, e.g. earthworms, which in turn speed up decomposition and mineralization (Mikkola 1985, Saetre et al. 1999).

- If more light reaches the forest floor, at least in spring before leafing, the soil temperature and hence mineralization rates are increased (Mikkola 1985).

- The possible intraspecific rooting volume is greater in a mixture of species with different rooting patterns than in a monoculture. Total root occupation of the soil is greater in mixed-species stands than in monocultures (Debrinyuk 1990, Brown 1992, Morgan et al. 1992). This implies a greater total nutrient availability experienced by each individual tree. Nutrients taken up from deeper soil layers by a deep-rooted species will reach the organic layer through litterfall and thus increase the nutrient availability for the shallow-rooted species and promote litter quality (Man and Lieffers 1999). Roots in deeper horizons in a mixture can take up nutrients leached from superficial layers. Also, there may be a division between species as to the timing of nutrient uptake (Chapman, 1986) and in what chemical forms nutrients are acquired.

- Canopy filtration of air pollutants is greater in Norway spruce monocultures than in mixed-species stands. Norway spruce monocultures need to buffer a larger amount of deposited acidity and take care of more deposited N than hardwood stands (Brown and Iles 1991, Bergkvist and Folkesson 1995).

- N retention by an active understorey may lower the N availability to the trees reducing the risks of tree nutrient imbalance. Also, deciduous species have a greater N concentration per volume biomass than Norway spruce (Nihlgård 1972; Thelin et al., 200x).

Growing shallow-rooted species with a high growth rate in monocultures may result in nutrient depletion of top soil layers. Lower growth rate in a mixed-species stand and hence less removal of nutrients from the site per time unit would improve the possibilities of achieving tree nutrient balance. However, even if the growth rate in a mixture equals that of a Norway spruce monoculture the nutrient uptake is distributed in a larger soil volume hence reducing the risk of nutrient depletion.

Recently, modeling of weathering rates and the calculation of mass balances have shown a greater biogeochemical sustainability in mixed-species stands than in spruce monocultures (Thelin, et al., 200x). It is likely that several of the above factors may also account

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for limited nutrient losses from mixed-species stands. It appears that differences in deposition levels and rooting depth between spruce monocultures and mixtures are of greatest importance to the mass balances (Thelin et al., 200x). Further studies are needed to investigate e. g. the connection between rooting depth and nutrient uptake.

Conclusions

The nutrient imbalance induced by nitrogen and acidification in the forests of southern Sweden is a serious and increasing threat to forest health and long-term productivity. The studies presented here show that cultivation of Norway spruce in monocultures does not constitute sustainable forest management in a high N deposition environment.The combination of leaching due to acidification and N-induced high growth rates causes soil reserves of nutrients to decrease. This will increase the risk of nutrient imbalance within the trees when nutrient demands are not met. The increasing use of nutrient-depleting operations like slash removal (for bioenergy) would make the problem even worse. I have shown that an imbalanced tree nutrient status reduces tree vitality. This predisposes the trees to other kinds of stress. In order to maintain production at a high level, countermeasures are needed in order to either remove less nutrients from, or add more nutrients to, the Norway spruce forests in southern Sweden. Site-adaption of fertilizers will most likely improve the possibilities of a positive response on tree growth and vitality in declining stands. By using mixed-species stands the needs for nutrient additions are most likely decreased. Although changed management and nutrient compensation may improve the situation in south Swedish forests, it is of utmost importance that N deposition to the forest ecosystems is decreased. The responsibility for this lies heavily upon the political establishment.

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