Relationships between forest condition and stress factors in The Netherlands in 1995

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ABSTRACT

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Relationships between the condition of 200 forest stands in The Netherlands and stress factors were researched by means of multiple linear regression. Forest condition indices used were defoliation, crown transparency and foliar composition. Data were gathered to calculate parameters indicating meteorological stress (drought, temperature, frost), nutrient stress (foliar composition, soil chemical composition), biotic stress (pests and diseases) and anthropogenic stress (air pollutants and toxic soil compounds). Results show that tree species, stand age, insect damage, winter frost and foliar nutrient contents are important factors showing relationships with forest condition.

Keywords: air pollutants, crown transparency, defoliation, insect damage, nutrient composition, nutrient stress, *Pinus sylvestris, Quercus robur*, water stress.

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Contents

Annexes

Preface

This report is written at the request of IKC-N and will be used as background document for the Reconnaissance of Nature 1997 (Natuurverkenningen, 1997). The project is carried out as a joint survey of DLO-Winand Staring Centre (SC-DLO), DLO-Institute for Forest and Nature Research (IBN-DLO), the Centre for Biometrics Wageningen (CBW) and the National Institute of Public Health and the Environment (RIVM).

This report is part of a series of reports handling about forest condition:
- Assessment of the possibilities to derive relationships between stress factors and forest condition for the Netherlands (Report 147);
- Relationships between forest condition and stress factors in The Netherlands in 1995 (Report 148);
- Assessment of the possibilities to derive relationships between stress factors and forest condition for Europe (Report 149);
- Relationships between forest condition and natural and anthropogenic stress factors on the European scale; pilot study (Report 150);
- Relationships between forest condition and natural and anthropogenic stress factors on the European scale; comprehensive study (Report 151).

Reports 147 and 148 are dealing with the forest condition in The Netherlands, reports 149, 150, and 151 are dealing with the forest condition in Europe. In reports 147 and 149 data availability and possible methods to analyze forest condition data are reported. In reports 148, 150 and 151 the results are described of the execution of the proposed methods (reports 147 and 149). The studies on the Netherlands and European scale were executed simultaneously.

This report (148) is largely written by C.M.A. Hendriks (SC-DLO) and J. van den Burg (IBN-DLO). E.P. van Leeuwen (RIVM) calculated site specific deposition fluxes, air concentrations of air pollutants, carried out the weather interpolation and reported about all this. J.H. Oude Voshaar comprehensively supported in the choice and execution of the statistical methods, and contributed to the reporting about that part. The project management was in hands of C.M.A. Hendriks.

Chapter 2 is largely copied from a definition study (Hendriks, 1997) which was executed preceding the operational phase which is described in this report. The methods and the report form the synthesis of a profound discussion of the authors with an expert panel on forest condition consisting of P.J.H.M. Reuver (IKC-N), W. de Vries (SC-DLO), J.W. Erisman (RIVM) and A.F.M. Olsthoorn (IBN-DLO).

Summary

Forest condition in The Netherlands is monitored and reported annually since 1983. In these annual reports the effect of stress factors, such as weather and components of air pollution, is mentioned only as a possible cause of the state of forest condition. Until now, these factors have not been fully quantified, nor related to forest condition indices. In the 1995 report on forest condition in The Netherlands a survey on the relationship between forest condition and stress factors was announced. The intended survey has been carried out and reported here.

The aim of the survey was to examine the relationships between forest condition indices (defoliation, transparency and foliar nutrient content) and a selected number of natural and anthropogenic stress factors, including ozone and hydrological stress. The survey should provide more insight into the kind and magnitude of these relationships. A method developed earlier, with which the relationships between forest condition and stress factors can be investigated, was applied and tuned to the qualities and peculiarities of the 1995 data set. The relationships are researched for pedunculate oak and Scots pine. Some attention is given as well to the other tree species of the new monitoring network on forest condition (viz. beech, Corsican pine, Douglas-fir, Norway spruce and Japanese larch).

Forest condition is monitored annually in 200 stands, representative for forests on sandy soils, by recording the indices defoliation and foliar discoloration. Since 1995 additionally crown transparency is recorded. Also insect and fungal damage are monitored, as well as the chemical composition of the soil, foliar nutrient composition, vegetation and mycorrhizas.

Several stress factors were assessed which possibly affected forest condition in 1995. These factors are stand and site characteristics, water stress, frost stress, nutrient stress, biotic stress, and anthropogenic stress, which was subdivided in air pollutants and toxic elements in the soil.

The relationships between the forest condition indices and stress factors were researched using an advanced multiple regression technique. For this the RSELECT procedure of GENSTAT was used. In the RSELECT procedure, all possible subsets of regression models are calculated. Selection of explaining models was based on statistical criteria (Mallow's Cp and the significance of t-values) and the plausibility of the kind of relationships. In order to make a more meaningful use of linear and additive models, foliar loss and crown transparency were transformed to logit values.

Important predictors affecting 1995 leaf loss of pedunculate oak were stand age, insect damage and the minimum temperature in January. Together they explained about 59% of the leaf loss. Stand age was fitted in the model as the natural logarithm of stand age, and insect damage with a threshold of about 15% damage. When insect and fungal damage are not included in the model, the best model that explains leaf loss contains age, crown projection percentage, minimum temperature in January, temperature sum during the growing season, and AOT40, all together explaining about 58% of the leaf loss. Because the models with and without insect damage both

explain about the same it might be the case that insect damage is convertible with crown projection, temperature sum of the growing season and AOT40. However, it seems unlikely that insect damage is affected by these parameters. Besides, if insects partly or fully dispatch foliage, this will find expression in the recorded leaf loss.

Needle loss of Scots pine was best explained by a model containing stand age and the foliar P/N ratio, explaining 38% of the logit transformation of the needle loss.

Crown transparency of pedunculate oak was best explained by three candidate models in which insect damage and SO_x deposition are constant terms. All models explain about 60% of the crown transparency. In two models also the amount of precipitation and AOT40 show up while the foliar N content and crown projection seem convertible. The third model contains, besides insect damage and SO_x deposition, the minimum January temperature, stand age and the foliar N content. Because of the inclusion of age a slight preference is given to this third model. Exclusion of insect and fungal damage from the model resulted in three candidate models containing stand age (as ln(age)), foliar Mg content, the minimum temperature in January, the amount of precipitation during the growing season, O_3, and the SO_x deposition. All three models explain about 38% of the crown transparency of pedunculate oak. The plausibility of the models containing SO_x deposition, however, is doubtful because the sulphur status of the investigated stands was too low to suggest sulphur toxicity.

Crown transparency of Scots pine was affected by stand age, precipitation during the growing season, minimum temperature in January, temperature sum of the growing season, foliar P content and NH_x deposition. This model explained about 51% of the 1995 crown transparency of Scots pine. The effect of stand age on crown transparency was contrary to the effect on foliar loss, which might be related to provenance.

Foliar composition of all surveyed elements, except for K and heavy metals, was to some extent correlated to the concentration of that element in the soil solution. Often, the foliar content of an element seems to be affected by the content or concentration of antagonistic elements in the soil. For K no relationship was found with any K content or concentration in the soil. Heavy metal contents in the foliage were highly correlated to the contents of the separate metals in the forest floor, except for Cu which was correlated to other heavy metals in the forest floor.

Through single linear regression a positive correlation was found between foliar N content of Corsican pine, Norway spruce and Japanese larch, and the atmospheric N deposition and the NH_3 air concentration. Multiple regression on pedunculate oak and Scots pine also showed correlations between forest condition indices and air pollutants (SO_x and NH_x deposition and NH_3 air concentration), but the effects were less pronounced than for the other species and showed up in only some of the explaining models.

It seems likely that in 1995 ozone, in combination with drought, had a negative effect on forest condition in The Netherlands because it affected the forest condition indices foliar loss (pedunculate oak), crown transparency (pedunculate oak) and foliar composition (pedunculate oak and Scots pine).

The results of this study are referring only to the 1995 crown condition in The Netherlands. In order to enlarge the validity of the results, it is recommended to study more consecutive years and to increase the number of plots for at least two or three tree species to at least 100 stands per species.

In order to provide insight in the uncertainties of the model derived data, it is recommended to create possibilities for validation of these data. Therefore site specific measurements should be carried out on deposition (NO_y, NH_x, SO_x) and air concentration data (NH_3, SO_4, O_3), and the meteorological data (temperature, precipitation, global radiation). This can be done on, for instance, the intensive monitoring plots of the European network on forest condition (Level 2 plots).

1 Introduction

1.1 Problem definition

At present it is clear that large-scale forest dieback is not caused by one stress factor only, e.g. air pollution. Apart from single explanation theories, multiple stress theories thus have received increased attention. It became increasingly clear that spatial patterns of different types of forest decline exist, each with different causes, and that large-scale forest declines have not been demonstrated (Innes, 1993).

In the annual reports of the forest condition inventory in The Netherlands (e.g. Hilgen, 1995; Reuver, 1996) the effect of stress factors, such as weather and components of air pollution, is mentioned only as a plausible cause. Until now, these factors have not been fully quantified, nor related to forest condition indices. In the national monitoring programme forest condition is based on the crown condition indices defoliation and discoloration, both estimated in 5% classes. Hendriks et al. (1994) investigated the relationships between defoliation and discoloration and chemical composition of soil, soil solution and atmospheric deposition of 150 forest stands in The Netherlands, which form part of the national monitoring network. No significant relation was found between foliar loss and atmospheric deposition. Atmospheric deposition however, showed a clear relation with the foliar nutrient status and the chemical composition of the soil moisture. In the research of Hendriks et al. (1994) the possible effects of stress factors such as frost, drought and ozone were not taken into account. Also, no allowance was made for the effects of pests and diseases.

1.2 Forest health monitoring in The Netherlands

Forest condition in The Netherlands was surveyed for the first time in 1983 on an ad-hoc basis. The condition has been monitored according to standardised methods during the period 1984-1994 (Hilgen & Reuver, 1996). Forest condition in The Netherlands is usually recorded by estimation of foliar loss, and foliar and crown discoloration. In 1995 the Dutch Ministry of Agriculture, Nature Management and Fisheries established a new network of survey plots tot assess forest health (Hilgen, 1995). The network aims to monitor changes in the condition of seven major tree species and changes in the forest ecosystem as a whole. It also aims to provide a better understanding of the causes of such changes. In 200 stands, representative for forests on sandy soils, defoliation, crown discoloration, insect and fungal damage were monitored following a standard procedure (Hilgen & Reuver, 1996) as well as the chemical composition of the soil, foliage nutrient composition, vegetation and mycorrhizas. Additionally, also crown transparency was recorded.

1.3 Aim

The aim of this study was to examine the relationships between the 1995 forest condition indices (defoliation, transparency and foliar nutrient content), stand characteristics (age, tree height, forest management), natural stress factors (frost, drought), biotic stress factors (insect and fungal damage) and anthropogenic stress factors (air pollutants and toxic elements) for the 200 forest stands of the national monitoring network on forest condition.

1.4 Method

In the report on forest condition in The Netherlands in 1995, Hilgen (1995) announced a survey on the relationship between forest condition and its stress factors. For this purpose, Hendriks et al. (1997) have developed a method with which the relationships between forest condition and stress factors, including ozone and hydrological stress, can be investigated. In this research the method developed by Hendriks et al. (1997) is applied. Due to the limited number of smaple plots the method could only be applied fully to pedunculate oak and Scots pine. The other species are mentioned only briefly.

1.5 Outline of the report

The adequacy of defoliation and discoloration to describe forest condition is discussed in Chapter 2, in view of other effect parameters reflecting forest condition. Chapter 2 is mainly taken from a literature survey reported by Hendriks et al. (1997). Furthermore, an overview is given of the relevant stress factors in relation to forest condition. For each stress factor possible stress parameters are given which can be used when analysing forest condition. Chapter 3 presents information about the location of the surveyed stands, mode of sampling, chemical analysis of foliage and soil solution, and data processing. Results are presented in Chapter 4, and are discussed in Chapter 5. In Chapter 6 a general discussion on the results is given. Chapter 7 contains conclusions which can be drawn from this 1995 survey. In Chapter 8 recommendations for future research are given.

2 Forest condition and stress factors

2.1 Stress factors determining forest condition

Much research has already been done in search of answers to explain the changes in forest condition. Innes (1993) gives a very extensive review on the theme forest condition. Several hypotheses have circulated in the past to explain forest health including effects of traditional stress factors (drought, nutrient availability, frost, pests and diseases), air pollution (SO_x, O_3), eutrophication (increased N input) and acidification (increased Al and heavy metal concentration).

As stated in Section 1.1, the importance of multiple-stress theories to explain differences of forest condition in space and time, has increased since the early 1990's. Besides air pollution, stand characteristics, site characteristics, meteorological stress, nutrient stress, pests and diseases, and toxic elements are important for forest condition, as was already known from decennia of forestry practice. Some research confirmed the supposition that because of the nutritional imbalance, caused by air pollution, forest condition is more vulnerable to natural stresses such as drought (Mather, 1994), frost, diseases and plagues (De Kamet al., 1991). Others (e.g. Kandler, 1992; Landmann, 1992) argued that many cases of forest decline are the result of a combination of silvicultural treatment, soil conditions and climate (altitude) but they all excluded air pollution. Innes (1993) seems to share this opinion. However, he also mentioned that in parts of The Netherlands the impact of air pollution on forests, being involved in a multiple stress complex, seems convincing.

In order to disentangle the impacts of, and interactions between environmental stress factors - including air pollution - on forest condition it is important to have insight in:

(i) Relevant natural and anthropogenic stress factors affecting forest condition.
(ii) The interaction between natural and anthropogenic stress factors.
(iii) The occurrence of chronic or acute effects related to the temporal frequency of data on stress factors (intra- and interannual) (Ellenberg, 1994).
(iv) Differences in tree species sensitivities to the stress factors considered.
(v) The occurrence of threshold (critical) values for stress factors, either related or unrelated to tree species.
(vi) Relevant effect parameters describing the forest condition in relation to stress factors.

Forest health (recently also called 'forest vitality') is governed by many causes. Innes (1993) has distinguished three groups of factors, which in his opinion are mainly responsible for the present state of health of forests of the temperate zone, viz. (i) climate (particularly drought), (ii) forest management (e.g. provenance, impoverished soils, litter removal, thinning), and (iii) air pollution (which causes two types of injury, namely (a) acute, and (b) chronic, which types must carefully be distinguished. This classification can be used to describe causes which are held responsible for the present status of forest health in western Europe, and which may be relevant for the explanation of intensity of foliar loss and crown transparency of Dutch forests in 1995.

Three groups of stress factors that are affecting forest condition can be distinguished: The first group consists of what may be called 'structural factors', i.e. factors which have some influence on foliar loss and crown transparency of forest tree stands, based on tree physiology as such, and irrespective of air pollution and atmospheric deposition.

The second group consists of what may be called 'conjunctural factors', i.e. factors which have some influence on foliar loss and crown transparency of forest tree stands, but occur at irregular intervals. It is a matter of discussion whether e.g. damage by insects is triggered by predisposing conditions (e.g. foliar composition that is favourable for insects, but is at least partly influenced by increased atmospheric deposition or pollution), or that is more or less independent of prevailing tree conditions. Damage by *insects* is considered a main cause of deterioration of oak stands in Europe (Hartmann & Blank, 1992; Hartmann, 1996; Schröck, 1996), especially if an attack by insects occurs in a period when the oak stand suffers from winter frost and summer drought. Damage by *fungi* occasionally occurs. One is referred for these subjects to the reports of the annual forest vitality surveys in The Netherlands since 1984.

The third group of factors, which exerts influence on foliar loss of forest tree stands, consists of 'air pollution and atmospheric deposition'. Innes (1993) biasses the importance of the distinction between factors which cause 'acute damage' (like NH_3, SO_2 and O_3), and factors which cause 'chronic damage' (like acid deposition, heavy metal deposition, and nitrogen deposition). Because it was the intention of this report to quantify the actual role of air pollution and atmospheric deposition for a specific case, i.e. forest stands in The Netherlands in 1995, the - vast amount of - literature on air pollution and forest health will not be discussed.

The first question to be solved when assessing relationships between forest condition and stress factors quantitatively, is which stress parameters should be included in a statistical model to test various hypothesis on these relationships. These aspects are discussed consecutively in the following paragraphs.

2.1.1 Stand and site characteristics

In a research on the effects of acid deposition on 150 forest stands in The Netherlands Hendriks et al. (1994) showed that defoliation strongly increased (which means a decreasing forest condition) with increasing stand age. Besides the ageing effect, tree species were found to have their own defoliation standard. Stand age and tree species together explained about 44% of the defoliation class. Age and species effects are also mentioned in the reports on forest condition of Europe by the United Nations Economic Commission for Europe (UN-ECE) and the Commission of the European Communities (CEC). According to Gower et al. (1996), foliar mass of trees decreases at a higher age, which seems to be a general rule. This is paralleled by the observations of Landmann (1995), and Ortloff & Schlaepfer (1996) for Norway spruce and silver fir. Göttlein & Pruscha (1996) observed these symptoms in stands of beech, Norway spruce, and larch, but stands of Scots pine and oak (presumably pedunculate oak and sessile oak) behaved differently. Foliar loss of Scots pine stands did not show a distinct relationship between foliar loss and age, and foliar loss of oak stands was maximal for the age class 50-100 year, whereas stands of younger and older age classes had lower foliar loss.

The research of Hendriks et al. (1994) showed that, on the national scale, differences in soil type and groundwatertable were relatively unimportant for the explanation of the defoliation class. A significant negative relation between soil type and defoliation was found only for Umbric Gleysoils. The research, however, was focused on dry acidic sandy soils. It may be expected that differences in forest condition find expression when differences in soil type and groundwatertable are larger, e.g. sandy soils and clay soils.

In some cases a poor forest health is caused by an incorrect species or provenance selection. In Scotland, such examples are known in cases of Sitka spruce and Scots pine (Innes, 1993). In The Netherlands only fragmentational insight on this theme is available. Indicative research showed that an incorrect species choice was made for only a small fraction of the sites involved in the national forest health inventory (Hendriks, 1995). Although differences in tree condition are supposed between coastal and more inland provenances of Douglas-fir, Olsthoorn & Maas (1994) did not found any significant difference between tree vigour of different provenances of douglas fir growing in the same stands.

A structural factor which is often neglected, is *forest management*, which is mentioned by Landmann (1992; 1995), but without detailed information. Becker et al. (1995) consider forest treatment as an important factor for the explanation of differences of foliar loss between stands of Norway spruce, or Abies alba. Pritscher et al. (1994) found that foliar loss of Norway spruce was lower in closed stands, and Heinsdorf & Chrzon (1997) found that foliar loss in beech stands was less for dominant trees. An important aspect of forest treatment in The Netherlands is provenance, especially for Scots pine (also mentioned by Fraude (1987)), Douglas-fir, and Norway spruce.

Former land use may affect the present condition. Olsthoorn & Maas (1994) found a relation between the occurrence of the fungus *Heterobasidion annosum* on Douglas-fir and former agricultural land use.

We used the crown projection percentage as an indicator for forest management because no other information was available on this subject. Crown projection gives some information on the thinning regime, although we recognize the restrictions, realizing that also other factors are of importance.

2.1.2 Water stress

Climate is, according to Innes (1993), a main cause of differences in forest vitality, and especially *drought* as 'short-term climatic factor' (Innes, 1992). This subject in general is dealt with by e.g. Landmann (1992; 1995), Rehfuess (1987; 1988), Göttlein & Pruscha (1996), Innes (1992; 1993), Ortloff & Schlaepfer (1996) and Ellenberg (1995). Hofmann et al. (1991), Ellenberg (1994) and Stribley (1996) lay bias on the importance of variation in drought intensity between consecutive years. Information about this subject is presented for Norway spruce by Van den Brakel & Visser (1996), Solberg (1993), Pritscheret al. (1994), Becker et al. (1995), Webster et al. (1996), for Scots pine by Hill (1993), for oak by Hartmann (1996), Maciaszek (1996), Van der Aa (1996), Landmann (1993), for beech by Innes (1992), Webster et al. (1996), Heinsdorf & Chrzon (1997), for silver fir by Becker et al. (1995), and Webster et al. (1996). However, exceptions to this rule occur. Foliar loss in one year in Swiss forests, caused by restricted water supply was expected, but turned out to different for silver fir and Norway spruce (significant relationship between water supply and foliar loss), and beech (no significant relationship) (Webster et al. (1996). On the other hand, Landmann (1993) for oak, and Saxe (1993) for Norway spruce, have stressed the importance of after-effects of drought in preceding years, often going back 7-10 years. Landmann (1995) mentioned that defoliation appears to be highest in soils poorly supplied with water and/or in stands in which trees, at some stage of development, have suffered from competition for water. The effects of water stress may diverge from yellowing of the foliage, foliage necrosis to complete defoliation following extreme drought events (Innes, 1993; Landmann, 1995).

Effects of *soil classification units* on foliar loss, apart from water supply, are apparently not very important (Hofmannn et al., 1991; Heinsdorf, 1996; Pritscher et al., 1994). Poor soil drainage has a negative effect on vitality of oak (Hartmann, 1996). Hofmann et al. (1991) found that foliar retention of beech on rich, dry soils, was better than on poor, dry soils. On moist soils, no effect on foliar retention due to soil fertility, was observed.

Potential and actual (evapo)transpiration (E_p, E_a, ET_p, ET_a), relative (evapo)-transpiration (E_{Ta}:E_{Tp}), sap flow (Q_{wt}), crop conductance (g_c) and the predawn leaf water potential ($\_{}_p$) are used often as tree specific parameters to indicate drought stress of forests (Federer, 1980; Schulzeet al., 1989; Ciencialaet al., 1994; Mather, 1994; Bréda et al., 1995).

Because a lack of time we did not calculate the relative transpiration ratio (RET = T_a:T_p), which was originally our intention (Hendrikset al., 1997). In stead of the RET we calculated the amount of precipitation during the growing season the soil moisture availability (SMA) as calculated by Hendriks (1995). The SMA was calculated based on the soil physical data which was recorded on the monitoring plots, and is expressed in classes with a range of 50 mm. In the statistical model the class median is used, which is resp. 25, 75, 125, 175 and 225 mm.

2.1.3 Temperature stress

Temperature, apart from drought, is considered a factor of some general importance, as is claimed by Bert (1993). According to this author, a higher temperature stimulates needle loss. Visser et al. (1994) suggest that a high summer temperature has a negative influence on (diameter)growth of pedunculate oak in the next year, whereas a high autumn temperature promotes growth in the consecutive summer. with consequences for foliar mass.

A climatic factor, often cited as exerting important impacts on forest trees, is *frost*. Rehfuess (1987; 1995) considers this factor (winter frost 1987/79, late winter frost in 1981 and 1982) as the main cause of damage in stands of Norway spruce in West-Germany in the period 1980-1987. Damage of oak stands in Germany is attributed to frost ((deep) winter frost, late winter frost) by Rehfuess (1995), Hartmann & Blank (1992), Thomas & Koehne (1995), Hartmann (1996), and Thomas & Blank (1996). Enhanced N concentration of bark, due to increased atmospheric N deposition, is considered by Thomas & Koehne (1995) as a cause of bark damage by winter frost.

While high temperatures mainly affect transpiration rates, and through that depletion of available soil water, low temperatures can cause damage in cases of winter frost and late night-frosts, occurring in spring. In general, winter frosts hardly cause detrimental effects on a large scale in The Netherlands (Van Broekhuizen, 1982). In cases of very low temperatures and prolongated cold and dry periods, however, especially in young stands damage can occur. Following Van den Burg (personal communication, 1996) especially the temperature during the month January is of interest. Therefore, the monthly average minimum temperature during January is selected as stress parameter for winterfrost.

Late night-frosts in spring can cause serious damage to trees because growth then has started again and the new plant parts are very sensitive to frost. Damage, however, is often very local. When damage has occurred, new foliage is build up from the assimilate pool. This new foliage is smaller than the first. Late night-frosts are thus most harmful in the months that bud burst takes place. In The Netherlands this occurs in the months April and May, while in June the young foliage, shoots and flowers are still sensitive to frost (Innes, 1993). The lowest minimum temperature of April is used as stress parameters for late night-frosts.

2.1.4 Nutrient stress

A poor foliar composition is often considered one of the causes of reduced forest tree condition. Foliar composition, however, may depend on many factors such as nutrient supply, air pollution and toxic elements. The supposed relationship between forest condition and mineral nutrition has led to the application of forest fertilization and liming. Van den Burg & Olsthoorn (1994) reported about the results of some fertilization experiments which were investigated in The Netherlands in the period 1985/'86-1991/'92. The practical implications of this research (e.g. positive effect of P fertilization on condition and growth of Douglas-fir and Japanese larch) were transformed into guide-lines for forest fertilization (Van den Burg & Schaap, 1995). Because of the apparent importance of mineral nutrient status for forest condition, the question was raised whether this mineral nutrient status could be predicted from environmental characteristics, i.e. soil characteristics and atmospheric deposition. In general, the effects of air pollution are attributed to a direct impact of gaseous components like NH_3 and SO_2 on leaves and needles. However, it is supposed that NH_3 also influences the tree by deposition and subsequent uptake by the tree roots. These relationships imply that foliar N and S might be related to the concentration of atmospheric NH_3 and SO_2, and N and S deposition. Van den Burg & Kiewiet (1989) and Van den Burg et al. (1988) found a significant and positive relationship between atmospheric N deposition (computed for areas of the size of a municipality) and foliar N content of Scots pine, Corsican, pine and Douglas-fir.

Because in The Netherlands a lot of forest stands are positioned on sites which originally were low in N supply, high N deposition initially enhanced tree growth (De Kort, 1986). But the prolongated high levels of N deposition stimulated growth up to levels where other nutrients, like P, become limiting (Mohren et al., 1986). Needle loss of Douglas-fir, Scots pine and Norway spruce is intensified by a low foliar P concentration or a low foliar P/N ratio (Olsthoorn & Maas, 1994; Aronsson 1985; Liu et al., 1994; Van den Burg, 1991).

No relationship between oak damage and foliar N concentration has as yet been postulated (Thomas & Koehne, 1995; Hartmann, 1996; Oosterbaan, 1988), although Hartmann (1996) considers the foliar N concentration of oak stands in Northwestern Germany as 'higher than usual'. Heinsdorf (1996) even observed that healthy oak stands had higher foliar concentrations of N (and P, K, Ca, and Mg) than unhealthy stands. According to Thomas & Koehne (1995), high N concentration of bark increases the frost sensitivity of oaks. Hartmann et al. (1989) mention an 'association' of foliar Mg deficiency with increased intensity of damage for oaks.

Increased growth can also cause growth dilution of Mg, resulting in yellowing of older needles or even foliar loss (Oren et al., 1989; Rehfuess, 1995). However, discoloration can also be the result of absolute deficiencies (Landmann & Bonneau, 1995).

In some forests in The Netherlands a nutritional imbalance is evident (Mohren et al., 1986; Van den Burg & Kiewiet, 1989; Hendriks et al., 1994; Van den Burg & Olsthoorn, 1994).

Parameters which can be used to evaluate the nutrient status of forests are nutrient contents in the foliage and concentrations in the soil (Lambert, 1984; Kaupenjohann et al., 1989). The nutrient status of forests can be evaluated using the criteria given by Van den Burg & Schaap (1995). Also ratios of the nutrients compared to N supplies additional information about the state of nutrition.

2.1.5 Pests and diseases

Insects, fungi and bacteria can be of influence on forest condition. In The Netherlands in the eighties severe insect damage has occurred in oak by caterpillars of wintermoths (*Operopthera brumata* and *Erannis defoliaria*) and the green oak leafroller (*Tortrix viridana*). The pests culminated in 1986 and 1987 and were decreasing only slowly (Moraal, 1990).

In several cases the occurrence of pests and diseases can be correlated to elevated levels of N deposition and ambient concentrations (Van Dijk et al., 1992; Pérez-Soba, 1995). Also common forest practice such as large areas of pure and even-aged stands, and episodic natural events can facilitate favourable circumstances for plagues and diseases (Innes, 1993; Landmann & Bonneau, 1995).

Besides as stress parameters, pests and diseases can also be considered to be an effect parameter in cases when infection or damages take place in forests of which the condition is already weakened because of other stress factors such as drought. Actually, pests and diseases are measured as damage and not on the base of presence of insects and fungi. In most cases the peak of insect plagues is already passed when the forest condition is recorded, while the presence of some fungi is hard to detect or to recognize.

2.1.6 Air pollutants

In the Dutch Priority Programme on Acidification (Heij & Schneider, 1991; 1995) direct above ground effects of air pollutants on forest condition were judged to be relatively insignificant at the ambient concentration levels of SO_x, NO_y and O_3 found in The Netherlands, except for NH_x near sources (Van der Eerdenet al., 1995). Tree health can be affected directly by high concentrations of SO_x, NO_x, NH_x, and O_3 in ambient air, rain and mist (Darrell, 1989). The effect of prolonged exposure to low concentrations of air pollutants is not quite understood (Innes, 1993). It has been shown that responses to pollutant mixtures are often different from those of single pollutants (e.g. Van der Eerden et al., 1993; Taylor & Dobson, 1989). Wet and dry deposition of pollutants cause many soil mediated indirect effects (Heij & Schneider, 1991; 1995) while ambient concentrations of air pollutants can effect tree physiology (Pérez-Soba, 1995). From other countries it is known that extensive damage to forests can occur around specific sources of air pollution, e.g. Sudbury Canada (Freedman & Hutchinson, 1980) and Sudeten Mountains in Poland (Mazurski, 1986). Besides these local effects, the role of air pollution as a determining factor of forest condition is toned down (Innes, 1993; Landmann & Bonneau, 1995).

Sulphur dioxide, Nitrogen oxide, Ammonium

In the Fichtel Mountains, Germany, it was initially thought that the high ambient concentrations of SO_x found in that region caused needle yellowing and defoliation of Norway spruce (Eiden et al., 1989). Ambient concentrations and estimated canopy uptake were potentially sufficient to surpass the buffering capacity of the leaf cytoplasm by which severe metabolic damage can occur (Lange et al., 1989).

However, no relation was found between ambient concentrations and photosynthesis (Oren & Zimmerman, 1989). Following Schulze et al. (1989) the lack of a detrimental response to direct effects of SO_x might relate to the seasonal distribution of its concentrations. At present, however, it is known that in many cases a Mg deficiency is the cause of many of the cases of needle yellowing in spruce and fir (Innes, 1993).

In The Netherlands, present SO_x concentrations exceed the critical level for epiphytic lichens, while effects on tree species are not expected (Heij & Schneider, 1995).

The effects of nitrogen deposition on forests mainly comprises eutrophication, soil acidification, and an increase in susceptibility to plagues and diseases (Lekkerkerk et al., 1995). Roelofs et al. (1985) showed that uptake of NH_x caused leaching of K, Mg and Ca from needles of Corsican pine. This often results in deficiencies of these nutrients and may lead to premature shedding of needles. Also plant physiology can be deregulated by large foliar N uptake (Pérez-Soba, 1995). Boxman et al. (1995) showed for stands of Scots pine and Douglas-fir that NH_4 concentration in the soil solution rapidly decreased when atmospheric inputs of N are lowered by means of a roof. Foliar N content changed more slowly, after 4 years the contents in needles of Scots pine were significant lower in the roofed plot, for Douglas-fir no significant changes were observed (Boxman et al., 1995).

Ozone

Prinz et al. (1987) suggest that ozone and acidic mist are the primary pollutants which can explain forest decline at high altitudes. Ashmore et al. (1988) confirmed this by experiments. At high elevations, unlike at lower elevations, high O_3 concentrations persist throughout the day (Ashmore et al., 1985). At lower altitudes, especially high summer concentrations of O_3 are of importance. Because of the episodic course of O_3 throughout the day, it is difficult to correlate its effect to forest condition. Most experiments with gas chambers have not taken the episodic course into account. The experiments generally show a growth reduction at high concentrations (Lefohn, 1992). Heij & Schneider (1995) mention a growth reduction of 0-15% at present concentrations of O_3 in The Netherlands. Van der Eerden et al. (1993) were aware of the episodic aspect and found a negative effect of O_3 on fine roots and transpiration of beech. O_3 combined with elevated ambient CO_2 also showed a reduced specific root length (SRL), but the effect on transpiration was comparable to that of O_3 alone.

A critical level for O_3 often is expressed as the cumulative exposure over a concentration of 40 ppb. This exposure index is referred to as AOT40 (Accumulated exposure Over a Threshold of 40 ppb), and is calculated as the sum of the differences between the hourly concentration (in ppb) an 40 ppb for each hour the concentration exceeds 40 ppb during light-time hours . In a Manual on mapping critical loads (UBA, 1996) a critical AOT40 of 3000 ppb h is mentioned, which corresponds to a 5% yield loss. The value is only applicable when nutrient supply and soil moisture are not limiting, and are related to open-top chamber experiments with crops (wheat). For the protection of European forests trees, a critical level for O_3 is proposed to be a provisional AOT40 value of 10 000 ppb h (Lucas & Skärby, 1994; Skeffington & McLeod, 1996). This critical value refers is based on open-top experiments with beech seedlings.

In this study we used the AOT40 and the annual average O_3 concentration (µg m^{-3}) as predictor variables in the statistical models.

2.1.7 Toxic elements

Aluminium

Through input of acidifying pollutants in the soil, aluminium can dissolve and become toxic to for instance tree roots and fungi. In this process Ca as well as other basic cations also play a role. Ulrich & Matzner (1983) found through laboratory experiments a correlation between Al concentration in the soil solution, root injury and strained nutrient uptake. This led to the hypothesis that increasing Al concentrations in the soil solution, caused by acid deposition, results in a decreasing forest condition. However, Hendriks et al. (1994) found no significant correlation between Al concentration in the soil solution and the defoliation measured in 150 forests stands. This suggests that (mature) trees in their natural environment are more tolerant to high Al concentrations than might be expected on the base of laboratory experiments with young trees, which is confirmed by Clegg (1996) and Kreutzer (1994). Such a conclusion is also drawn by Sverdrup & Warfvinge (1993) who propose that trees may reallocate root growth and nutrient uptake to soil layers with a favourable basic cation (K+Ca+Mg) to aluminium ratio (BC/Al ratio).

Heavy metals

The role of heavy metals on forest condition is very uncertain. Innes (1993) supposes that in most areas heavy metals are not the major factors affecting tree condition. In correlative studies Nuorteva (1990) and Hendriks et al. (1994) did not found any significant relationship between heavy metal concentrations and tree health in Finland and The Netherlands respectively. However, Nuorteva (1990) found that the mineralization of humus was delayed and tree roots were damaged by metal accumulation. Hendriks et al. (1994) found a negative correlation between the P and Mg content of the foliage and the heavy metal content of the humus layer, which also indicates a hampered humus conversion. The impact of heavy metals on other components of the ecosystem than trees, especially the soil micro-fauna, may be considerable (Innes, 1993; Paulus & Bresinsky, 1989; Nuorteva, 1990). Recently, Gawel et al. (1996) showed a relation for red spruce between heavy metals and decline. They found a significant increase of phytochelatines, which are metal-binding peptides that act as specific indicators of metal stress, and the extent of tree damage in forest stands in the northeastern part of the United States.

2.2 Interactions between natural and anthropogenic stress factors

When developing a statistical model relating forest condition to stress factors, it is important to know whether there are interactions between the stress factors that have to be included in the model. Interactions between stress factors means that the effect of one factor depends on another factor. Interactions indeed exist between natural stress factors (e.g. drought, frost, pests and diseases) and anthropogenic stress factors such as elevated i) SO_2, NO_x, NH_x and O_3 concentrations in air, ii) S and N deposition, and iii) Al and heavy metal contents in the soil.

In The Netherlands nitrogen is one of the most important pollutants because of the very high deposition levels, up to 4000 mol ha^{-1} a^{-1}, which for about 2/3 can be attributed to NH_4^+ (Erisman & Bleeker, 1995). Direct effects of ambient nitrogen can be expected at extreme high nitrogen concentration levels (Lekkerkerk et al., 1995; Pérez-Soba, 1995). Such direct effects do not occur on a wide scale because there are large spatial differences in concentration levels. Ambient nitrogen influences forest condition both directly and indirectly. Directly through foliar uptake causing an imbalanced nutrient status of the foliage (Pérez-Soba, 1995). Indirectly, nitrogen deposition influences the composition of the soil solution (Leeters et al., 1994) and through that also mycorrhiza infection, in turn reducing nutrient uptake by trees (Boxman & Roelofs, 1988; Roelofs et al., 1985).

One of the secondary effects of nitrogen deposition is the occurrence of relative shortage of especially phosphorus, magnesium and potassium (Mohren et al., 1986; Van den Burg & Olsthoorn, 1994). Because a higher nitrogen input results in a higher level of growth, the requirements for other essential elements such as phosphorus, magnesium and potassium also increase. On nutrient limited sites, as most Netherlands forests sites on sandy soils are, higher nutrient requirements are not always met by the nutrient availability, so that a (relative) shortage occurs.

Water stress can be another secondary effect of nitrogen (De Visser, 1994). It is likely that nitrogen inputs in forests from air pollution has stimulated above ground tree growth more than root growth (Linder & Axelsson, 1982). An increase of the leaf area index (LAI) will also raise the demand for soil water, needed for transpiration, which then has to be supplied by a relative smaller root system. De Visser (1994) postulates that this will make forests more sensitive to drought. Resistance to drought also may be decreased because tree roots become thickened and shortened by soil acidification (Olsthoorn et al., 1991) and stomatal control will decrease due to a combination of air pollution and disturbed nutrition of K and P (Pérez-Soba, 1995). In contradiction to this, Fife & Nambiar (1995) found that nitrogen fertilization in *Pinus radiata* stands lowered water stress in the summer period and increased the growth rates, probably due to an enhanced water use efficiency. Possibly the different results of De Visser (1994) and Fife & Nambiar (1995) can be explained by a shortage of nitrogen on the Australian sites while on The Netherlands sites the nitrogen nutrition was optimal.

The nutritional status of trees, especially the N content, plays a role in the sensitivity to frosts (Aronsson, 1980; Skre, 1988; Timmis, 1974; Van den Burg & Kiewiet, 1989). Through fumigation experiments, Dueck et al. (1990) found that high ambient concentrations of SO_x and NH_x increased frost sensitivity of Scots pine at temperatures of -10 °C.

The infection of the fungus Sphaeropsis sapinea proved to be related with high nitrogen contents in the needles (Boxman & Van Dijk, 1989; Van Dijk et al., 1992). Van den Burg et al. (1988) found that crown dieback in Scots pine caused by

Sphaeropsis sapinea appears more frequent at a needle N-content of 24 g kg^{-1} than at 22 g kg^{-1}. For Corsican pine, Van den Burg & Kiewit (1989) concluded that affection of *Sphaeropsis sapinea* is low when needle N content is lower than 15 g kg^{-1}, affection increases when the needle N-content is in between 16-18 g kg^{-1} and affection is very strong at needle N-contents above 19 g kg^{-1}. Pérez-Soba (1995) proved that needles of Scots pine take up NH_x from the air, by which tree metabolism becomes affected.

Effects of climate change on the forest condition is out of the scope of this research, although interactions exist between combined exposure of greenhouse gasses and air pollutants (e.g. Van der Eerden et al., 1993). Supposed trends in the change of precipitation patterns and temperature rise may affect forest condition by earlier bud burst, by which frost stress becomes a raised risk and transpiration might change (Kramer, 1996).

2.3 Temporal dynamics in stress factors

In deriving a reliable statistical model, it is essential to know the required temporal resolution of recording or calculation of the stress parameters affecting defoliation and discoloration. Relevant questions in this context are: i) are the effects acute due to high concentrations of air pollutants in a short period or chronic due to prolonged elevated concentrations and ii) does the occurrence of stress in a certain year affect the condition of forests in the following years (after-effect).

Stand and site characteristics can be recorded once during a stand rotation because they do not change (species, provenance, soil type, history), or can be recovered from stand observation (height) or forest administration (age) or fluctuate between known margins (groundwatertable).

The meteorological stress factors are of interest at two different temporal resolutions. Drought will show effects on defoliation and discoloration only after some period of time, when the stock of soil moisture has been depleted. It is assumed that effects may be expected after a period of one or several months of drought. In such cases also effects may be expected for periods of a year or the growing season. The precise effect is supposed to work out different per tree species. For instance, because of the drought tolerance of Corsican pine the effect of drought will probably be better correlated with a significant lower amount of precipitation during the whole growing season than with a significant lower amount of precipitation for only one month.

In The Netherlands the major temperature stress consists of winterfrost and late spring frost. Daily minimum temperatures and daily averages are important when correlating late spring frosts. For short winterfrosts events daily values seem relevant, while monthly averages may give responses for longer periods of winterfrosts.

The foliar nutrient status can be evaluated on the basis of an annual sampling of the nutrient content of half year old needles and leafs. These contents reflect the uptake capacity of the tree and the nutrient availability in the soil.

A measure of insect and fungal damage is necessary. The effects of pests can have direct effects on defoliation when for example caterpillars have partly swallowed the leaf biomass.

It is assumed that effects of heavy metal contents in the soil can be assessed at a time scale of one or several years because the inputs are small and through that also the changes in total contents are small.

At present still little is known about dynamics in the Al concentration of the soil moisture. High Al concentrations can directly affect the root system, whereafter indirect effects may occur in the foliage, but only after some period of delay. Therefore it is assumed that an annual measurement is representative for the year of measurement. Recent publications (Kreutzer, 1994; Clegg, 1996) suggest that conditions for roots in nutrient solutions, and in the rhizosphere of soils differ so much that results from nutrient solutions cannot simply be transferred to stand conditions.

2.4 Sensitivity of tree species to stress factors

In developing a statistical model it is relevant to know whether all tree species can be lumped when assessing relationships between forest condition and stress factors or not. Lumping without taking into account interactions between tree species and stress factors is only possible when effects of stress factors are similar for all tree species. Literature indicates that the tree species, monitored in the forest condition programme, do have a different sensitivity for the various stress factors.

There are stress factors of which the effect is tree species specific (e.g. meteorological stress and BC/Al ratio) and factors of which the effect seem to be independent of tree species such as nutrient stress, and possibly also heavy metal contents (Table 1).

Table 1 Preliminary scaling of relative sensitivity of tree species for stress factors

Tree species	Stress factor						
	drought	winter frost	nutrient deficiency*)	pests and diseases	ozone	BC/Al ratio	heavy metals
Scots pine	-/+	-	-	+	+	+	?
Corsican pine	-	++	-	+	?	+	?
douglas-fir	-/+	+	+	-	?	-	?
Norway spruce	+/++	+	+	-	?	+	?
Japanese larch	+/++	+	+	-	?	++	?
pedunculate oak	+	+	-	+	?	-/+	?
beech	++	-	-	?	+	-/+	?

sensitivity - : little, -/+ : moderate, + : high, ++ : very high, ? : unknown, *) mainly N and P

2.5 Effect parameters for forest condition

Forest condition can be studied on different scales (e.g. ecosystem, stand and tree level). This study is focused on the stand level because the available forest condition data of the monitoring networks, i.e. defoliation and discoloration, have been recorded on this scale. Many of the research on stand level is based on measurements of one or a few trees being representative for a forest stand or area. Defoliation and discoloration are the two most widespread indices on forest condition. In almost all European countries these two indices are recorded in monitoring programmes on forest condition. With this it is assumed that the amount and colour of the foliage are expressing the health status of the trees. In cases of extreme events, e.g. extreme droughts or air pollution, the foliage can show a fast reaction by discolouring or falling. In most cases however, it is difficult to attribute one ore more events directly to the state of defoliation and discoloration, because interactions of events take place and the effects of an event shows up proceed only after a period of time.

There are many other indices that can be determined when monitoring forest condition. Innes (1993) gives an overview of the indices used in the 1991 British assessment programme. Some of these indices are canopy closure, crown form, defoliation type, dead shoots in conifers, crown dieback in broadleaves, discoloration, needle retention, leader condition in conifers, flowering in Scots pine, fruiting, secondary shoots in spruce, epicormic branches on oak, leaf size in beech and presence of insects and fungi. Also more comprehensive effect parameters can be used which are related to tree physiological processes such as leaf biomass or leaf area index (LAI), biomass growth, basal area increment, root biomass/length.

Effect parameters, other than defoliation and discoloration can be used to reflect forest condition. Defoliation is one of the most widespread indices (Innes, 1993). It is an integrative index, combining a number of different parameters. As such it provides an indication of the overall condition of the crown. Moreover, in our study no other parameters than defoliation, transparency and foliar nutrient content were available.

3 Data and methods

3.1 Selection of tree species

In principle the analysis on the relationships between forest condition and stress factors can be performed on two data sets: (i) all monitoring plots together, containing all seven tree species and (ii) subsets of the monitoring plots per tree species.

Table 2 Number of stands per tree species of the new forest health monitoring network

Tree species		Number of stands
Beech	*(Fagus sylvatica)*	27
Corsican pine	*(Pinus nigra spp. laricio)*	20
Douglas-fir	*(Pseudotsuga menziesii)*	27
Norway spruce	*(Picea abies)*	20
Scots pine	*(Pinus sylvestris)*	42
Japanese larch	*(Larix kaempferi)*	13
Pedunculate oak	*(Quercus robur)*	51
Total		200

An analysis per tree species will only give reliable results if enough sample plots are available. Oude Voshaar (1994) stated that in obtaining stable models, the number of plots must be at least 3 to 5 times the number of predictor variables. Hendriks et al. (1997) selected more than 30 predictors which can be related to forest condition indices. Thus, about 90 to 150 plots per tree species are needed. Because this number of plots is not available (Table 2), the number of predictors that can be included in the statistical model must be reduced seriously (see Section 3.2). From Table 2 it can be derived that in a statistical model for pedunculate oak about 10 to 17 predictors can be included and in a model for Scots pine 8 to 14. For all other tree species (far) less than 10 predictors can be included. From the multiple stress theory it follows that forest condition depends on many factors. Hence, an analysis with only few stress parameters can not be not very significant. Therefore, only for pedunculate oak and Scots pine an analysis of the relationships between forest condition indices and stress factors is considered to be useful. For the other tree species the results of such an analysis must be considered as tentative. Although the number of plots for pedunculate oak and Scots pine is higher than for the other tree species, it is still very limited since many possible effects were to be excluded a priori, which may influence the results.

At first sight it seems tempting to analyze all plots together since that increases the number of plots to 200 (Table 2). A large number of plots permits also a large number of predictors to be included in the analysis (Oude Voshaar, 1994). This advantage only holds if stress factors have the same effect on the condition of the tree species included in the analysis, viz. there are no interactions between factors. If, however, interactions can not be excluded a priori, they have to be included in the analysis to take them into account. Then the advantage of the large number of plots vanishes because interactions require large degrees of freedom. The only advantage is that conclusions can be drawn on which stress factors have tree species specific effects. In our study, however, this was not a relevant question. At least interaction between tree species and respectively age, meteorological stress factors, foliar nutrients, and toxic elements are to be expected (Hendriks et al., 1997).

3.2 Selection of effect and stress parameters

A discussion about important indices expressing forest condition, which can be used as effect variables, and stress parameters, which are actually or presumably directly related to the effect parameters by causal relationships, has been presented in Chapter 2. The choice of predictor and effect variables used in this study is based on that report.

Three effect parameters (response) were selected:
- Defoliation; an average percentage of foliar loss per plot, estimated in classes of 5% for 25 trees per plot.
- Transparency; an average percentage of crown transparency per plot, estimated in classes of 5% for 25 trees per plot.
- Foliar composition; foliar contents of N, P, K, Mg, Ca, Na, S, Mn, Fe, Cu and Zn analyzed on foliar samples from the monitoring plots.

Next to the above mentioned indices there are may other indices that can be used to express forest condition (Section 2.5). It is not quite clear, which index can be considered as the best. Likely different indices are related to different types of stress, and possibly more than one index is needed to explain forest condition (Innes, 1993). The effect parameters mentioned above are, however, the only indices available for the plots of the new forest health monitoring network. Considering the foregoing, it might be clear that the results of an analysis of the relationships between forest condition and stress factors strongly depend on the significance and quality of the effect parameter.

Besides the choice of the effect parameter, of course also the choice of the stress parameters is important. Selection of predictors was necessary because the number of observation per tree species was limited, viz. 51 plots for pedunculate oak and 42 for Scots pine. The selection of stress parameters is discussed in Hendriks et al. (1997). Based on that report, 22 predictor variables (Table 3) were selected for the statistical analysis of which only 14 to 17 predictor variables could be included in the statistical model to obtain stable model results.

Table 3 Description of predictor variables and the source from which they are derived

Predictor	Unit	Code	Description	Source
Stand age	years	age/ln(age)	age of forest stand	forest administration
Crown projection	%	crown%	horizontal crown projection on the surface indicating canopy closure	visual estimation
Mean highest ground-water level	cm	MHG	depth of the highest groundwater level indicating the aeration status	field estimation
Soil moisture capacity	mm	SMC	estimated amount of soil moisture available in the rooted soil	model estimation
Precipitation in the growing season	mm	Psum	amount of precipitation during the growing season (1 April to 1 October 1995)	weather station data
Minimum temperature in January	°C	Tmin1	minimum temperature in January 1995	interpolated weather station data
Minimum temperature in april data	°C	Tmin4	minimum temperature in April 1995	interpolated weather station
Temperature of the growing season	degree days	TGsum	temperature sum during the growing season (1 April to 1 October 1995)	interpolated weather station data
Foliar N content	g kg^{-1}	foliar N	nitrogen content in leaves and needles	laboratory analysis
Foliar P content	g kg^{-1}	foliar P	phosphorus content in leaves and needles	laboratory analysis
Foliar K content	g kg^{-1}	foliar K	potassium content in leaves and needles	laboratory analysis
Foliar Mg content	g kg^{-1}	foliar Mg	magnesium content in leaves and needles	laboratory analysis
NH_3 concentration	µg m^{-3}	NH_3	mean NH_3 air concentration in 1995	model estimation
O_3 concentration	µg m^{-3}	O_3	mean O_3 air concentration in 1995	model estimation
AOT40	ppb h	AOT40	accumulated ozone exposure over a threshold of 40 ppb	model estimation
NH_x deposition	mol ha^{-1}	NH_x	site specific NH_x deposition flux over 1995	model estimation
NO_y deposition	mol ha^{-1}	NO_y	site specific NO_y deposition flux over 1995	model estimation
SO_x deposition	mol ha^{-1}	SO_x	site specific SO_x deposition flux over 1995	model estimation
Na deposition	mol ha^{-1}	Na dep	site specific sodium deposition flux over 1993	model estimation
BC/Al ratio	mol mol^{-1}	BC/Al	ratio basic cations (K+Mg+Ca) over aluminium in the soil solution	laboratory analysis
Insect damage	% class	insect(25)	amount of foliage damaged or eaten by insects	visual estimation
Fungal damage	% class	fungi	amount of foliage infected by fungi	visual estimation

To reduce the number of predictors, NH_x and NO_y deposition were combined to one parameter total 'N deposition'. All three parameters were included in separate runs in the statistical model to detect which parameter showed the best performance in the regression analysis. With the same aim separate runs were also preformed for ozone, viz. in one run O_3 was included and in an another run AOT40. Also separate runs were performed for NH_3 concentration, SO_x deposition, Na deposition, and the BC/AL ratio. Further, no stress parameter on heavy metals, after-effects and interactions were included.

The predictors included in the model can be divided into i) *primary predictors* of which it is assumed that they are directly affecting the condition indices (e.g. drought, air pollution) ii) *corrective predictors* which affect the quality of the estimation of the effect parameter (e.g. age, crown projection) and iii) *intermediate predictors* directly affect the condition indices but they may also affect other stress factors (e.g. insect and fungal damage). Corrective predictors can affect the accuracy of the estimation, but can also have direct physiological effects affecting foliar loss and crown transparency, which is most probably the case with stand age and crown projection. For intermediate predictors it is doubtful whether they should be considered as effect variables or as predictors, or even as both. In the case of defoliation by insect or fungal damage correction is needed, because these predictors (can) cause foliar loss, but it is not clear whether they are autonomous or affected by other stress factors which are included in the model, e.g. foliar N content. However, multiple regression on insect and fungal damage showed no significant relationships with the other predictors included in the model. This may, however, be related to our data set and does not guarantee the absolute absence of such a relationship. If such a relationship exists, insect and/or fungal damage may not be included in the model because it then can be confounded with other predictors which then possibly seem to have no effect.

In order to test wether insect and fungal damage is to be considered as primary/ corrective or as intermediate predictors, several statistical models are applied. In a first run all predictors mentioned in Table 3 are included in the model. In case that insect and/or fungal damage show up from this complete model as relevant predictors in the explanation of the crown condition indices, they are excluded from the model after which another run is made. If the results of the latter model are about as good as from the model in which insect and fungal damage are included, the 'new' predictors may be the underlying factors explaining insect or fungal damage. This explanation, of coarse, must be plausible. If the performance of the second model is clearly worse than the first model, insect and or fungal damage possibly are the real explaining factors. Another possibility is that in such case other predictors, which were not included in the model, are the underlying factors. This latter is not expected on the forehand because important climatological stress factors such as winterfrost and precipitation are included which are believed to be the major key factors (Moraal, 1996).

3.3 Basic data and data processing

3.3.1 Stand selection

The 200 forest stands of the monitoring network are distributed throughout the non-calcareous sandy soils of The Netherlands. The 150 forest stands, sampled by the DLO-Winand Staring Centre in 1990 (e.g. Leeters et al., 1994; Hendriks et al., 1994) were used as the basis in the set-up of the new forest health monitoring network. From these 150 stands, 124 stands matched the criteria of an equable distribution of tree species over 5 distinguished forest regions in The Netherlands. Additionally, 76 stands were selected, mainly on the base of tree species, spatial distribution, age, soil type and groundwatertable.

3.3.2 Data supply

Site specific data for 1995 was gathered on the general stand information, forest condition indices, foliar nutrient status soil chemical and physical status, air concentrations and deposition fluxes of air pollutants, and meteorological conditions. The data were supplied by several institutes.

General stand characteristics
IKC-N has recorded the general stand characteristics such as tree species, age etc. within the frame-work of the monitoring network on forest condition. The data was provided for use in this study and comprises a location number, tree species, year of germination, mean height (dm), crown projection.

Forest condition indices
Within the frame-work of the monitoring network IKC-N has also recorded the defoliation and crown transparency following the recording instructions of Hilgen & Reuver (1996). Per plot, mean classes of defoliation and transparency from the 1995 survey were provided together with indices for insect damage and fungal damage.

Foliar nutrient contents
In 1995 for all 200 stands of the monitoring network the chemical composition of the foliage was analyzed conform the directives of the commission for forest fertilization (Eindrapport, 1990; Van den Burg & Schaap, 1995). For deciduous tree species sampling took place in August and September, for Japanese larch in September, and for the other coniferous species in October to December 1995. The chemical composition was analyzed by IBN-DLO. Provided data on the foliar nutrient contents in 1995 comprised foliar contents for N, P, K, Mg, Ca, Na, Cu, Zn, Mn, Fe, S and Al.

Estimation of site-specific atmospheric deposition and ozone exposure
Deposition data cannot directly be obtained from on site measurements and are therefore generated by means of simulation. For describing deposition in The Netherlands and the contribution of different source categories or countries the

DEADM (Dutch Empirical Acid Deposition Model) and OPS (Operationele Prioritaire Stoffen) models are used. The DEADM model has been described extensively in Erisman (1992; 1993) as well as in Asman & Van Jaarsveld (1992) and the OPS model in Van Jaarsveld (1990; 1995). Site-specific atmospheric deposition estimates are derived from DEADM calculations using interpolated concentration measurements, except for ammonia, where modelled OPS concentrations are used. Ozone exposure estimates are obtained using the method presented by De Leeuw & Van Zantvoort (1995).

The DEADM model calculates deposition fluxes of the most important acidifying components and base cations on a small spatial scale for each two hour period using the inferential method based on information obtained mainly from measurements. To obtain site-specific dry deposition estimates for sulphur and oxidised nitrogen species, ambient concentrations obtained from interpolation of measurements of SO_2, SO_4, and NO, NO_2, NO_3 and HNO_3 made within the National Air Quality Monitoring Network (RIVM, 1994) are combined with parametrised dry deposition velocities. For reduced nitrogen species, annual average ammonia and ammonium concentration and deposition fields over The Netherlands calculated by the OPS model are used as input for DEADM. Wet deposition, obtained from interpolation of precipitation concentration and amount measurements made within the LML, is added to the dry deposition to estimate total deposition at each site. The model also allows for estimation of dry deposition of base cations (Erisman et al. 1994a). A problem with generalisation of the results obtained for base cations is that there is a serious lack of measured or estimated base cation concentrations in The Netherlands, as elsewhere in Europe. In order to estimate regional dry deposition of base cations, the method using scavenging ratios as explained in Eder & Dennis (1990) is used. This approach is based on the premise that cloud droplets and precipitation efficiently scavenge particles resulting in a strong correlation between concentrations in precipitation and the surface-level air.

For site-specific ozone exposure estimates, observed concentration levels mapped on a 5 x 5 km^2 resolution are used (De Leeuw & Van Zantvoort, 1995). The spatial interpolation procedure is based on measurements made at the rural ('background') stations within the LML. The Ozone concentration values at each monitoring site will be obtained by overlaying the locations of the sites with the AOT40 maps. Calculations are based on measurements made at a height of 4 m above the ground. It should be noted that these results are not fully representative for higher vegetation. For further details on the methods used the reader is referred to Annex 2.

Estimation of site-specific meteorological data

RIVM supplied site specific meteorological data on a daily base. Using DEADM, hourly measured values of temperature, wind speed, relative humidity, global radiation, and amount and duration of precipitation at 12 stations in The Netherlands are interpolated to all sites using an inverse distance weighting procedure. These values are averaged to daily values and subsequently written to daily files. It should be noted that, especially for parameters showing strong regional differences, e.g. precipitation amount, interpolated values are subject to considerable uncertainty.

Nevertheless, the values obtained are the best currently available. From this data meteorological stress factors were derived.

Soil chemical composition
The soil chemical composition of the soil moisture is recorded once in a period of five years. In 1990 the first sampling took place in 124 stands of the monitoring network. A second sampling, in all 200 stands, was carried out in 1995. The soil moisture samples are analyzed on pH and concentrations of Si, Al, Fe, Ca, Mg, K, Na, NH_4, Mn, NO_3, Cl, SO_4 and PO_4. More information on methods used and results is given in De Vries & Leeters (in prep.).

Recent soil chemical data of the mineral soil and the forest floor became only available during this research and could therefore not be processed. This lack of data was overcome by assuming that changes in atmospheric deposition are much faster reflected in changes of the soil solution composition than in changes of the composition of the solid soil phase. Therefore, soil chemical data measured in 1990 were used (Leeters et al., 1994). The data of the solid phase overlapped for only 124 of the 200 stands. For pedunculate oak for only 22 of the 51 stands the chemical composition of solid phase was available and for Scots pine 35 of the 42 stands. For pedunculate oak, no meaningful regression could be made using the 1990 data because of the limited number of stands. Therefore we used only the 1995 data, but one should be aware of this when interpreting the results. Data of the mineral soil comprised total amounts of N and P (g kg^{-1}) and exchangeable concentrations (mmol m^{-3}) of N, P, K, Mg, Ca, Mn, Al, and Fe. Data of the forest floor comprised amounts of total N, P, Cu, Zn, Cd and Pb and exchangeable concentrations of N, P, K, Mg, Ca, Mn, Al, and Fe.

Soil physical information
Soil physical information such as texture class, organic matter content, mean highest and lowest groundwatertable are recorded by SC-DLO in 1990 for 124 stands (Leeters et al., 1994) and in 1995 for the remaining 76 stands (Leeters & De Vries in prep.). Based on these data Hendriks (1995) has calculated the soil water availability with the expertsystem KLASSE (Hendriks et al. in prep.). Mean highest groundwater level and soil water availability are provided by SC-DLO for use in the statistical model.

3.3.3 Data processing

Foliar loss and transparency originally were provided in 5% classes (class 1 = 0% foliar loss/ transparency; 2 = 1-5% foliar loss/transparency; 21 = 96-100% foliar loss/transparency). On each plot, foliar loss was estimated in 5% classes per tree, which were averaged to obtain an average defoliation class per stand. These average classes are conversed to percentages following the equation:

$$\text{percentage} = (\text{class} - 1)*5 - 2.5 \qquad (1)$$

Eq. 1 generates class median i.e. 2.5%, 7.5% ... 97.5%. An exception in the calculation for class 1 was made. The percentage of this class is standard set to 0% because Eq. 1 generates a negative value.

In the statistical model the percentage foliar loss and transparency is transformed into a logit value in order to make a more meaningful use of linear and additive models. Logit transformation is done following the equation:

$$\text{logit}(fl) = \ln(fl\% \,/\, (100\% - fl\%)) \tag{2}$$

in which:
fl = foliar loss

The logit value stretches the values in the range 0-20% and 80-100% by which differences in this range become more clear. To avoid the calculation of the logit of zero, which can not be calculated, 0% is replaced by 1%.

Insect and fungal damage were provided in six damage classes: 1 = 0% injury, 2 = 0-10% injury, 3 = 11-25% injury; 4 = 26-60% damage, 5 = > 60% damage, 6 = dead. These class indices were used as parameter in the statistical model.

3.3.4 Uncertainties in the data

Condition indices

Defoliation and crown transparency data have not been surveyed on their quality. Therefore the uncertainty of these data can not be specified. The recording of these two crown parameters are carried out following the international directives drawn up by the UN-ECE (UN-ECE, 1994). These directives have been worked out in a specific recording-instruction for The Netherlands (Hilgen & Reuver, 1996). Emphasis of these directives is put on the comparability of estimations made by the different recording teams. This, however, is no guarantee that the absolute estimation will be correct. The uncertainty in the foliar composition is discussed in a separate section.

Stand and site characteristics

Age is derived from forest management archives, in which the year of germination is given. Except in cases a mistake is made in copying the year, this value presents the exact age of a stand.

Crown projection is estimated in the stands in the 5% classes. Estimation is done by the same teams that carry out the recording of the defoliation and discoloration. No studies on the quality of these estimations have been undertaken and also no measurements of crown projection are available for the stands of the monitoring network. Hence, no judgement about the quality of the data on crown projection can be given. For pedunculate oak the values are within a realistic range (Fig. 2). For Scots pine some stands have a crown projection of less than 20%. Although very low, and not very common for normal Sots pine stands, such values can occur, e.g. in cases of regeneration or after a storm.

The soil moisture supply capacity is model derived (Hendriks et al. in prep.). Estimation in the stands itself, might have resulted in more precise values. However, in the model used, besides soil physical data also 'expert-knowledge' is included in order to obtain the 'best possible' estimation. Hendriks et al. (in prep.) have found that the model, especially for sandy soils, resulted in comparable values as calculated for the Soil Map of The Netherlands, Scale 1: 50 000. The values calculated for the 200 stands of the monitoring network seem very realistic. For instance, Figure 3 shows that the soils under the pedunculate oak stands in general have a higher soil moisture supply capacity than the soils under Scots pine stands. This is quite plausible when considering the site requirements of both species and forestry practice, for as far as species selection is concerned.

Meteorological data

The site-specific meteorological data, which were used to calculate the water stress and temperature stress parameters, are interpolated weather station data. One may assume that the original data, measured at the head stations of the KNMI (Netherlands meteorological institute), are of excellent quality. The data base was checked on deviant values, but no remarkable values were found. Through the interpolation procedure uncertainty in the site-specific data was introduced, especially for precipitation, which in general show large spatial variation. Interpolation was the only way to obtain site-specific meteorological data. Because no measured values are available for the stands of the monitoring network, no validation of the interpolated data is possible. The interpolation procedure used (Van der Voet et al., 1994) is known to give a good performance, especially under field conditions occurring in The Netherlands.

Composition of the foliar, the soil moisture, the mineral soil and the humus layer

The foliar composition and the composition of the soil moisture, mineral soil and the humus layer was analyzed in laboratories. Obtained values have a low degree of uncertainty.

Air pollutants and deposition fluxes

An extensive uncertainty analysis on the DEADM deposition estimates has been published by Erisman (1992; 1993). Through comparison between monthly average modelled dry deposition velocities of SO_2, NH_3, NO_2 and SO_4^{2-} -aerosol measured at Speuld (36 m above the surface) and calculated with DEADM (50 m above the surface) for 1993, it was found that the agreement is reasonably good, with an average deviation of about 25%. An extensive discussion about the uncertainty in modelled data of air pollutants and deposition fluxes is given in Annex 2.

3.4 Statistical method

As a first step the basic data were analyzed by making tables presenting minimum, maximum, mean, median values and the 0.05 and 0.95 probability classes for each variable (Annex 1).

In a second step, simple linear regression equations were computed for each of the predictor variables with the FIT statement of GENSTAT (Payne et al., 1993). The results of the simple regressions must be considered tentative because regression for only one predictor is calculated and effects of other predictors are ignored. The preliminary results of these computations provide some insight in the possible relationship between predictors and effect parameters.

Next, multiple linear regression analysis was performed, using the RSELECT procedure of GENSTAT (Goedhart, 1994) for the selection of the best set of predictor variables to explain the forest condition indices. In the RSELECT procedure, all possible subsets of regression models are calculated. The choice of the 'candidate models' is based on the criterion of 'Mallows Cp' (Oude Voshaar, 1994). Following this criterion, all models which satisfy the condition $Cp < p+3$ (p = number of predictors + 1) are candidate models if all included terms are also significant (t value > 2.0). During the selection of models, the plausibility of the type of relationships is of equal importance to the significance of t-values. Models which are apparently biologically meaningless are rejected as candidate models. The procedure can result in more than one model explaining the condition index. In such cases, predictors are exchangeable, for instance when they are confounded.

To detect whether predictors should be included linear or non-linear in the model two multiple regressions were calculated. In the first regression model all predictors were included linear and in the second model a non-linear function for the predictors was fitted. If the non-linear fit resulted in a better model, e.g. a higher percentage accounted for, the non-linear function was selected for further regression analysis. The non-linear fitting of predictors was performed using a combination of the FIT directive and the SSPLINE function of GENSTAT (Payne et al., 1993). The SSPLINE function specifies a cubic smoothing spline for the effect of a variate.

The SSPLINE function, however, can not be included in the RSELECT procedure. Therefore SSPLINE was combined with the FIT directive. When the FIT directive is used, the programmer himself has to decide which predictors have to be added to or dropped from the model. As a support in this selection procedure, the STEP directive was used (stepwise regression, Payne et al., 1993)

The disadvantage of the combined FIT/SSPLINE/STEP procedure is that it result in only one model, obtained by adding and dropping of the respectively most and worst explaining variables. Other possible models are neglected (in contrary to the RSELECT procdure). Therefore, if non-linear relationships of single predictors were found to give the best explanation, it was checked whether this non-linear function could be described with a known function such as a logarithmic, reciprocal, square root, or power function. If this was possible, the predictor was transformed, and included in the RSELECT procedure, and all possible models were explored. For instance, if for temperature an exponential fit is found, temperature can be fitted non-linear through inclusion of the (natural) logarithm of the temperature in the model.

In the multiple regression analysis for foliar Zn and Cu contents the chemical composition of the forest floor as measured in 1990 was used because no other data on these elements were available. Due to this, the number of stands was restricted to 22 stands for pedunculate oak, and 35 for Scots pine. The number of stress parameters that could be included in the statistical model was adapted in accordance to the number of observations.

Further, stands on calcareous soils were excluded from the regression analysis on the foliar composition, because a supposed effect on the foliar composition. Through this the number of pedunculate oak stands was reduced to 48 stands. No Scots pine stands in the monitoring network grow on sites with a pH-KCl above 5.6.

The relationships between the foliar nutrient composition and stress parameters were analyzed, comparable to the foliar loss and crown transparency, through multiple-regression analysis based on the RSELECT-procedure, and was also restricted to pedunculate oak and Scots pine.

Because for trees only the total amount of nutrients is important, some new variables were defined, derived from both the forest floor and the mineral top soil. By combination of the soil parameters, the number of parameters that were included in the model could be reduced. The new parameters were:

totPop = P concentration of organic matter in the forest floor (Pstr) + P concentration of the soil solution (cPO_4)

totPva = total P concentration of the forest floor (Ptot_str) + total P concentration of the top soil (Ptot_min)

totNop = N concentration of organic matter in the forest floor (Nstr) + NH_4 concentration of the soil solution (cNH_4) + NO_3 concentration of the soil solution (cNO_3).

totNva = total N concentration of the forest floor (Ntot_str) + total N concentration of the top soil (Ntot_min)

4 Results

Chapter 4 is made up of three main sections. In Section 4.1 results are presented of the 1995 survey, concerning foliar loss, crown transparency and foliar composition. In Section 4.2 the results for the stress factors are presented. Section 4.3 comprises the results of the multiple regression analysis which was used to explain the forest condition indices using stress parameters to indicate the stress factors.

4.1 Forest condition indices

In this study, three indices to express forest condition were used, i.e. foliar loss, crown transparency and foliar composition. The results of the indices are successively discussed in the Sections 4.1.1 to 4.1.3.

4.1.1 Foliar loss

The data reflect the findings of the Dutch national survey of forest condition in 1995 (Hilgen, 1995). Of the monitored tree species, the mean foliar loss of Japanese larch was the smallest (8.9%) and for Douglas fir the highest (41.7%). Based on the foliar loss two major groups of tree species can be distinguished. First group contains pedunculate oak, beech, Scots pine and Japanese larch, all showing a mean foliar loss of about 10% (Table 4). The second group, contains Corsican pine, Douglas fir and Norway spruce, which species have a considerable higher foliar loss viz. 30% to 40%.

Table 4 Mean foliar loss (%) per forest region and tree species

Forest region	*n*	Tree species							
		oa	be	sp	cp	df	jl	ns	Mean
Northern	50	8.93	14.10	4.38	27.83	47.35	5.35	25.35	18.52
Eastern	31	15.69	10.90	15.38	.	38.43	19.60	46.10	19.24
Central	48	13.48	14.25	7.45	31.10	39.86	18.50	20.20	19.44
Southern	48	6.86	16.97	10.98	34.72	38.38	14.30	38.73	21.25
Coastal	6	5.10	.	.	22.25	.	.	.	16.53
Rest	17	8.86	8.95	.	18.55	.	1.00	.	9.56
Mean	200	10.54	13.12	9.58	29.22	41.65	8.91	30.93	18.69

Tree species: oa = pedunculate oak (*Quercus robur*); **be** = beech (*Fagus sylvatica*); **sp** = Scots pine (*Pinus sylvestris*); **pn** = Corsican pine (*Pinus nigra ssp. laricio*); **df** = Douglas-fir (*Pseudotsuga menziesii*); **ns** = Norway spruce (*Picea abies*); **jl** = Japanese larch (*Larix kaempferi*)
Forest areas: Northern = Drenthe; **Eastern** = southern Drenthe, Overijssel, eastern Gelderland; **Central** = De Veluwe, Utrechtse Heuvelrug, 't Gooi; **Southern** = Noord-Brabant, northern Limburg; **Coastal** = coastal area of Zeeland, Zuid-Holland, Noord-Holland, Friesland, Groningen; **Rest** = Rest areas of Zeeland, Noord- and Zuid-Holland, Friesland, Groningen, Flevopolders, central river area, southern Limburg.

Leaf loss of pedunculate oak was considerable higher in the eastern and central forest region than in the other regions. Needle loss of Scots pine was at its height in the eastern forest region.

Some regional differences are apparent, e.g. relatively high foliar loss for Douglas-fir in the northern forest region (47.4% foliar loss), and for Norway spruce in the eastern and southern forest region (resp. 46.1% and 38.7 foliar loss). Except for Douglas-fir, which species show a poor defoliation status in all regions, all tree species show notable differences in foliar loss per region. No large differences are found in the mean foliar loss of all tree species per region. In the rest area foliar loss seems to be lesser, but this is mainly because species which in general have high foliar loss percentages, are not included in these regions.

4.1.2 Crown transparency

Differences in crown transparency between tree species are less pronounced than differences in foliar loss (Table 5). It is remarkable that species with high percentages foliar loss (e.g. Douglas-fir, Norway spruce and Corsican pine), have relative low percentages crown transparency. For the other species (pedunculate oak, beech, Scots pine and Japanese larch), transparency is higher than foliar loss.

Crown transparency of pedunculate oak was at its height in the eastern and central forest region, which was also found for foliar loss. Crown transparency of Scots pine was at its lowest in the eastern region (not significant at p = 0.05), while foliar loss in this region was at its height.

Table 5 Mean crown transparency (%) per tree species and forest region

Forest region	*n*	Tree species							
		oa	be	sp	cp	df	jl	ns	Mean
Northern	50	13.25	18.65	14.52	26.10	22.88	10.72	14.10	15.99
Eastern	31	22.26	12.82	14.28	.	20.70	25.60	15.80	18.07
Central	48	21.64	16.50	15.25	22.80	18.10	14.70	10.20	17.64
Southern	48	14.43	17.63	15.36	24.94	20.86	23.30	16.33	17.95
Coastal	6	7.00	.	.	14.45	.	.	.	11.97
Rest	17	13.49	10.05	.	8.45	.	8.10	.	11.77
Mean	200	16.72	15.26	14.92	21.16	20.31	14.08	14.55	16.69

abbreviations: see Table 4

By means of multiple linear regression the relation between foliar loss and crown transparency was surveyed (Table 6). Foliar loss (estimated in 5% classes) was used as response variable. Predictor variables were the percentage crown transparency estimated in 5% classes (trans5%), crown projection percentage (crown%), stand age (age), and the mean tree height (Havg). See Table 2 for further explanation of the predictor variables.

Table 6 Relationships between foliar loss (%) and crown transparency

Tree species	Explaining model	p	$R^2_{adj.}$
pedunculate oak	-0.14 +0.639*trans5%	<0.001	71.2
beech	11.89 +0.871*trans5%	<0.001	90.9
	-0.1393*crown%	0.019	
Scots pine	(a) 23.32 -0.211*crown%	0.008	14.4
	(b) -1.05 +0.179*age	0.017	12.8
Corsican pine	15.55 +0.841*trans5%	<0.001	75.0
	-0.313*age	0.013	
	+0.788*Havg	0.023	
Douglas-fir	27.39 +0.702*trans5%	0.011	20.3
Japanese larch	-2.39 +0.838*trans5%	<0.001	78.0
Norway spruce	8.27 +1.557*trans5%	0.005	32.4

For pedunculate oak, beech, Corsican pine and Japanese larch a strong significant relation was found between foliar loss and crown transparency. Although addition of an extra stress parameter gave a better result for beech and Corsican pine, crown transparency alone explained most of the relationship (88.9% and 65.1% resp.). For Douglas fir and Norway spruce, the relationship was relatively weak. It is highly remarkable that only a poor relationship was found for Scots pine. The meaning of the relationship between foliar loss and crown transparency indicates that these two forest condition indices might be exchangeable for oak, beech, Corsican pine and Japanese larch. For Scots pine, Douglas fir and Norway spruce, it seems that foliar loss and crown transparency are two independent indices.

4.1.3 Foliar composition

Foliar composition data are presented in Tables 7 to 13. It is not the intention to discuss these data in detail in this report. They can be judged by comparison with critical levels given by Van den Burg & Schaap (1996) (Annex 1, Table A1.34) Some main conclusions that can drawn from the data are:

(a) All element contents, except that of P, Mg, Na, Zn and Al, are the highest for both deciduous tree species pedunculate oak and beech. For Al it is just the other way round.
(b) The N content in the needles of the surveyed Corsican pine stands is lower than that in the needles of other surveyed conifers.
(c) The needle N content is high in a substantial part of the surveyed stands of Douglas-fir (66%), Norway spruce (45%), Scots pine (60%) and Japanese larch (39%) (Annex1; Table A1.35).
(d) The foliar P content is low for a major part of all surveyed stand of all tree species except for pedunculate oak (Annex1; Table A1.35).

(e) Differences of substrates are slightly reflected in foliar composition, e.g. higher Ca, and lower Mn and Al contents on calcareous, reclaimed former marine deposits.
(f) The Al content in the foliage of pedunculate oak, in general, is low while the Cu content is high.
(g) Foliar Zn contents in the southern forest region are higher than in other regions, which presumably reflects the neighbourhood of zinc factories.
(h) Foliar Na content is relatively high in the coastal forest region near the North Sea.
(i) Foliar N content of conifers, in general, is higher in the southern forest region than in other regions, possibly reflecting higher atmospheric NH_3 concentration and or N deposition in this region.

Table 7 Mean foliar composition of pedunculate oak in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	8	24.6	1.5	7.9	4.4	1.8	1.6	0.13	6.9	22	85	510	62
Eastern	10	25.9	1.5	10.2	5.2	1.6	1.7	0.17	8.1	24	147	618	76
Central	10	25.9	1.5	8.3	3.9	1.6	1.8	0.13	7.7	22	122	818	90
Southern	11	25.5	1.5	8.6	5.1	1.5	1.7	0.11	7.4	29	141	643	94
Coastal	2	25.0	1.6	8.2	6.7	2.0	1.6	0.25	7.5	25	139	654	47
Rest	10	25.1	1.5	9.7	7.1	1.8	1.6	0.14	8.1	25	121	484	74
Mean	51	25.4	1.5	8.9	5.2	1.7	1.7	0.14	7.6	25	126	621	79

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 8 Mean foliar composition of beech in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	4	24.8	1.1	5.9	4.1	1.1	1.4	0.20	7.0	22	99	328	75
Eastern	5	26.9	1.2	7.8	4.6	1.2	1.8	0.16	7.1	32	106	647	99
Central	11	26.2	1.3	8.1	4.7	1.2	1.9	0.25	7.7	31	128	1025	122
Southern	3	24.3	1.2	7.7	4.2	1.1	1.8	0.13	6.5	33	131	762	153
Coastal	0	.	.	.	.	.	.	.	.	.	.	.	.
Rest	4	27.2	1.4	8.4	10.3	1.9	1.7	0.20	8.3	44	149	554	110
Mean	27	26.0	1.3	7.7	5.4	1.3	1.8	0.21	7.4	32	123	753	112

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 9 Mean foliar composition of Scots pine in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	9	16.9	1.2	6.0	1.7	0.8	1.1	0.14	3.5	40	45	218	193
Eastern	9	18.1	1.3	6.1	2.0	0.7	1.2	0.18	3.8	43	73	284	198
Central	11	18.4	1.4	6.0	1.8	0.7	1.2	0.18	3.5	44	71	263	226
Southern	13	20.1	1.3	6.2	1.9	0.6	1.2	0.15	3.9	57	72	186	197
Coastal	0	.	.	.	.	.	.	.	.	.	.	.	.
Rest	0	.	.	.	.	.	.	.	.	.	.	.	.
Mean	42	18.5	1.3	6.1	1.8	0.7	1.2	0.16	3.7	47	66	234	204

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 10 Mean foliar composition of Corsican pine in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	3	12.8	1.0	5.8	0.7	0.8	0.9	0.13	4.3	39	41	84	315
Eastern	0	.	.	.	.	.	.	.	.	.	.	.	.
Central	2	13.5	1.3	5.6	1.0	0.9	1.0	0.10	2.3	34	43	237	359
Southern	9	15.8	1.0	5.9	1.1	0.7	1.0	0.14	4.6	49	62	121	294
Coastal	4	12.8	1.3	5.9	1.6	1.3	1.0	2.27	4.8	45	65	134	186
Rest	2	13.5	1.3	6.5	1.5	1.1	0.9	0.15	3.6	34	48	66	169
Mean	20	14.3	1.1	5.9	1.2	0.9	1.0	0.56	4.2	44	56	124	269

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 11 Mean foliar composition of Douglas-fir in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	8	17.9	1.1	6.8	2.5	1.4	1.4	0.15	3.9	22	64	178	226
Eastern	3	20.6	1.3	6.9	2.7	1.3	1.4	0.20	4.1	27	109	304	284
Central	11	19.0	1.3	6.4	2.5	1.4	1.5	0.12	3.9	27	93	571	287
Southern	5	21.9	1.1	6.6	2.5	1.0	1.4	0.14	5.0	37	112	262	231
Coastal	0	.	.	.	.	.	.	.	.	.	.	.	.
Rest	0	.	.	.	.	.	.	.	.	.	.	.	.
Mean	27	19.4	1.2	6.6	2.5	1.3	1.4	0.14	4.1	27	89	368	258

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 12 Mean foliar composition of Japanese larch in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	8	21.1	1.3	6.9	3.0	1.4	1.4	0.38	3.9	20	53	124	155
Eastern	2	25.7	1.4	6.9	2.7	1.5	1.8	0.30	4.4	23	101	230	209
Central	1	27.5	1.3	5.0	3.5	1.8	1.4	0.40	4.0	26	123	223	249
Southern	1	26.3	1.4	4.9	4.7	1.6	1.7	0.20	5.2	42	71	258	225
Coastal	0	.	.	.	.	.	.	.	.	.	.	.	.
Rest	1	19.6	1.7	5.8	6.2	2.1	1.3	0.20	3.3	22	56	134	45
Mean	13	22.6	1.3	6.5	3.4	1.5	1.4	0.34	4.1	23	67	159	167

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

Table 13 Mean foliar composition of Norway spruce in 1995

Forest region	*n*	N	P	K	Ca	Mg	S	Na	Cu	Zn	Fe	Mn	Al
Northern	10	16.4	1.3	5.7	2.8	0.9	1.1	0.12	2.6	22	49	315	93
Eastern	2	18.8	1.4	6.2	2.8	0.8	1.1	0.10	3.2	22	73	242	94
Central	2	16.0	1.1	5.6	2.4	0.7	0.9	0.10	3.0	23	76	747	136
Southern	6	17.9	1.3	6.0	2.0	0.7	1.2	0.13	2.9	27	76	160	147
Coastal	0	.	.	.	.	.	.	.	.	.	.	.	.
Rest	0	.	.	.	.	.	.	.	.	.	.	.	.
Mean	20	17.1	1.3	5.8	2.5	0.8	1.1	0.12	2.8	24	62	304	114

N, P, K, Ca, Mg, S, Na: g kg^{-1} (dm); Cu, Zn, Fe, Mn, Al: mg kg^{-1} (dm)

4.2 Stress factors

4.2.1 Stand and site characteristics

The median value for age of all 200 stands is 51 years (Annex 1: Table A1.6). The mean age for stands of beech and pedunculate oak are significantly higher than that of the coniferous species. Most of the stands of pedunculate oak (38 or 75%) are in between 25 and 100 years of age (Fig. 1). Only 2 stands (4%) are older than 125 years. 36 Scots pine stands (85%) are in the age of 25 to 100 years. Only 2 stands are older than 100 years and 4 are younger than 25 years (Fig. 1).

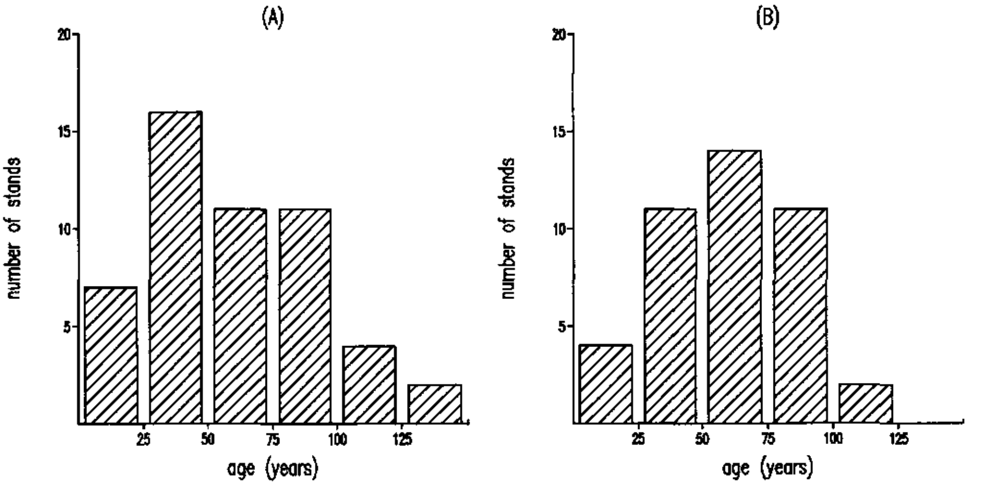

Fig. 1 Distribution of the age in 1995 of forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

The median value for crown projection percentage of all 200 stands is 80% (Table A1.9). For pedunculate oak the crown projection percentage range from 50% to 100% with a median value of 80%. Most stands (48 or 94%) have a crown projection higher than 60% (Fig. 2). The range in crown projection of Scots pine is notably higher than for pedunculate oak: a range of 10% to 100% crown projection was measured, with a median value of 70%. Compared to pedunculate oak, the crown projection of Scots pine is lower and more scattered (Fig. 2).

4.2.2 Water stress indices

Meteorological conditions are important in relation to water and temperature stress. To give some insight in the meteorological conditions of 1995, a short comment is given here. Information is descended from the annual weather overview of the Dutch meteorological institute (KNMI, 1995).

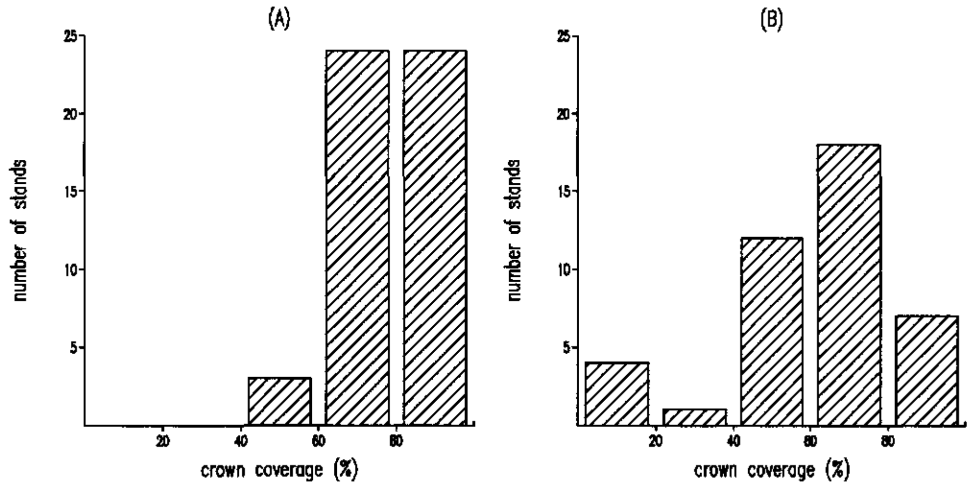

Fig. 2 Distribution of the crown projection in 1995 of forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

On the average the year 1995 was very warm and somewhat dry. The monthly variation in temperature and precipitation, however, was large. Februari, July, August and October were very warm, while temperature in June was below normal. In De Bilt, 41 summery days and 11 tropical days were measured, while the long year average is resp. 19 and 2. The average amount of precipitation in 1995 was 739 mm, the long year average is 792 mm. In the growing season (April to October), an average amount of precipitation of 366 mm was measured. The long year average is 460 mm. Especially April and August were very dry months both with 29 mm precipitation while the long year average is resp. 50 mm and 69 mm. The months January, Februari and March, however, were very wet with a total of 295 mm against 175 mm as a long year average.

The estimated values of the soil moisture supply are in the range of 25 mm to 225 mm. A soil moisture supply of 50 mm can be considered as very low. Forest stands on such sites are for moisture supply highly dependent from the amount of precipitation. A soil moisture supply capacity exceeding 200 mm is enough to compensate the evaporative demand in a 10% dry year (a dry year in which the amount of precipitation statisticaly occurs once in 10 years). 25 mm was found for only a few stands of beech and Scots pine (Annex 1: Table A1.14). Scots pine has the lowest mean soil moisture supply (128 mm) and Japanese larch and pedunculate oak the highest (167 mm and 162 mm respectively). Figure 3 shows that 23 (45%) pedunculate oak stands have a soil moisture supply of more than 200 mm. For these stands it can be assumed that they have a sufficient soil moisture supply under all weather conditions. For Scots pine only 3 stands (7%) have such a rich soil moisture supply. The distribution in soil moisture supply between pedunculate oak and Scots pine is as expected. It is known that Scots pine can be grown on dryer sites than pedunculate oak.

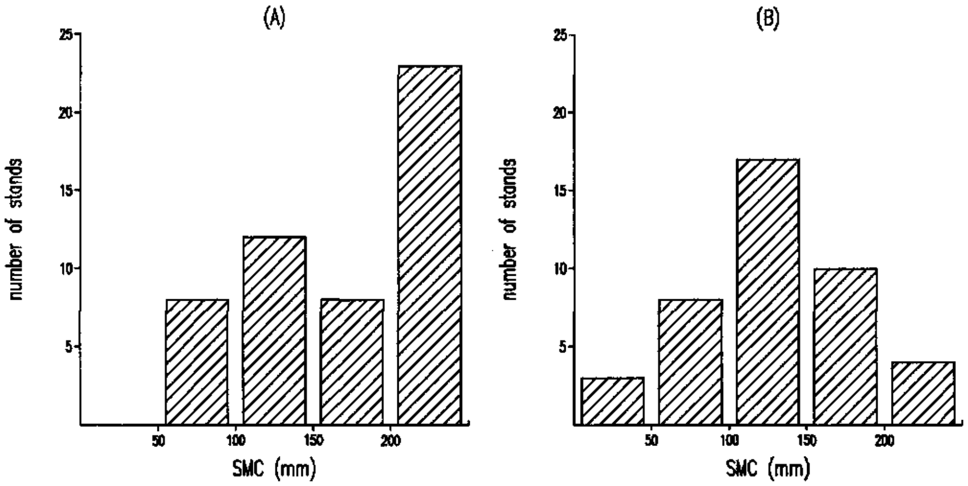

Fig. 3 Distribution of the soil moisture supply capacity (SMC) of soils under forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

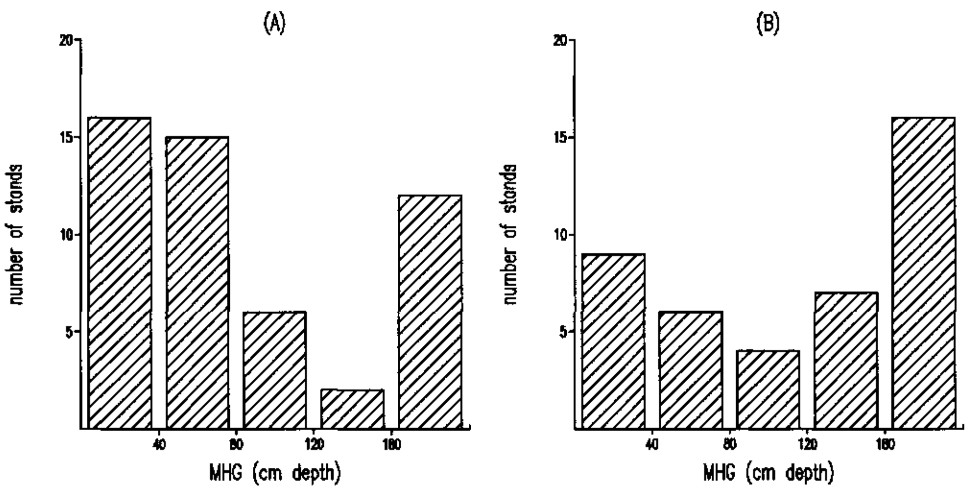

Fig. 4 Distribution of the mean highest winter groundwater level (MHG) under forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

The median of the mean highest groundwater level for all 200 plots was 110 cm below surface (Annex 1: Table A1.15). On the mean, Norway spruce occurs on the wettest places and beech on the driest. All tree species, except Japanese larch which occurs only on dry sites (GHG > 80 cm bs.), occur on both wet (GHG < 40 cm bs.) and dry sites (GHG > 80 cm bs.). Differences in the GHG distribution show that the sites of pedunculate oak on the average are wetter than that of Scots pine (Fig. 4). The amount of precipitation during the growing season of 1995 (Psum) was very low, an average of 170 mm was calculated for the 200 plots. The range of the Psum was in between 124 mm and 218 mm. For all tree species the range of the Psum was about similar except for Japanese larch, for which a median Psum of 212 was calculated, which is significantly higher than the about 170 mm for the other tree species (Annex 1: Table A1.16). Figure 5 shows that the distribution of stands over the different classes of Psum are about equal for pedunculate oak and Scots pine.

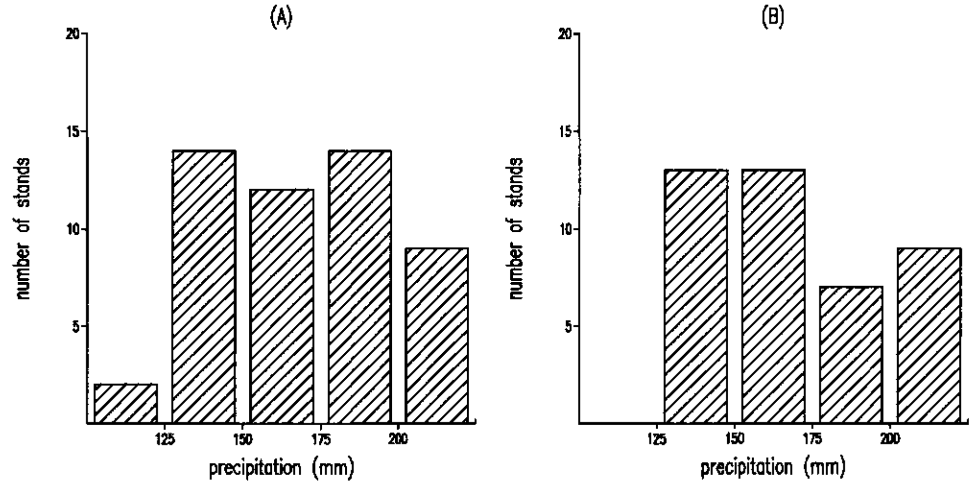

Fig. 5 Distribution of the amount of precipitation in the growing season (April to October 1995) in forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

4.2.3 Frost stress indices

The range in the minimum temperature of January 1995 (Tmin1) was very small (Annex 1: Table A1.17). For most plots a minimum January temperature of -4.8 °C was calculated. For 90% of the plots the minimum January temperature was in the range of -4.8 °C to -4.6 °C. The distribution of Tmin1 over different classes was about equal for pedunculate oak and Scots pine (Fig. 6).

Although larger than the range in Tmin1, the range in the minimum temperature of April (Tmin4) was also small. 90% of the plots fit in the range -1.6 °C to 0 °C. On the average plots of pedunculate oak had a somewhat higher Tmin4 than plots with Scots pine (Fig. 7).

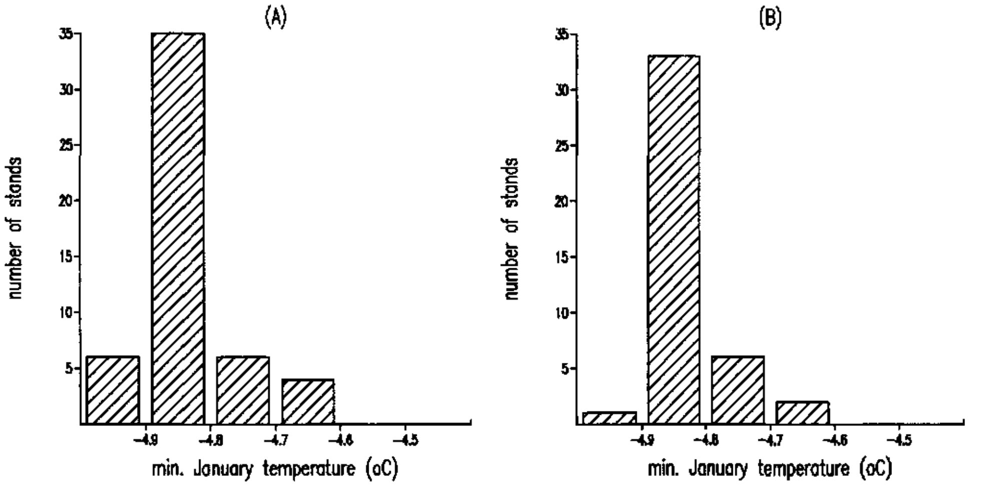

Fig. 6 Distribution of the minimum January temperature in 1995 in forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

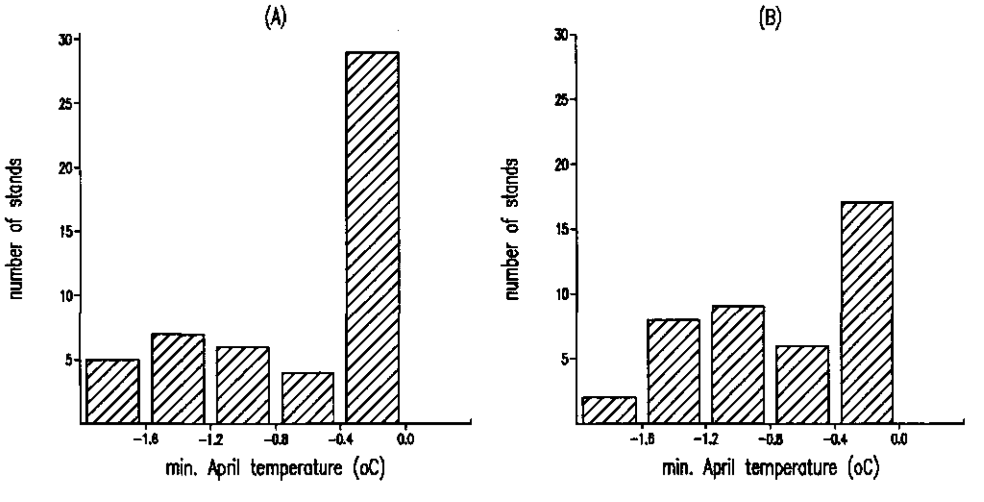

Fig. 7 Distribution of the minimum April temperature in 1995 in forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

4.2.4 Nutrient stress indices

Foliar nutrient contents of N, P, K, Mg and Ca are used to express the nutrient status of the forest stands, indicating a possible nutrient stress which might be a deficiency as well as an excess. In Annex 1, Tables A1.20 to A1.34, mean values of the measured foliar composition in 1995 of the stands of the monitoring network are given. In Annex 1; Table A1.34 the criteria for judgement of the foliar composition are given. With these criteria the percentage of stands were calculated that had a high

N status or a low P, K, Ca or Mg status. The results are shown in Annex 1; Table A1.35 and A1.36.

Corsican pine (5.0%) and pedunculate oak (4.1%) have relative few stands with a high foliar N content. All other tree species have a considerable percentage of stands with a high foliar N content. Scots pine (59.5%) and Douglas-fir (65.4%) have the highest percentage of stands with a high foliar N content.

A low foliar P content was found in 57.6% of all stands. For Japanese larch even 100% of the stands have a low foliar P content. For Douglas-fir stands this percentage was 88.5%. Only 14.3% of the stands of pedunculate oak had a low foliar P content. For Scots pine this percentage was about equal to the mean, 54.8%.

Low foliar K contents especially occurred in stands of Japanese larch (83.3%). For Scots pine (0%) and pedunculate oak (2.0%) no or little stands with a low foliar K content were found.

A low foliar Ca content was measured in about 30% of the stands of all tree species, except for Corsican pine, were the percentage was 45%, and pedunculate oak, were the percentage was 4.2%.

The percentage of stands having a low foliar Mg content was very scattered. For Corsican pine, Douglas-fir and Japanese larch no stands with a low foliar Mg content were found, for Norway spruce, Scots pine and pedunculate oak this percentage was round about 20% while for beech 74.1% of the stands had a low foliar Mg content.

A low foliar P/N ratio was found for many of the beech stands (55.6%). For Scots pine (0%) and pedunculate oak (18.4%) this percentage was much lower. Low K/N ratios were found in relative little stands, the mean percentage was 5.6%. The percentage of stands with a low foliar Mg/N ratio was, the same as for the foliar Mg content, very scattered. Scots pine had the largest percentage stands with a low foliar Mg/N ratio, while pedunculate oak had the lowest percentage (4.1%).

4.2.5 Pests and diseases

In 1995 no severe insect damage was found at time of the recording of the forest condition (Table 14). Most damage was found in the deciduous species pedunculate oak and beech. About 18% of the pedunculate oak stands and 9% of the beech stands were damaged (26-60%) or severely damaged (> 60%) by insects, mainly caterpillars. Also no severe fungal damage was found in the monitoring stands (Table 15). Pedunculate oak was the most infected tree species, about 10% of the stands were infected with mildew. About 5% of the recorded Scots pine trees were little (11-25%) or moderately (26-60%) infected by the fungi *Sphaeropsis sapinea*.

Table 14 Percentage of trees damaged by insects (source: Hilgen, 1995)

Tree species	Percentage of damaged foliage			
	0-10%	11-25%	26-60%	>60%
pedunculate oak	56.1	26.1	15.6	2.2
beech	79.1	12.3	8.3	0.3
Scots pine	100	0	0	0
Corsican pine	99.8	0.2	0	0
Douglas-fir	100	0	0	0
Norway spruce	88.8	5.6	4.8	0.8
Japanese larch	90.8	6.8	2.5	0

Table 15 Percentage of trees damaged by fungi (source: Hilgen, 1995)

Tree species	Percentage of damaged foliage			
	0-10%	11-25%	26-60%	>60%
pedunculate oak	89.5	5.2	4.1	1.2
beech	100	0	0	0
Scots pine	95.0	4.4	0.6	0
Corsican pine	95.6	3.2	1.2	0
Douglas-fir	100	0	0	0
Norway spruce	97.6	1.6	0.6	0.2
Japanese larch	100	0	0	0

4.2.6 Air pollutants

Ozone

Although for the yearly average O_3 concentration no critical levels were found in literature, this variate was included in the statistical model to test whether it would give an additional or better explanation than the AOT40 values. For pedunculate oak the p05, median and p95 values are respectively 38, 41 and 45 µg m^{-3}. For Scots pine these values are respectively 39, 41 and 43 µg m^{-3} (Annex 1; Table A1.7). The calculated yearly average O_3 concentrations for the monitoring plots are near the long term mean in The Netherlands for the period 1978 to 1993, which is about 40 µg m^{-3} (Heij & Schneider, 1995).

The AOT40 levels found for the 200 plots are all around the critical level of 10 000 ppb h (Annex 1; Table A1.8). For pedunculate oak the p05, median and p95 values are respectively 8 500, 11 600, 13 600 ppb h, and for Scots pine respectively 8 800, 11 700 and 13 700 ppb h.

On the forehand the effect of O_3 or the AOT40 on the crown condition indices was not expected to be very large since the variance in O_3 concentrations in The Netherlands, and through that also the AOT40 values, is not very large.

Nitrogen

For nitrogen the mean NH_3 air concentration and the NH_3 and NO_x deposition flux in 1995 were calculated. The NH_3 concentration and deposition show conciderable regional variation throughout The Netherlands while the NO_x deposition does not (Annex 1; Table A1.6, A1.10, A1.11).

Sulphur
Present SO_2 air concentrations in The Netherlands are that low that no direct effects on tree species are expected (Heij & Schneider, 1995). SO_x however, is an important component in total acid deposition. The SO_x deposition shows considerable regional variation throughout The Netherlands (Annex 1; Table A1.9). On base of this variation effects of soil acidifying processes on crown condition, if any, may be expected.

4.2.7 Toxic elements

The critical Al concentration in the soil solution of 0.2 mol_c m^{-3}, above which root damage may occur (De Vries, 1993), is exceeded in most stands of pedunculate oak as well as and Scots pine stands (Fig. 8). However, Sverdrup & Warfvinge (1993) mentioned that the BC/Al ratio is a better measure for root damage. Hendriks et al. (1997) presented critical BC/Al ratios, which is 0.6 mol mol^{-1} for pedunculate oak and 1.2 mol mol^{-1} for Scots pine.

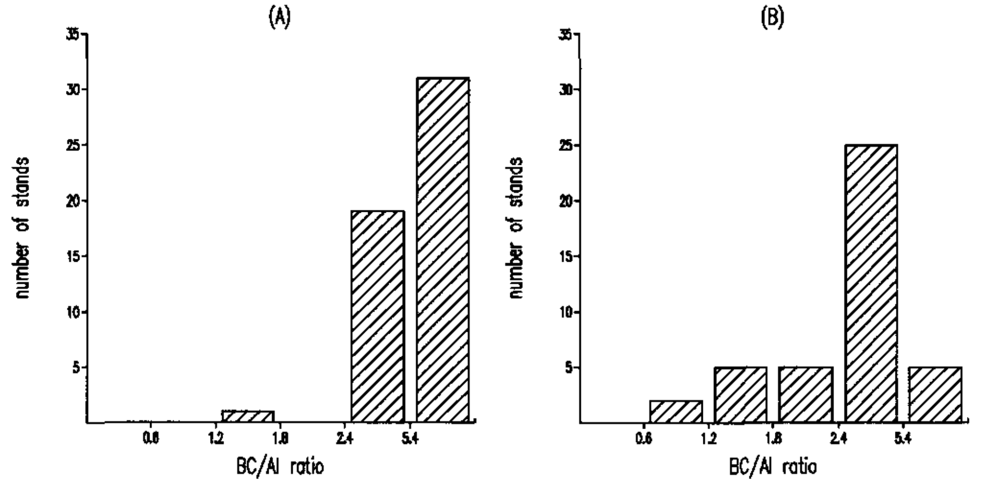

Fig. 8 Distribution of the Al concentration in the soil solution in 1995 of forest stands of pedunculate oak (A) and Scots pine (B) for the Dutch Forest Health Monitoring Network

Figure 9 shows that none of the pedunculate oak stands exceed this threshold and only 2 stands of Scots pine (both having a ratio of about 0.9 mol mol^{-1}). Based on these results we do not expect any influence of the Al concentration in the soil solution or the BC/Al ratio on the forest condition indices.

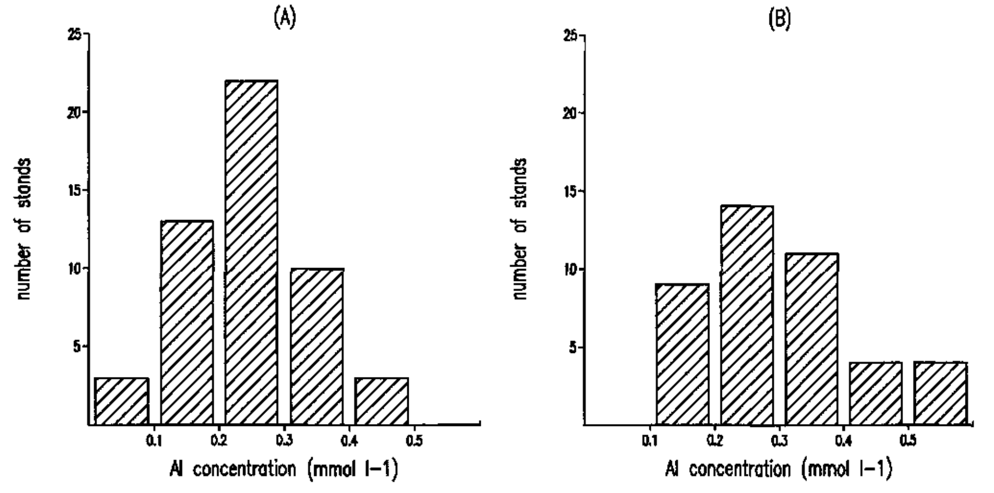

Fig. 9 Distribution of the BC/Al ratio of the soil solution in 1995 in forest stands of pedunculate oak (A) and Scots pine (B) of the Dutch Forest Health Monitoring Network

4.3 Relationships between forest condition indices and stress factors

4.3.1 Foliar loss

From the simple regression analysis it followed that no common stress parameters are found explaining defoliation for all tree species (Annex 3). It also may be concluded that more than one predictor is needed to explain defoliation, hence multiple-regression gives a better description of the effects.

The number of surveyed stands permitted a stable multiple-regression and selection of predictors only for Scots pine (n = 42) and pedunculate oak (n = 51). From comparison between models with defoliation and logit defoliation as response variates, it followed that logit transformation of defoliation gave a better result in explaining the percentage accounted for (Annex 4).

Pedunculate oak
Through use of the SSPLINE function we found that for age and insect a non-linear term performed a better fit than a linear fit. When age, corrected for other predictors, was plotted against logit defoliation, an exponential curve was detected. Therefore we transformed age to the natural logarithm of age, ln(age), and included it in the regression. Inclusion of ln(age) produced significantly higher percentages accounted for than age (70% versus 57%).

SSPLINE also showed non-linear shape for the predictor insect. When plotted, a 'broken-stick' model gave the best fit through the spline. From class 1 to about class 2.5 there was no apart effect of insect damage on foliar loss. Above a mean class of 2.5 insect showed a positive linear correlation with foliar loss, i.e. the higher the insect damage, the higher the foliar loss. Therefore we transformed the insect damage index into a new predictor named 'insect25', which is a combination of two sub variables, one consisting of all observations below a mean damage class of 2.5, and the other one of all observations above this limit. The class value 2.5 is considered as a threshold value, below which insect damage has a constant impact on foliar loss and crown transparency. The meaning of such a threshold may be a visual detection threshold, below which the percentage of damage can not be reliable estimated. A mean class of 2.5 can be interpreted as about 15% of the foliar biomass is damaged by insects.

Table 16 Models explaining logit foliar loss of pedunculate oak (Models including insect and fungal damage (A), excluding fungal damage (B) and excluding insect and fungal damage (C))

Model	Equation		p	R^2_{adj}
A	1 logit fol.loss =	-15.99		70.9
		+0.840*ln(age)	<0.001	
		-0.015*crown%	0.044	
		+0.613*insect25	<0.001	
		-0.365*fungi	<0.001	
		-3.748*tmin1	<0.001	
		-0.003*tgsum	0.012	
B	2 logit fol.loss =	-23.81		58.9
		+0.968*ln(age)	<0.001	
		+0.681*insect25	<0.001	
		-3.27*tmin1	0.004	
C	3 logit fol.loss =	-10.24		54.8
		+0.682*ln(age)	<0.001	
		-0.029*crown%	<0.001	
		+0.023*psum	0.002	
		+0.00032*AOT40	0.018	
	4 logit fol.loss =	-10.4		57.6
		+0.741*ln(age)	<0.001	
		-0.028*crown%	0.002	
		-3.21*tmin1	0.006	
		-0.013*tgsum	0.015	
		+0.000323*AOT40	0.034	

From a first execution of the multiple-regression procedure with RSELECT, in which ln(age) and insect25 were included, one candidate model was selected (Eq. 1 in Table 16). No other models met the Cp criterion. In this run all predictors were included (Table 2). Eq. 1 shows a high percentage accounted for, but it contains a negative correlation between foliar loss and fungal damage, meaning decreasing foliar loss with increasing fungal damage, which seems not plausible. Analysis of the data on fungal damage showed that for nearly all plots with pedunculate oak fungal damage was near 0%. For three plots, however, a high percentage of fungal damage was observed while defoliation was low. Due to the unequal distribution of the observations, the three plots had a high leverage (inflence) on the relation. Therefore a second run without fungal damage was executed, resulting in also one candidate model (Eq. 2 in Table 16). Other models did not meet the Cp criterion or included not significant predictors.

A third regression was calculated with exclusion of both fungal damage and insect damage (insect25). This resulted in two candidate models (Eqs. 3 and 4 in Table 16).

As mentioned in Section 3.1, age and the percentage crown coverage, can be considered as predictors correcting the estimation of the foliar loss. Correction of defoliation for insect and fungal damage is also needed, because these predictors can cause foliar loss, but it is not clear whether they are autonomous or influenced by other stress factors. Therefore two multiple-regression runs were calculated one on a set of predictors with and one on a set without insect and fungal damage.

Stand age, transformed as ln(age), and the tmin1 showed to be important predictors, they are part of all equations. Ln(age) alone explains 39.5% of the total variance, and tmin1 just 7.3%. From the selected candidate models Eq. 2 can be selected as the best model when insect damage is included in the regression. Eq. 1 is not plausible because the negative correlation of fungal damage. If Eq. 2 is correct, foliar loss increases with age and with increasing insect damage, and decreases with increasing (warmer) January temperatures.

When both fungi and insect damage are excluded from the regression, it is not clear which model must be selected as the best. At first sight Eq. 3 seems not plausible because the coefficient of the amount of precipitation (psum) is positive, while it was expected to be negative, i.e. decreasing foliar loss with increasing precipitation. In combination with O_3, however, the effect of precipitation might be predicted right. O_3 can only enter stomata when they are opened, which is only the case when sufficient moisture is available. Then Eq. 3 and 4 are much alike because psum and tgsum are related to each other. Eq. 4 indeed has a higher percentage accounted for, but it also includes 5 predictors while Eq. 3 includes 4.

Scots pine

Comparison of the results of regressions on foliar loss and logit-transformed foliar loss showed that the logit-transformation had a better result (Annex 4 vs. Table 17). The regression model in which the foliar nutrient ratios were included resulted in a better explanation that the models with the foliar nutrient contents did.

The logit-transformation of foliar loss and multiple-regression analysis yielded 4 candidate models (Table 17). All models followed from the regression with all predictors included. Eq. 3 and 4 already matched the C_p criterion but Eq. 1 and 2 were also selected because they added (quite) some explanation while the models are quite plausible.

Table 17 Multiple linear regression models explaining the logit foliar loss of Scots pine

Equation		p	R^2_{adj}
1	logit fol.loss = -2.11		38.1%
	+0.031*age	<0.001	
	-35.6*P/N	0.015	
2	logit fol.loss = +1.80		36.0%
	-0.032*crown%	<0.001	
	-35.2*P/N	0.018	
3	logit fol.loss = -4.636		29.6%
	+0.030*age	<0.001	
4	logit fol.loss = -0.774		27.8%
	-0.0316*crown%	<0.001	

As Eq. 1 and 2 give the best result it can be selected as the best models explaining foliar loss of Scots pine. Table 17 shows that age and crown projection percentage are exchangeable predictors, with age resulting in a somewhat higher explanation. Age or crown projection percentage and foliar P/N ratio are plausible as well as predictor as in the kind of correlations. From eq. 1 it can be interpreted that needle loss of Scots pine increases with increasing age and decreases when the foliar P/N ratio is higher. A higher P/N ratio might point out a better nutrient balance resulting in a better condition.

No non-linear fits for the included predictors were found that gave better results in the explanation of foliar loss of Scots pine than the linear fits did.

Compared to pedunculate oak, it is remarkable that both crown projection and insect damage did not show up as explaining predictors. It was therefore not necessary to delete them from the model, as was done for pedunculate oak.

4.3.2 Crown transparency

From the simple regression analysis it followed that no common stress parameters were found explaining transparency for all tree species (Annex 5). It can also be concluded that more than one predictor is needed to explain crown transparency.

The multiple-regression analyses for the effect-parameters crown transparency and logit crown transparency, were carried out similar as for foliar loss and logit foliar loss (Section 4.3.1).

Pedunculate oak

In Table 18 multiple linear regression models are presented that include the natural logarithm of age (ln(age)). Log transformation of age resulted in a higher percentage explained variance than the untransformed age value did.

Table 18 Multiple linear regression models explaining crown transparency (%) of pedunculate oak (Models including insect and fungal damage (A), excluding fungal damage (B) and excluding insect and fungal damage (C))

Model	Equation	p	R^2_{adj}
A	1 cr.transp. = -179.0		62.5
	+7.19*ln(age)	<0.001	
	+9.77*insect25	<0.001	
	-3.58*fungi	0.002	
	-30.3*tmin1	0.007	
B	2 cr.transp. = -127.8		62.4
	+10.13*insect25	<0.001	
	+0.083*psum	<0.001	
	+0.006*AOT40	<0.001	
	+0.036*SO_x	<0.001	
	-1.280*foliar-N	0.011	
	3 cr.transp. = -161.5		60.5
	+4.89*ln(age)	0.012	
	+11.42*insect25	<0.001	
	-31.0*tmin1	0.008	
	-1.227*foliar-N	0.018	
	+0.016*SO_x	0.016	
	4 cr.transp. = -124.6		60.2
	+8.60*insect25	<0.001	
	+0.327*psum	<0.001	
	+0.005*AOT40	<0.001	
	+0.025*SO_x	0.002	
	-0.162*crown%	0.045	
C	5 cr.transp. = -177.7		38.3
	+0.480*psum	<0.001	
	+0.008*AOT40	<0.001	
	+0.035*SO_x	<0.001	
	6 cr.transp. = -130.6		37.8
	+7.18*ln(age)	<0.001	
	-28.2*tmin1	0.042	
	-9.80*foliar-Mg	0.014	
	7 cr.transp. = -60.8		37.2
	-0.351*crown%	<0.001	
	+0.273*psum	0.002	
	+0.005*AOT40	0.001	

Multiple regression on crown transparency of pedunculate oak resulted in a higher percentage variance accounted for (Table 18) than regression on the logit transformed transparency did (Annex 6). This especially holds for the models from which fungal damage was excluded (Model B).

The regression with all predictors included in the model (model A) resulted in a model with the highest percentage accounted for (Table 18, Eq. 1). This model, however, includes fungal damage with a negative coefficient, meaning that crown transparency decreases with increasing fungal damage, which is not plausible. Therefore a regression was calculated with a model from which fungal damage was excluded as a predictor (model B).

The regression without fungal damage resulted in three candidate models which matched the statistical criteria (Table 18, Eq. 2 to 4). Eq. 2 and 4 both contain the precipitation amount over the growing season (psum) with a positive coefficient which may be plausible in combination with ozone (see Section 4.3.1). However, because of the inclusion of age in Eq. 3 slight preference is given to this model.

When both insect and fungal damage are excluded as predictors (model C), three candidate models were found which matched the statistical criteria (Table 18, Eq. 5 to 7). The percentage accounted for, however, is much lower then for equations from models A and B. Similar to Eq. 2 and 4, Eq. 5 and 7 contain psum with a positive coefficient while it was expected to be negative. Thus, Eq. 6 seems to be the most plausible one, explaining crown transparency with ln(age), minimum temperature in January (tmin1) and the foliar Mg content.

Scots pine

Regression on crown transparency of Scots pine resulted in models with a higher percentage accounted for than regression on the logit transformed crown transparency (Table 19 vs. Annex 7). In contrast with pedunculate oak, a linear fit of age produced the best results for Scots pine. Since insect and fungal damage did not show up as stress parameters in the candidate model found, there was no need to delete them from the set of predictors.

When foliar nutrient ratios were included as predictors in the models, both foliar N and foliar P/N ratio showed up as explaining stress parameters, indicating that possibly only the foliar P content was needed. Regression with foliar nutrient contents indeed resulted in better models than with foliar nutrient ratios.

Table 19 Multiple linear regression models explaining crown transparency (%) of Scots pine

Equation			p	R^2_{adj}
1	cr. transp. =	386		51.2
		-0.088*age	0.007	
		-0.642*psum	0.002	
		-81.30*tmin1	<0.001	
		-0.226*tgsum	0.009	
		-21.17*foliar-P	<0.001	
		-0.003*NH_x	0.016	

Only one model from the regression analysis matched the statistical criteria (Table 19; Eq. 1). Although 6 stress parameters are included in the model, they are plausible and have a correct coefficient, except age, for which a positive coefficient was expected. The effect of age, however, on the crown transparency in this relationship is very minor, and therefore this apparently incorrectness can be excepted. The influence of NH_x may indicate a fertilizing effect of nitrogen. Most dominant factors in this relationship are the January minimum temperature (tmin1) and the foliar P content.

4.3.3 Foliar composition

Pedunculate oak

The results of the multiple-regression, performed with the RSELECT procedure of GENSTAT 5.3.2, for pedunculate oak are presented in Table 20. Some main conclusions can be drawn from the data presented in Table 20:

The foliar N content depends on the NO_3 concentration of the soil solution (cNO_3) and the temperature sum of the growing season (tgsum). The contribution of cNO_3 is in a sense unexpected, because evidence of significant relationships between soil N and foliar N in forest stands is scarce (Van den Burg, 1996). The contribution of the predictor variable tgsum can be explained by the positive influence of soil temperature (which is related to air temperature) on soil N mineralization. Reich et al. (1997) found that in North-Central USA forests mean annual temperature, litterfall N, and soil texture explained 81% of the variance of soil N mineralization. No significant ($p < 0.05$) correlation was established between foliar N and N-deposition (Ntotdep).

Table 20 Relationships between foliar composition of pedunculate oak, and stress parameters (n = 48)

Element	Equation	p	R^2_{adj} (%)
Foliar N =	- 1.00		28.2
	+ 2.000*cNO_3	<0.001	
	+ 0.00862*tgsum	0.006	
Foliar P =	+ 1.4491		24.1
	+ 6.78*cPO_4	0.002	
	- 0.888*cFe	0.034	
Foliar K =	+ 8.764		30.3
	+ 0.01991*age	0.002	
	+ 1.093*ln(cCa)	0.003	
Foliar K =	+ 6.859		24.7
	+ 0.02159*age	0.001	
	+ 1.584*cCa	0.017	
Foliar K =	+ 8.369		22.6
	+ 0.2290*age	<0.001	
	- 0.000345*Nadep	0.035	
Foliar Ca =	+ 1.927		47.3
	+ 1.391*cCa	0.001	
	+ 0.00733*vlmm	0.017	
	- 0.001262*Ntotdep	<0.001	
	+ 0.2066*NH_3	0.001	
	+ 0.00694*SO_x	<0.001	
	- 3.19*cNa	0.010	
Foliar Ca =	+ 4.259		28.6
	+ 3.034*cCa	<0.001	
	- 40.8*cPO_4	0.008	

Table 20 continued

Element	Equation	p	R^2_{adj} (%)
Foliar Mg =	+ 1.9953		50.8
	+ 2.655*cMg	<0.001	
	- 0.003329*age	<0.001	
	- 4.90*cMn	<0.001	
	- 1.002*cK	0.002	
	- 1.255*cNa	<0.001	
Foliar Al =	- 28.1		36.2
	+ 83.3*cAl	0.031	
	- 114.0*cFe	0.010	
	+ 0.00828*AOT40	<0.001	
Foliar Fe =	+ 325.1		41.5
	+ 363.5*cFe	<0.001	
	+ 74.8*cCa	<0.001	
	- 1205.0*cPO_4	0.006	
	- 60.6*pH-KCl	0.005	
Foliar Mn =	+ 391.4		58.7
	+ 10869*cMn	<0.001	
	- 1070*cAl	0.011	
Foliar Zn =	+ 17.52		70.3
	+ 0.05867*Znstr	<0.001	
Foliar Zn =	+ 11.68		85.3
	+ 0.0297*Znstr	0.022	
	+ 0.0838*Custr	0.017	
	+ 7.47*Cdstr	0.009	
Foliar Cu =	+ 6.870		69.7
	+ 0.00395*Znstr	0.017	
	+ 0.01896*Crstr	0.011	
	- 41.58*cPO_4	<0.001	
Foliar Cu =	+ 6.757		67.6
	+ 0.00525*Znstr	0.002	
	+ 0.00404*Pbstr	0.020	
	- 44.68*cPO_4	<0.001	
Foliar Cu =	+ 6.625		67.4
	+ 0.01795*Crstr	0.022	
	+ 0.0730*Cdstr	0.034	
	- 36.78*cPO_4	<0.001	

The foliar P content is positively correlated with the P concentration in the soil solution (cPO_4) - which is also unexpected, but plausible - and negatively with the Fe concentration in the soil solution. The latter referring to the well-known soil physical Ca-Al-Fe-phosphate solubility relations: at low pH values, Fe and Al precipitate phosphate ions, which thus become less available for uptake by the roots.

No correlation was found between the foliar K content and the K concentration in the soil solution (cK). The positive effect of the Ca concentration in the soil solution (cCa) on the foliar K content ignores the K-Ca antagonism, and, for that reason, it can not be accepted as a direct effect. The third presented equation relates foliar K to stand age (positive) and atmospheric Na deposition (Nadep, negative). The effect of age on the foliar K content was established earlier for Scots pine by Heinsdorf (1976). It is suggested that Nadep actually represents the total atmospheric deposition of basic cations, which implies antagonistic effects of basic cations (Na, Ca, Mg) on K uptake.

The relationship between the response variable foliar Ca content and predictor variables could be described by two candidate models. First equation explains 53% of the variation in the foliar Ca content, but for this, it needs 6 stress parameters which may be to many for a stable model. Therefore the second model is presented, which does not quite match the statistical criteria, but it seems a quite plausible one explaining the foliar Ca content out of the Ca and PO_4 concentration in the soil solution.

The variation in the foliar Mg content was explained by soil solution concentrations of Mg (positive), K, Na and Mn (all negative) (respectively cMg, cK, cNa and cMn) and stand age (negative). This relationship points to a Mg-(K, Na, Mn) antagonism in the soil solution. The relationship between foliar Mg content and stand age is negative, which is contrary to the relationship between foliar K and stand age.

No significant relationship between foliar S and S-deposition or any other predictor variable could be established.

Foliar Al content was positively related to the Al concentration in the soil solution, and negatively to the Fe concentration in the soil solution. This points to a plausible Al-Fe antagonism in the soil solution. The contribution of the atmospheric ozone concentration (AOT40) to foliar Al is further discussed in Chapter 5.

The foliar Fe content was explained by four soil variables: the concentration in the soil solution of Fe, Ca, PO_4 and the pH-KCl of the soil solution. The positive effect of the Fe concentration in the soil solution does not offer problems, nor does the negative effect of the PO_4 concentration in the soil solution (see above: foliar P content). The positive effect of cCa may be attributed to the requirement of Ca to maintain the formation of new root tips. Fe uptake by the roots apparently takes place by the root tips only (Mengel & Kirkby, 1987). The negative contribution of the soil pH can be explained by the extremely strong (negative) pH dependency of the solubility of Fe^{3+}-ions.

Foliar Mn content was principally explained by the Mn concentration in the soil solution (positive), and the Al concentration in the soil solution (cAl) (negative). This negative contribution of cAl can be contributed to ion antagonism.

Foliar Zn content was explained for a major degree by the Zn content in the forest floor, but also the Cu and Cd content in the forest floor contributed significantly to the explanation.

It is remarkable that the foliar Cu content was found to depended on Zn, Pb, Cr and Cd contents in the forest floor, but not on the Cu content itself. These variables were exchangeable. The only consistent stress parameter found, was the negative effect on the foliar Cu content of the PO_4 concentration in the soil solution, irrespective of the effects of the heavy metals.

Scots pine

The data of Scots pine were treated in the same way as those for pedunculate oak. The results of the multiple-regressions computations for Scots pine, based on selection of models by the RSELECT procedure of GENSTAT 5.3.2, are presented in Table 21.

Table 21 Relationships between needle composition of Scots pine, and stress parameters (n = 35 when 1990 and 1995 data is used, n = 42 when only 1995 data is used)

n	Element	Equation	p	$R^2_{adj.}$ (%)
35	Foliar N =	- 3.16		43.1
		+ 2.187*totNva	0.001	
		+ 0.01691*tgsum	<0.001	
35	Foliar N =	- 37.9		48.2
		- 0.00287*SO_x	0.050	
		+ 2.011*totNva	0.002	
		+ 0.02008*tgsum	<0.001	
42	Foliar N =	- 21.8		36.1
		+ 2.84*cNH_4	0.012	
		+ 0.01466*tgsum	<0.001	
42	Foliar N =	- 35.0		31.8
		- 0.00321*SO_x	0.049	
		+ 0.02053*tgsum	<0.001	
42	Foliar N =	+ 12.19		30.7
		+ 0.0005111*AOT40	0.004	
		+ 2.89*cNH_4	0.014	
35	Foliar P =	+ 1.1511		17.6
		+ 1.121*TotPva	0.007	
42	Foliar P =	+ 0.997		16.6
		+ 0.0000330*AOT40	0.04	
		+ 11.49*cPO_4	0.039	
		- 2.288*cFe	0.017	
42	Foliar K =	+ 6.473		11.5
		- 0.0001362*Nadep	0.016	
35	Foliar Ca =	+ 1.183		46.9
		+ 1.173*cCa	<0.001	
		+ 0.389*Cauit	0.003	
42	Foliar Ca =	+ 1.333		55.1
		+ 2.014*cCa	<0.001	
		+ 1.573*cK	0.003	
		- 0.332*cNa	0.007	
		- 18.76*cMn	0.041	
42	Foliar Ca =	+ 1.440		44.6
		+ 1.969*cCa	<0.001	
		- 0.422*cNa	0.001	

Table 21 continued

n	Element	Equation	p	R^2_{adj} (%)
35	Foliar Mg =	+ 1.184		64.6
		+ 0.0001119*Mgstr	0.054	
		- 0.0000332*AOT40	0.003	
		- 0.0000906*Kstr	0.031	
		+ 0.0521*cNa	0.030	
		- 4.45*cMn	0.036	
		- 0.258*Kuit	0.019	
		+ 0.339*Nauit	0.005	
42	Foliar Mg =	+ 1.2295		45.2
		-0.00004434*AOT40	<0.001	
		+ 0.0515*cNa	0.056	
		- 4.34*cMn	0.052	
42	Foliar Mg =	+ 1.230		37.1
		- 0.00004416*AOT40	<0.001	
35	Foliar Al =	+ 183.1		27.1
		+ 0.00907*Alstr	0.004	
		- 0.580*cFe	0.006	
35	Foliar Fe =	+ 51.45		18.7
		+ 0.00324*Festr	<0.001	
35	Foliar Mn =	+ 193.2		90.5
		+ 4703*cMn	0.005	
		+ 2776*Mnuit	<0.001	
		- 436*cMg	0.003	
35	Foliar Mn =	+ 151.8		87.0
		+ 2784*Mnuit	<0.001	
35	Foliar Zn =	+ 38.78		88.3
		+ 0.04997*Znstr	<0.001	
35	Foliar Zn =	+ 33.91		87.5
		+ 8.679*Cdstr	<0.001	
35	Foliar Cu =	+ 3.505		9.4
		+ 0.1200*Cdstr	0.041	
35	Foliar Cu =	+ 3.338		8.8
		+ 0.001819*Pbstr	0.046	
36	Foliar Cu =	+ 3.577		8.7
		+ 0.000670*Znstr	0.047	

The results of the multiple-regression computations for the foliar composition of Scots pine can be summarized as follows:

The response variable foliar N content was explained by five candidate models, based on two data sets (with 1990 solid phase data, i.e. exchangeable cations: n = 35; without exchangeable cations, but with 1995 soil solution data: n = 42) (see Section 3.3.2). The two equations of the first group both contain the predictor variables totNva (sum of amount of total N in the forest floor and in the mineral top soil) and temperature sum of the growing season (tgsum). The first predictor variable is plausible. The effect van tgsum might be compared with that by the mean annual temperature, the positive effect of which on soil N mineralisation in forest soils was established by Reich et al. (1997). The role of SO_x (atmospheric S deposition) in the second equation is not explainable. The three equations of the second group suggest that cNH_4 and SO_x are exchangeable, and so are tgsum and AOT40. The positive relationship between foliar N and cNH_4 is more plausible. The problem whether AOT40 (damage by tropospheric ozone) or tgsum acts directly on the foliar N content cannot be solved. At first sight, tgsum seems more plausible than AOT40 because higher soil temperature in the growing season (indicated by a higher value of tgsum) may intensify soil N mineralisation.

Foliar P content was explained by the total P stock in the forest floor and the mineral top soil, but the value of R^2_{adj} is rather low. An alternative model is composed of the predictor variables cPO_4 (positive), cFe (negative), and AOT40 (positive). The effect of the first two variables is plausible. The ozone effect on the foliar P content, might be comparable to that on the foliar N content, which is further is discussed in Chapter 5.

No relationship between the foliar K content and the K concentration in the soil solution, or exchangeable K was found. The only relationship which could be established was that between foliar K and the atmospheric Na deposition (Nadep), which might reflect the total atmospheric deposition of basic cations and their antagonistic effect on K uptake (the sign of the Nadep term is negative).

The variance in the foliar Ca content was explained for 55.1% by the predictor variables cCa (positive), cNa and cMn (both negative), and cK (positive). This relationship is rejected, because soil Ca and soil K are antagonists, thus a positive effect of cK on the foliar Ca content is doubtful. Two other (more plausible) relationships both contain cCa and Cauit, (exchangeable Ca content in the solid phase), which is perfectly possible. It is suggested that cCa stands for a Ca intensity parameter, and Cauit for a Ca capacity parameter. Cauit and -cNa reflect the soil Ca-Na antagonism.

Three multiple-regression equations were found which can explain the foliar Mg content. The first equation, explaining 64.6% of the variance, is not quite acceptable for two reasons. In the first place, it is made up of a rather large number (seven) of predictor variables. In the second place, the signs of the coefficients of the terms cNa and Nauit are positive, while negative coefficients were expected, due tot the monovalent (Na) - divalent (Ca) ion antagonism. The third model is quite simple, describing foliar Mg content solely as a negative function of AOT40 (see Chapter 5).

The foliar Al content was reasonably well explained by a combination of the Al content in the forest floor (Alstr) and cFe. This relationship points to the importance of the forest floor as source for the Al supply (Messenger et al., 1978).

The foliar Fe content is positively related to the Fe content in the forest floor (Festr).

Foliar Mn is very strongly related to exchangeable Mn (Mnuit: $R^2_{adj} = 87.0\%$). The Mn concentration in the soil solution (positive) and the Mg concentration in the soil solution (negative) are significant, but contribute only little to the explained variance.

Foliar Zn and foliar Cu could not be related to soil solution concentrations of these ions, because these concentrations were not measured. Foliar Zn was strongly correlated to both the Zn and the Cd content in the forest floor. Possibly, in the sampled stands, the Zn and the Cd contents in the forest floor are influenced by the same source of pollution and through that closely related.

4.3.4 Foliar-soil-atmosphere relationships for all tree species

Meaningful multiple regression equations could only be computed for pedunculate oak and Scots pine because of the number of stands. In order to get some insight in possible effects of stress factors on the condition of the other five tree species of the monitoring network (Corsican pine, Douglas fir, Norway spruce, Japanese larch and beech), soil solution composition, soil solid phase, atmospheric deposition, and air pollution, were related to foliar nutrient contents by means of simple linear regression. Foliar N content was related by simple regression analysis to mean annual atmospheric NH_3 concentration and to total atmospheric N deposition (Annex 7). Because no atmospheric SO_2 concentrations were computed, only the relationship between the foliar S status and the mean annual SO_x-deposition was surveyed. The relationships between foliar composition and some soil variables (solid phase in 1990: pH-KCl, N-total, N-organic, P-total; exchangeable cations; soil solution composition in 1995) were surveyed by computation of multiple regression functions, based on plausibility of the contribution of soil variables (Annex 8). Because foliar composition is depending on more than one factor, the results of these simple regression analysis must be considered preliminary. The results of these analyses can be summarized as follows:

A positively and significant ($p < 0.05$) relationship between the foliar N content and total atmospheric N deposition was found for Corsican pine, Norway spruce, and Japanese larch (Annex 7; Table A7.1). For beech and Douglas-fir no significant relationship ($p = 0.05$) was found. Multiple regression analysis on the foliar N content of Scots pine and pedunculate oak showed no relationship with N deposition (Table 20 and 21).

The foliar N content of Corsican pine and Japanese larch, was positively and significantly ($p < 0.05$) related to the atmospheric NH_3 concentration (Annex 7; Table A7.2). From the multiple regression analysis on the foliar N content of Scots pine and pedunculate oak no relationship resulted with NH_3 concentration (Table 20 and 21). It may be expected that the effect of NH_3 on the foliar N content of Corsican pine and Japanese larch is robust because of the high percentage explained variance and because of the plausibility. In the literature the relationship between NH_3 concentration and foliar N content was demonstrated (e.g. Pérez-Soba, 1995). Therefore it is expected that the NH_3 air concentration will be a significant stress parameter when a solid analysis can be performed for these tree species (e.g. more plots available).

No clear relationship between any of the soil P parameters and the foliar P content was found. It was unexpected thath no effect of total soil-P on foliar P content was found, which contradicts with earlier findings (Van den Burg, 1996).

No significant relationship was established between foliar S content of any tree species, and the SO_x deposition in 1995.

Concentrations of N, Ca, and Mn in the soil solution had notable, positive influence on the respective foliar contents of these elements (Annex 8; Table A8.2).

From the regression analysis with only soil fertility data it was found that a high P status of the soil (indexed as total soil P) seems to stimulate the foliar Fe status of Douglas-fir, Corsican pine and Japanese larch. From the multiple regression analysis on the foliar Fe content of pedunculate oak, in which all predictors were included, however, a high PO_4 concentration in the soil solution seems to reduce the foliar Fe content which is more plausible (Table 20).

For none of the tree species a relationship between the foliar K content and any of the soil K parameters was found. This is in accordance with the results from the multiple regression analysis (Table 20 and 21).

A relationship between foliar Mg and Mg in the soil solution was found for beech and Corsican pine (Annex 8). The other tree species did not show such a relationship, which is in accordance with the findings of the multiple regression analysis (Table 20 and 21). Foliar Al was not significantly related to exchangeable Al. The Al concentration in the soil solution contributed for a large extend to the explanaition of the foliar Al content of Japanese larch (Annex 8) and, to a lesser extend, also for pedunculate oak (Table 20).

5 Discussion

In the following the results of the multiple-regression analyses for pedunculate oak and Scots pine are discussed in relation to literature. The three indices for forest condition used in this study, i.e. foliar loss, crown transparency and nutrient composition, are discussed separately.

5.1 Foliar loss

5.1.1 Pedunculate oak

Foliar loss is dependent on many factors and therefore the possible explanation of it is also depending on the completeness of the set of parameters to which it is related. This is shown in Table 16 and 17, were possible equations describing the contribution of predictor variables to the intensity of foliar loss, are listed. Stress parameters that contribute significantly ($p < 0.05$) to the explanation of the variance in foliar loss, are (with the + and - mark a positive respectively negative relationship with foliar loss is indicated):

+ age (ln(age))
- crown projection percentage (crown%)
+ amount of precipitation in the growing season (psum)
- minimum January temperature (tmin1)
- temperature sum of the growing season (tgsum)
+ insect damage (insect25)
+ ozone air concentration (AOT40)

The inclusion of stand age in the explaining models is, in view of evidence in the literature, perfectly plausible. Foliar loss increases linear to a certain age, after which the increase in foliar loss decreases to an age above which the level of foliar loss remains about equal. Foliar loss decreases in stands with a higher percentage crown projection. Crown projection (canopy closure) may influence the estimation of foliar loss possibly because of a better view in more open stands or the higher light intensity. Therefore, crown projection possibly is a corrective parameter. Also plausible are the effects of the minimum January temperature (tmin1) and the cumulated temperature of the growing season (tgsum). A higher winter temperature means less damage of pedunculate oak by deep winter frost. A higher summer temperature stimulates, in case of sufficient water supply, production of foliar mass, and subsequently increased growth. This does not contradict the observation of Visser et al. (1994) that high summer temperature impairs growth of oak, because that effect may depend on the water supply.

A higher amount of precipitation in the growing season seems to increase foliar loss of pedunculate oak. Most likely, this relationship is an indirect one, because water supply of forest tree stands on sandy soils in The Netherlands is often limited, and therefore the direct effect of precipitation is expected to prevent foliar loss. Also, there was no indication that groundwater levels in the summer of 1995 were so high, that oak stands could be damaged, as was the case between 1982 and 1989 (Oosterbaan & Nabuurs, 1991). However, it is possible that the apparent effect of precipitation on foliar loss is connected with exposure to atmospheric ozone. High ozone concentrations (expressed as AOT40) have a negative effect on foliar retention, i.e. foliar loss increases at higher ozone concentrations.

Although effects of ozone on forest health is still unclear (Sandermann et al., 1997), some evidence might be offered for a direct relationship between atmospheric ozone concentration and health of oak in 1995 in The Netherlands. In the first place, oak and beech seem to be somewhat more susceptible to ozone than e.g. Norway spruce (Gasch & Krapfenbauer, 1990; Rösel & Reuther, 1997). In the second place, AOT40 values (annual means) in 1995 were in the range of 9 000-13 600 ppb h. The (proposed) critical value is 10 000 ppb h (Führer & Achermann, 1994), which value is situated in the range found in 1995. Precipitation might be triggering ozone damage, because under dry conditions stomatal opening decreases, by which diffusion of ozone into the inner part of leaves and needles is reduced. This is in agreement with results of Temple et al. (1993) who found in a three-years experiment that ponderosa pine was damaged by ozone under moist conditions, but not under dry conditions. Ro-Poulson et al. (1996) showed that ozone uptake by Norway spruce is significantly influenced by stomatal conductance. They also showed that total ozone uptake corresponds very well with the evapotranspiration.

The significant effect of attack by insects on foliar loss of pedunculate oak is in agreement with evidence found in the literature (Hartmann, 1996).

Among the predictors, which apparently did not contribute to the explanation of foliar loss of pedunculate oak, were soil water supply, atmospheric NH_3 concentration, atmospheric N deposition and atmospheric S deposition. The lack of evidence for a significant contribution of the soil water supply to the variance of foliar loss is unexpected because (i) a significant relationship was found between this predictor variable and site index of pedunculate oak (Oosterbaan, 1988), and (ii) drought is, according to evidence found in the literature, a main cause of foliar loss. It might be either that the variable chosen to express the soil moisture supply is less suited than e.g. relative transpiration in this respect or that the exceptional wet period january-march 1995 (precipitation 295 mm vs. 175 mm during the same period in a 'normal' year) caused a sufficient rate of water supply up to the period july/august 1995 (when tree health status was observed), despite the rather dry summer of 1995.

A trivial but notwithstanding important aspect for oaks is the different behaviour of pedunculate oak and sessile oak as far as drought tolerance, frost tolerance, and sensitivity to insect damage are concerned. On must carefully distinguish between these both oak species in studies on forest health (Thomas & Hartmann, 1996; Landmann, 1993; Mather et al., 1995). Some authors (Ulrich, 1988; Gasch & Krapfenbauer, 1990) are of the opinion that cause and effect in the relationship between foliar loss and water supply can be reversed: foliar loss, caused by a factor other than water supply, can lead to a reduced rate of transpiration.

Effects of atmospheric NH_3 were not expected because the actual range of NH_3 concentration amounted 0.7-20 $\mu g.m^{-3}$, whereas according to Van der Eerden (1982; 1992) the no-adverse level (annual mean) for many plant species is at least 75 $\mu g.m^{-3}$. Atmospheric N deposition and atmospheric S deposition cause more chronic than acute damage, so that the lack of evidence for a significant relationship between these predictors and foliar loss is plausible. The role of foliar composition for the intensity of foliar loss of pedunculate oak was negligible in 1995. This agrees with the fact that foliar N content of the investigated oak stands was high in only few stands, and with the North German experience that oak damage was not (yet) related to foliar N level (Thomas & Koehne, 1995).

5.1.2 Scots pine

The variance of needle loss of Scots pine was explained partly, by only two predictor variables, i.e. stand age, and foliar P/N ratio. This evidence for the involvement of age is plausible (see the discussion for pedunculate oak). Also the role of the P/N ratio is plausible. A negative effect of a low foliar P content or foliar P/N ratio has been established earlier for Scots pine, Douglas-fir, and Norway spruce (Aronsson, 1985; Van den Burg, 1991; Liu et al., 1994; Olsthoorn & Maas, 1994).

5.2 Crown transparency

5.2.1 Pedunculate oak

The next stress parameters contributed to the explanation of the variance of crown transparency of pedunculate oak (with the + and - mark a positive respectively negative relationship with crown transparency is indicated):

+ age (ln(age))
- crown projection percentage (crown%)
+ amount of precipitation in the growing season (psum)
- minimum temperature in January (tmin1)
+ air ozone concentration (AOT40)
+ sulphur deposition (SO_x)
- foliar N content
- foliar Mg content
+ insect damage (insect25)

A discussion on the effects of age, crown projection, precipitation, winter temperature, AOT40, and insect damage is given in Section 5.1.1. At optimal levels foliar N and foliar Mg content seems to stimulate a denser crown. This effect was also found by Heinsdorf (1996) for oak in eastern Germany. At a nitrogen status lower than optimal, N deposition can increase foliar N concentration, which stimulates both production of foliar mass, and growth. The implication of Mg has been suggested by Hartman et al. (1989) who found that foliar damage was associated with a low foliar Mg concentration, and by Heinsdorf & Chrzon (1997) who established a relationship between foliar loss and foliar discoloration of beech: discoloration in cases where

N deficiency is out of the question, will probably depend on the foliar K or Mg status. A low foliar K or Mg content can cause yellowing of the foliage.

The contribution of the SO_x deposition to the explanation of the variance of crown transparency of pedunculate oak was rather unexpected. This contribution has the implication that the soil S concentration was raised to such a level that the foliar S concentration might have damaged the foliage. Additional multiple-regression analysis with SO_x deposition, Ntotdep and foliar S/N ratio as predictor variables was carried out, which resulted in a series of equations with significant contributions of SO_x and foliar S/N ratio to the explanation of the variance of crown transparency, but at the cost of loss of the significant contribution of the ln(age)-term. A direct relationship between SO_x deposition and crown transparency would probably have been reflected in the foliar S/N ratio or the foliar S concentration. A comparison of foliar S/N ratios of pedunculate oak stands in 1995 revealed that the majority had foliar S/N ratios between 5:100 and 10:100, which does not point to a toxicity level of S. Also, foliar S concentration of pedunculate oak stands in 1995 amounted 1.2-2.3 g kg^{-1}, which is even lower than the range 1.8-2.8 g kg^{-1}, which was established for healthy oak stands in The Netherlands (Oosterbaan et al., 1987). This reasoning suggests that the correlation between SO_x deposition and crown transparency of pedunculate oak is in fact an indirect relationship, which hides a direct, but yet unknown, relationship.

5.2.2 Scots pine

Crown transparency of Scots pine was related to a number of stress parameters (all negatively related to crown transparency):

- age
- amount of precipitation in the growing season (psum)
- minimum temperature in January (tmin1)
- temperature sum in the growing season (tgsum)
- foliar P content
- ammonium deposition (NH_x)

It is clear that there are some important differences between the models explaining foliar loss and crown transparency of Scots pine. The only corresponding stress parameters are age and foliar P content (crown transparency) or foliar P/N ratio (foliar loss). The contributions of the stress parameters psum, tmin1, and tgsum to the explanation of crown transparency of Scots pine are all negative, which means that higher values of these variables promote a denser crown. This is physiologically perfectly possible, but rather unexpected for Scots pine, a tree species which is often considered rather tolerant against drought, low winter temperature, and variation in summer temperature. A positive effect of atmospheric ammonium deposition on crown density was established by Hofmann & Heinsdorf (1990) who found that in the sub-optimum N supply range (< ca. 18 g kg^{-1} in half-year-old needles) increasing foliar N content stimulated the production of foliar mass. A lower crown density occurred if the foliar N content was at least 21-24 g kg^{-1} (Hofmann et al., 1990; Heinsdorf & Krauss, 1991). The foliar N concentration of the investigated Scots pine stands in The Netherlands in 1995 amounted 14.6 - 21.9 g kg^{-1} (Annex 1; Table A1.19).

Less than 5% of the Scots pine stands had sub-optimal N content in which N fertilization (as atmospheric deposition) could stimulate the production of foliar mass, and thus stimulate a denser crown.

The negative effect of stand age on crown transparency means that the crown of a Scots pine stand is denser at a higher age. This result was rather unexpected and contradicts with the earlier demonstrated and accepted positive relation of age on increasing foliar loss. A possible explanation of this reverse age effect may be caused by the provenance. Recently, it was found that Scots pine stands in The Netherlands older than 70 years, had a higher site index (S = 23.1 m) than stands in the age of 30-70 years (S = 20.3 m) (Van den Burg, 1997). This difference could plausibly be attributed to the provenance of Scots pine. If this explanation is correct, one could assume that these two age groups do not only differ in provenance, but also in crown density, which might be related to site index (better growth coincides with a larger foliar mass). If there really are differences between provenances, it might also be an explanation for the lack of relationship between foliar loss and transparency as was found only for Scots pine (Table 6). Possibly the effect of differences in provenances might cause a reverse effect of age in the relationship with foliar loss and crown transparency. This explanation, however, is speculative and does not completely explain the difference in explanation of foliar loss and crown transparency. Demonstration of such a provenance effect will be very difficult because provenances are not registrated properly in forest management and provenances can not be recognized by phenological characteristics.

5.3 Foliar composition

The discussion is mainly devoted to pedunculate oak and Scots pine, because for these species enough data were available to permit computation of usefull multiple regression equations. The remaining five tree species are discussed more cursory.

An important question in the study of relationships between foliar composition and environmental variables posed was that of the effect of atmospheric N deposition on foliar N content. Answers of this question must take into consideration that (i) three main sources of N can be distinguished, viz. N becoming available through soil N mineralisation, N added into the soil by atmospheric deposition (the 'indirect way'), and direct foliar uptake of atmospheric NH_3 (the 'direct way', cf. Ortloff & Schlaepfer, 1996) and (ii) the effect of atmospheric N on trees depends on the actual foliar N content (Pérez-Soba, 1995).

As far as (i) is concerned, it is to be expected that regression models which pretend to explain the foliar N content of the foliage of a tree species, must not only include parameters for atmospheric N (e.g. NH_3 concentration, N deposition) but also at least one parameter reflecting soil N availability. The relation between atmospheric N and tree vitality (ii) probably can not be described as a straight line, but preferably as an unimodal curve (e.g. parabola). At increasing atmospheric N deposition, or atmospheric NH_3 concentration, foliar mass will increase, and foliar colour will become darker green, until the N supply is optimal. When atmospheric N deposition and concentrations further increases, trees will exhibit increasing symptoms of physiological distortion (foliar loss, discoloration, etc.) (Bergmann, 1990; Heinsdorf & Krauss, 1991; Den Boer & Masuch, 1986; Hofmann & Heinsdorf, 1990; Hofmann et al., 1991). It is e.g. interesting that Heinsdorf (1996) found that damaged oak stands had lower foliar N contents, as well as lower P, K, Ca, and Mg contents, than healthy oaks stands.

For these reasons, three groups of evidence can be mentioned, which suggest a positive effect of atmospheric N on foliar N content:
- recent investigations in The Netherlands (Houdijk, 1993; Van den Burg, 1989; Van den Burg et al., 1988),
- a positive, significant (or weakly significant) correlation between N deposition and foliar N content for some tree species in this research,
- a positive, significant (or weakly significant) correlation between atmospheric NH_3 concentration and foliar N content for some tree species in this research.

5.3.1 Pedunculate oak

No significant relationship was established between atmospheric N deposition and foliar N content of pedunculate oak. This agrees with results of earlier surveys, in which the foliar N content of Scots pine, Corsican pine and Douglas-fir was positively and significantly related to (modelled) atmospheric N deposition, but the foliar N content of pedunculate oak was not (Van den Burg et al., 1988; Van den Burg, 1989).

All calculated other relationships between foliar composition of pedunculate oak and soil solution characteristics (Ca, Mg, Al, Fe, Mn) are plausible. The positive effect of stand age on foliar K is negatively mirrored in the negative effect of stand age on foliar Mg. This might mean that the probability of K deficiency in pedunculate oak stands decreases with increasing age, whereas Mg deficiency might be found preferably in older stands.

It is remarkable that the foliar N content was positively related to the NO_3 concentration in the soil solution. Literature is divided on his point. In some research an effect of soil N concentration on foliar N content was established (Van Dijk, 1993; Heinsdorf, 1996), while such a relationship could not be demonstrated in national surveys of soil and foliar analytical data (Van den Burg, 1996).

Only one air concentration parameter was involved in the multiple-regression equations for the foliar composition of pedunculate oak, viz. AOT40, which had a positive effect on the foliar Al content of pedunculate oak. A tentative explanation is based on the observation that ozone has a relatively more negative effect on root growth than on aerial parts, which is expressed as a lowered root/shoot ratio, and as a reduced fine-root growth (Landmann, 1995; Rehfuess & Ziegler, 1986; Reinert et al., 1996; Samuelson, 1994), although this effect is not always observed (Rebbeck, 1996). Root damage seems to reduce in the first place the uptake of Mg (Binns & Redfern, 1983). Because of the well-known Mg-Al antagonism, as far as uptake by the roots of these ions is concerned, this process might be involved in the Al uptake by pedunculate oak.

The foliar Zn content was closely related to the Zn content in the forest floor (Annex 8), and to a lesser extend also to the Cd and Cu content in the forest floor. The relationship between the foliar Zn content and the Cd content in the forest floor reflects the strong chemical similarity of Cd and Zn (Mengel & Kirkby, 1987). Curiously, the foliar Cu content is related to contents of Zn, Pb, Cd and Cr in the forest floor, but not to the Cu content itself. In any case, these correlations stress the importance of uptake of metals from the forest floor, as was also shown for Al by Messenger et al. (1978).

5.3.2 Scots pine

The relationships between environmental characteristics and foliar composition of Scots pine were very similar to those of pedunculate oak. No effect of atmospheric N deposition on foliar N content was demonstrated. However, this does not imply that such a relationship does not exist, because in other research a significant positive relationship between foliar N content and N deposition was found for Scots pine, Corsican pine and Douglas-fir (Houdijk, 1993; Van den Burg, 1989; Van den Burg et al., 1988). The reason for the discrepancy between these earlier experiences and the results of 1995 might simply be a matter of number of surveyed stands (e.g. ca. 300 in Van den Burg (1989), vs. 42 in this survey).

Foliar N content of Scots pine was explained by five candidate models. Four of them contain a parameter which expresses soil N (totNva = total amount of N in the forest floor and in the mineral top soil; cNH_4 = NH_4 concentration in the soil solution). The negative effect of SO_x deposition could not be explained. Possibly the temperature during the growing season (tgsum), which occurs in four of the five multiple-regression equations, reflects the direct influence of the soil temperature on N mineralisation. The (positive) effect of AOT40 in one of the equations might be a real one (by interference of ozone with fine-root production), but it is also possible that the exchangeability of the growing season temperature and AOT40 can be explained by collinearity (in general higher temperatures go together with higher atmospheric ozone concentrations). For these reasons, the equation with the NH_4 concentration in the soil solution and the growing season temperature as parameters, explaining 36.1% of the variance of foliar N of the surveyed Scots pine stands, might be given preference.

The equations for Mg show two peculiarities. In the first place, AOT40 is (negatively) involved in all candidate models. This might be interpreted as a direct effect of ozone. In the second place a positive relationship between the foliar Mg content of Scots pine and the Mg concentration of the soil solution was only established in an equation of which the plausibility is doubtful because of the number of stress parameters in it, and the coefficient of some of these parameters. If one accepts the plausibility of the ozone-effect (AOT40) on foliar Mg content, this content could simply be described as a function of AOT40. This conclusion, however, is doubtful too, because no soil Mg is included. Because the Mg content in the forest floor does show a relation with the foliar Mg content, and the Mg concentration in the soil solution (cMg) does not, the latter might not be a proper indicator. One might speculate that a function describing the foliar Mg content of Scots pine stands on sandy soils, and exposed to rather high atmospheric ozone concentrations, might include stress parameters like AOT40, and some measure of Mg availability. Also counteracting cations like K, Ca, Na, Mn, Al, Fe as concentration in the soil solution and/or as exchangeable ions might be included.

Foliar Mn content was very well explained ($R^2_{adj.}$ = 90.5%) by the Mn concentration in the soil solution, the amount of exchangeable Mn in the solid phase, and the Mg concentration in the soil solution. Foliar Zn content was very well correlated to the Zn or the Cd content in the forest floor. This is discussed in Section 5.3.1.

6 Synthesis of results

The results of this 1995 survey of 200 forest tree stands can not be generalised for other years without further research. They are only relevant for the year 1995. One can imagine that results might have been different for observations done during the wet summer of 1993, or after the dry summer of 1996 (dry until August) after a very dry winter 1995/96, a dry spring and dry early summer of 1996, and the heavy insect damage of pedunculate oak which occurred in june/july 1996.

6.1 Uncertainties of the results

At first sight, the results of this analysis of the relation between foliar loss, crown transparency and various predictor variables are satisfying. For pedunculate oak and Scots pine respectively about 70% and 40% of the foliar loss was explained, and 60% and 50% of the crown transparency. It is, however, doubtful whether some predictors can be considered as predictor variables only, or that they can also be considered as effect parameters which are being influenced by stress factors. During this research the insight grew that the predictors included in the model could be divided into i) primary predictors of which it is assumed that they are directly correlated to the condition indices (e.g. drought, air pollution), ii) corrective predictors which correct the estimation of the effect parameter for a certain effect (e.g. age, crown projection) and, iii) intermediate predictors which are directly correlated to the condition indices but may also be correlated with other stress factors (e.g. insect and fungal damage).

As being indicated in this study, crown projection may have influence on the estimation of the foliar loss in forest stands. In open stands the view on the crowns is better than in more dense stands by which estimation of the degree of defoliation and crown transparency may be more easily. Also light intensity, which depends on crown projection and crown density, may play a role in the accuracy of the estimation. This theory is confirmed with our results, showing that crown projection is of influence on the condition indices for pedunculate oak but not for Scots pine. The crowns of Scots pine are naturally less dense than that of pedunculate oak, and also pine stands in general are more open than pedunculate oak stands. Besides, estimation of the defoliation of pedunculate oak is more difficult than that of Scots pine, because the number not flushed buds are estimated, while for Scots pine the number of needle age classes and the completeness of these classes are estimated, which is more easily to observe.

The effect of age can be strictly a physiological one (Gower et al., 1996), but can also be correlated with height, and through that with the accuracy of observation (Section 3.2). If a tree is higher, estimation of the foliar loss can be more difficult, simply because the distance between the eye and the foliage is larger. Hendriks et al. (1994) indeed found that height and age were exchangeable predictors in the explanation of foliar loss and discoloration.

The effect of insect and fungal damage can be mentioned as the most uncertain one. Insect damage is recorded by estimating the percentage of foliar affected by insects. The foliage can be eaten or damaged. The percentage foliar loss then has to be corrected for this effect. Of course, when insects swallow the foliage it directly affects the foliar biomass. However, the occurrence of insect plagues can be stimulated by the same causes as which are affecting foliar loss, for instance air pollutants. Brown (1995) found that elevated levels of NO_2, SO_2, and O_3 indirectly increased insect populations. The air pollutants can influence the N status and water status of the plants by which the food quality for insects can improve. Moraal (1995) found an indirect relationship between N deposition and insect damage in Scots pine. Through elevated N deposition grass growth in pine forests is stimulated. The grass was an important factor for the establishment of the insect *Haematoloma dorsatum* which causes band shrinkage in Scots pine needles. Besides air pollutants also weather conditions, and especially precipitation and temperature, can play a role in the severeness of insect plagues (Andriesse, 1990). If it is accepted that insect damage is also an effect parameter, it can not simply be included in the model as a predictor variable.

The success of the results is strongly depending on the inclusion of the corrective and intermediate predictors in the statistical models. Stand age and the minimum January temperature were the only stress parameters which contributed significantly to the explained variance in all models.

The analysis of the 1995 data has revealed that the number of stands per tree species is appropriate as far as it permits the description of the mineral nutrient status of these stands on the Dutch pleistocene sandy soils. The 'explanation' of forest condition by site characteristics however requires a minimum number of stands, depending on the number of predictor variables and their interactions to be tested by regression methods. Extension of the present number of stands per tree species will enlargen the possibilities for analyzing possible relationships. The value of data concerning tree species with a rather restricted number of stands (Corsican pine, Norway spruce, Japanese larch, beech) is limited, and does not add much evidence to the hypothesis of the multiple stress theory.

6.2 Effects of air pollutants

The effect of the stress factors deposition and air pollution could not be demonstrated to such an extend as expected, which can have many origins. At first, the uncertainty of the results is strongly depending on the extent of the available data sets for the monitoring sites. A record on the defoliation of 200 plots is available, but it is spread over 6 tree species. Only for pedunculate oak and Scots pine enough plots were recorded to perform a statistical analysis of some significance. But still for these species the number of plots was very limited and did not permit inclusion of all relevant predictors and their interactions. In order to create a stable model, the number of predictors that could be included in the model had to be reduced to about 15 to 17 (Oude Voshaar, 1994). This necessarily exclusion of predictors introduced a rather large share in the total uncertainty of the results.

A second cause may be found in the quality of the data. Most predictors values were not measured on the plots but derived from models. Deposition and concentrations of air pollutants are calculated from grid data which do not account for point emissions and through that may contain some under-estimation when local sources are present, or some over-estimation in absence of local sources. The meteorological data are interpolated from weather stations to the plots. Especially for precipitation it is known that interpolation introduces a large uncertainty (Van der Voet et al., 1994). The range of the values for a stress parameter may have influenced the possible relationships. The differences in the temperature indices and the deposition and concentration indices were small (Annex 1) through which beforehand little effect was expected of these parameters. Nevertheless they had some influence, which however, might be a year effect. Besides the accuracy of the predictors, also the accuracy of the effect parameter is important. It is, however, unknown and therefore introduced an unknown uncertainty in the results.

At third, the choice of the indices indicating both forest condition and stress factors is of the utmost importance to the uncertainty in the results. Although the indices were selected carefully (Hendriks et al., 1997) it does not guarantee that other indices would not have yielded better results.

6.3 Plausibility of explaining stress factors

The results for pedunculate oak, together with those for Scots pine, suggest that stand age as such is an important predictor variable. Gower et al. (1996), showed that the decrease of foliar mass at increasing age is a general symptom, independent of air pollution and atmospheric deposition. Part of the foliar loss and crown transparency of pedunculate oak is explained by the winter temperature, which matches the warmth-loving character of this tree species as mentioned by Hartmann (1996) en Landmann (1995). The first author emphasizes that the condition of pedunculate oak largely depends on the intensity of insect damages, in combination with unfavourable weather conditions, of which the negative aspect of winter frost on the condition of pedunculate oak is a very important aspect. Landmann asks attention for the fact that especially pedunculate oak in France was damaged by the extreme dry summer of 1976, the impact of which was still continuing on dry soils in the 1990's.

The results for Scots pine show that through a nutrient imbalance of N and P foliar loss and crown transparency are affected. Needle loss was dependent on the needle P/N ratio and crown transparency was dependent on the needle P status and the NH_x deposition. The effect of NH_x looks like a fertilizing effect by which growth is stimulated and through growth dilution, P becomes restrictive. This conclusion agrees with results of other forest health research in The Netherlands, which points to the often poor P status of especially Douglas fir (Olsthoorn & Maas, 1994) and the high N status of especially pine species.

6.4 Comparison of foliar loss, crown transparency and foliar composition

The choice whether foliar loss or crown transparency is a better effect parameter to indicate forest condition might be decided on the success of the explanation of these effect parameters by the stress parameters, i.e. the percentage of explained variance and the lowest number of predictor variables. For pedunculate oak the highest percentages accounted for were calculated in models using (logit) foliar loss as effect parameter. For Scots pine it was the other way round. However, the percentage accounted for was considerable lower for Scots pine than for pedunculate oak. The results do not clearly point out a 'best' effect parameter. It is possible that the best effect parameter will be different per tree species. Further research must point this out.

Foliar composition of all surveyed elements, except for K and heavy metals, was in a more or lesser extend correlated to the concentration of that element in the soil solution. Often, also antagonistic elements affected the foliar content. For K no relationship was found at all with any K content or concentration in the soil. Foliar heavy metal contents were highly correlated to the contents of the separate metals in the forest floor, except for Cu which was correlated to other heavy metals in the forest floor.

It is very difficult to interpret the foliar composition as some kind of index for forest condition because of the many and complex relationships between foliar composition and elements and processes involved. Criteria to judge the foliar composition, as given for example by Van den Burg & Schaap (1996), can give information about the nutritional status of forest stands but do not give information about any causes. From the multiple-regression analysis, by which insight on the causes can be gained, no strong evidence followed that air pollutants affect foliar composition. One important exception is the effect of ozone, for which correlations were found with foliar contents of N, P, Mg and Al. Because in the analysis of the foliar loss and crown transparency ozone was also found to be one of the explaining stress parameters, it seems likely that ozone in 1995 had a negative effect on forest condition in The Netherlands.

7 Conclusions

The results of this study are referring only to the 1995 forest condition in The Netherlands.

Relationships between the forest condition indices foliar loss, crown transparency and foliar composition in 1995, of stands of pedunculate oak and Scots pine and environmental stress factors were analyzed through apart multiple regression. The results of this research support the multiple stress theory, in which forest condition is believed to depend on the joint effect of several stress factors.

Major uncertainties of the results origin from the limited number of stands within the monitoring network, the accuracy of the data and the statistical model, and from the usefulness of the indices used to express forest condition and stress factors.

Although the results supported the multiple stress theory, the effect of primary stress factors such as air pollution and drought was not demonstrated in such an extend as expected.

1) It seems likely that in 1995 ozone, in combination with drought, had a negative effect on forest condition in The Netherlands because it affected all three surveyed forest condition indices: foliar loss (pedunculate oak), crown transparency (pedunculate oak) and foliar composition (pedunculate oak and Scots pine).

2) Correlations between forest condition indices and other air pollutants (SO_x and NH_x deposition and NH_3 air concentration) were found, but the effects were less pronounced than for ozone, showing up in only one or some possible explaining models.

3) Important predictors affecting 1995 leaf loss of pedunculate oak were stand age, insect damage and the minimum temperature in January. Together they explained about 59% of the leaf loss. Stand age was fitted in the model as the natural logarithm of age, and insect damage with a threshold of about 15% damage. When insect and fungal damage are not included in the model, the best model that explains leaf loss contains stand age, crown projection percentage, minimum temperature in January, temperature sum during the growing season, and AOT40, all together explaining about 58% of the leaf loss. Because the models with and without insect damage both explain about the same it might be the case that insect damage is convertible with crown projection, temperature sum of the growing season and AOT40. However, it seems unlikely that insect damage is affected by these parameters. Besides, if insects partly or fully dispatch foliage, this will find expression in the recorded leaf loss.

4) Needle loss of Scots pine was best explained by a model containing stand age and the foliar P/N ratio, explaining 38% of the logit transformation of the needle loss.

5) Crown transparency of pedunculate oak was best explained by three candidate models in which insect damage and SO_x deposition are constant terms. All models explain about 60% of the crown transparency. In two models also the amount of precipitation and AOT40 show up while the foliar N content and crown projection seems convertible. The third model contains, besides insect damage and SO_x deposition, the minimum January temperature, stand age and the foliar N content. Because of the inclusion of stand age a slight preference is given to this third model. Exclusion of insect and fungal damage from the model resulted in three candidate models containing stand age (as ln(age)), foliar Mg content, the minimum temperature in January, the amount of precipitation during the growing season, O_3, and the SO_x deposition. All three models explain about 38% of the crown transparency of pedunculate oak. The plausibility of the models containing SO_x deposition, however, is doubtful because the sulphur status of the investigated stands was too low to suggest sulphur toxicity.

6) Crown transparency of Scots pine was explained for more then 51% with a model containing stand age, precipitation during the growing season, minimum temperature in January, temperature sum of the growing season, foliar P content and NH_x deposition. The effect of stand age on crown transparency was contrary to the effect on foliar loss, which might be related to provenance. NH_x deposition as such positively affected crown transparency of Scots pine. This fertilizing effect of NH_x deposition, however, can bring about a P deficiency, which was also found for Scots pine. The negative effect of such a P deficiency is stronger than the positive effect of the N fertilizing, and therefore the overall effect must be considered negatively.

7) Foliar composition of all surveyed elements, except for K and heavy metals, was in a more or lesser extend correlated to the concentration of that element in the soil solution. Often, also antagonistic elements affected the foliar content. For K no relationship at was found with any K content or concentration in the soil. Foliar heavy metal contents were highly correlated to the contents of the separate metals in the forest floor, except for Cu which was correlated to other heavy metals in the forest floor.

8) Through single linear regression a positive correlation was found between foliar N content of Corsican pine, Norway spruce and Japanese larch and the atmospheric N deposition and the NH_3 air concentration. Multiple regression on pedunculate oak and Scots pine also showed correlations between forest condition indices and air pollutants (SO_x and NH_x deposition and NH_3 air concentration), but the effects were less pronounced than for the other species and showed up in only some of the explaining models. From this it may be concluded that the sensitivity for N deposition and NH_3 concentration is tree species specific.

8 Recommendations

Some recommendations can be made in order to improve future possibilities to research the relationships between forest condition indices and stress factors.

1) The forest condition of a sequence of years (e.g. 5 years) should be analyzed in order to gain more insight in explaining factors which are of influence on the yearly variation of forest condition. This would also enable investigation of stress of which the effects appear only after one or more years.

2) In order to analyze the interannual changes in crown condition, the number of monitoring stands per tree species should be increased. This will enlarge the possibilities of statistical analysis and, through that, increase the reliability of the results.

3) If the number of monitoring plots will be increased, the optimal scenario is to cover a large number of species for at least 100 stands per species. If, for economical reasons however, the number of plots that can be surveyed is (very) limited, it is better to monitor less species than to monitor less plots per species. One could think of about three species, for example pedunculate oak, Scots pine and Douglas-fir. The spatial distribution of the plots should be selected with regard to the ranges of the stress factors, by which extreme values should be superrepresented.

4) Recording of an extra effect parameter on tree growth is recommended. Together with defoliation, discoloration, crown transparency and foliar composition, this parameter can supply additional information on the relationships with stress factors. A great advantage of growth is that it easily can be measured while defoliation, discoloration and crown transparency are estimated.

5) Measurements should be carried out to provide insight in the quality of the model derived deposition and air concentration data, and the interpolated meteorological data. This can be done on, for instance, the intensive monitoring plots of the European network on forest condition (Level 2 plots).

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Annex 1 Presentation of basic data

A1.1 Numbers of stands per tree species per forest region for the 200 forest stands of the new monitoring network on forest health

Forest area	Tree species							
	oa	be	sp	cp	df	ns	jl	Total
Northern	8	4	9	3	8	10	8	50
Eastern	10	5	9	0	3	2	2	31
Central	10	11	11	2	11	2	1	48
Southern	11	3	13	9	5	6	1	48
Coastal	2	0	0	4	0	0	0	6
Rest	10	4	0	2	0	0	1	17
Total	51	27	42	20	27	20	13	200

values within brackets: percentage of stands per tree species (n per tree species*100/n per area) (n = number of stands)
Tree species: be = beech; cp = Corsican pine; df = Douglas-fir; ns = Norway spruce; sp = Scots pine; jl = Japanese larch; oa = pedunculate oak

A1.2 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: Hmean (m)

Tree species	n	min	5%	50%	mean	95%	max
be	27	6.2	6.7	25.0	23.6	32.6	33.3
cp	20	5.9	6.0	11.0	11.3	16.6	17.2
df	27	9.6	10.4	23.0	22.2	34.2	35.6
ns	20	7.5	8.6	14.9	15.4	24.8	27.0
sp	42	6.0	9.4	14.1	14.5	20.4	21.1
jl	13	17.5	17.7	21.9	21.4	24.4	24.4
oa	51	5.1	7.7	16.3	16.2	24.7	29.0
mean	200	5.1	7.5	17.4	17.4	29.9	35.6

A1.3 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: Htop (m)

Tree species	n	min	5%	50%	mean	95%	max
be	27	8.5	6.7	25.0	23.6	32.6	33.3
cp	20	7.4	6.0	11.0	11.3	16.6	17.2
df	27	11.0	10.4	23.0	22.2	34.2	35.6
ns	20	9.8	8.6	14.9	15.4	24.8	27.0
sp	42	7.5	9.4	14.1	14.5	20.4	21.1
jl	13	18.9	17.7	21.9	21.4	24.4	24.4
oa	51	6.6	7.7	16.3	16.2	24.7	29.0
mean	200	6.6	9.2	18.9	19.1	31.8	37.0

A1.4 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: Site index (S-value, m)

Tree	n	min	5%	50%	mean	95%	max	Median of the Dutch yield table (1996)
be	27	14.2	28.2	42.4	43.2	59.5	62.5	44.5
cp	20	17.5	18.0	26.7	27.2	39.8	39.9	29.8
df	27	27.7	29.9	39.6	40.4	52.4	61.1	33.6
ns	20	27.1	27.6	38.1	38.7	48.2	49.4	34.4
sp	42	13.3	15.2	21.4	22.6	39.6	49.0	24.4
jl	13	23.0	23.0	28.0	26.7	29.5	29.5	28.4
oa	51	19.8	22.4	26.7	28.4	39.7	43.1	36.1
mean	200	13.3	17.4	29.4	31.6	50.0	62.5	33.0

A1.5 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: age (years from germination)

Tree species	n	min	5%	50%	mean	95%	max
be	27	21.0	21.8	71.0	79.9	216.0	216.0
cp	20	19.0	22.5	38.0	44.0	67.5	72.0
df	27	21.0	21.8	50.0	50.8	103.3	105.0
ns	20	15.0	16.0	36.0	37.4	62.0	64.0
sp	42	17.0	21.2	58.5	59.4	101.0	110.0
jl	13	41.0	41.3	53.0	53.8	65.7	66.0
oa	51	15.0	20.0	56.0	62.4	113.8	168.0
margin	200	15.0	21.0	51.0	57.7	108.0	216.0

A1.6 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in forest areas, in 1995: atmospheric NH_3-conc ($\mu g.m^{-3}$) (annual mean)

forest area	n	mean	min	5%	50%	95%	max
Northen	50	3.20	2.00	2.00	3.00	6.00	6.00
Eastern	31	7.10	4.00	4.05	7.00	10.95	13.00
Central	48	4.00	2.00	2.00	4.00	8.40	14.00
Southern	48	7.46	3.00	3.00	6.00	20.00	20.00
Coastal	6	0.92	0.70	0.66	0.95	1.00	1.00
Rest	17	2.59	1.00	1.00	2.00	5.00	5.00
Total	200	4.90	0.70	1.50	4.00	11.00	20.00

A1.7 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in forest areas, in 1995: atmospheric O_3-conc ($\mu g.m^{-3}$) (annual mean)

forest area	n	mean	min	5%	50%	95%	max
Northern	50	42.36	41.00	41.00	42.00	44.00	44.00
Eastern	31	40.61	39.00	40.00	41.00	41.95	42.00
Central	48	41.25	40.00	40.00	41.00	42.00	43.00
Southern	48	39.08	38.00	39.00	39.00	40.00	40.00
Coastal	6	44.67	44.00	44.00	44.50	46.20	46.00
Rest	17	42.59	38.00	38.00	44.00	46.00	46.00
Total	200	41.13	38.00	39.00	41.00	44.00	46.00

A1.8 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in forest areas, in 1995: atmospheric AOT40 (ppb h)

Forest area	n	mean	min	5%	50%	95%	max
Northern	50	9007	8085	8390	8897	10458	10520
Eastern	31	11504	10631	10860	11508	12078	12159
Central	48	11711	10974	11178	11707	12137	12165
Southern	48	12928	12020	12071	13057	13759	13974
Coastal	6	11137	10346	10312	11227	11828	11807
Rest	17	10823	8376	8411	9872	13812	13921
Total	200	11202	8085	8596	11618	13580	13974

A1.9 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for seven tree species in forest areas, in 1995: atmospheric SO_x-deposition ($mol.ha^{-1}.year^{-1}$)

Forest area	n	mean	min	5%	50%	95%	max
Northern	50	553.78	338.00	407.00	560.50	664.00	697.00
Eastern	31	602.94	316.00	388.90	609.00	719.00	800.00
Central	48	793.35	414.00	530.60	770.50	1150.70	1226.00
Southern	48	722.94	136.00	457.50	764.00	922.30	1146.00
Coastal	6	948.17	674.00	637.40	949.50	1169.40	1158.00
Rest	17	718.12	486.00	491.25	620.00	1022.25	1031.00
Total	200	685.29	136.00	467.00	652.50	1068.00	1226.00

A1.10 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in forest areas, in 1995:atmospheric NO_x-deposition ($mol.ha^{-1}.year^{-1}$)

forest area	n	mean	min	5%	50%	95%	max
Northern	50	819.98	510.00	591.00	833.50	998.00	1027.00
Eastern	31	825.42	477.00	522.40	835.00	970.50	977.00
Central	48	1005.83	467.00	623.00	996.50	1338.70	1424.00
Southern	48	853.15	238.00	514.20	888.00	1120.10	1155.00
Coastal	6	961.33	824.00	814.80	911.00	1155.40	1147.00
Rest	17	928.35	752.00	758.30	918.00	1114.80	1119.00
Total	200	886.84	238.00	546.00	882.50	1171.50	1424.00

A1.11 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in forest areas, in 1995:atmospheric NH_3-deposition ($mol.ha^{-1}.year^{-1}$)

forest area	n	mean	min	5%	50%	95%	max
Northern	50	1384.4	886.0	986.0	1402.0	1807.0	1904.0
Eastern	31	2180.3	1574.0	1609.4	2203.0	2785.1	2875.0
Central	48	2212.1	1275.0	1305.7	1878.5	4133.2	5146.0
Southern	48	2531.9	1359.0	1526.4	2558.0	3840.0	3996.0
Coastal	6	836.8	572.0	564.8	755.0	1629.6	1497.0
Rest	17	1327.2	680.0	718.5	1352.0	1805.5	1809.0
Total	200	1960.5	572.0	905.5	1754.5	3693.5	5146.0

A1.12 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: total atmospheric Ndeposition (Ntotdep) ($mol.ha^{-1}.year^{-1}$)

tree species	n	mean	min	5%	50%	95%	max
be	27	2985	1810	1832	2720	5530	6122
cp	20	2504	1396	1445	2463	3585	3597
df	27	3103	1682	2032	3056	5145	5321
ns	20	2801	1958	1988	2552	4399	4585
sp	42	2901	1477	1754	2638	4406	6365
jl	13	2638	1808	1824	2243	4043	5040
oa	51	2785	1599	1678	2622	4095	4831
mean	200	2847	1396	1764	2638	4655	6365

A1.13 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: soil water supply (vlmm, mm)

tree species	n	min	5%	50%	mean	95%	max
be	27	25	25	125	128	225	225
cp	20	75	75	150	150	225	225
df	27	75	75	125	147	225	225
ns	20	75	75	125	138	225	225
sp	42	25	55	175	155	225	225
jl	13	75	75	175	167	225	225
oa	51	75	75	175	162	225	225
mean	200	25	75	125	151	225	225

A1.14 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: mean highest groundwater level (cm - surface)

tree species	n	min	5%	50%	mean	95%	max
be	27	20	20	141	135	316	400
cp	20	20	20	130	138	376	501
df	27	0	8.5	125	126	300	301
ns	20	5	12.5	70	101	226	250
sp	42	10	15	85	130	441	501
jl	13	50	50	120	130	243	250
oa	51	0	15	95	112	201	300
mean	200	0	17.5	110	124	251	501

A1.15 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: precipitation in the growing season (mm, April to October)

tree species	n	min	5%	50%	mean	95%	max
be	27	124	124	161	165	214	217
cp	20	134	134	143	156	213	214
df	27	134	135	170	173	216	216
ns	20	135	135	186	179	215	215
sp	42	132	133	164	168	213	218
jl	13	135	138	212	197	218	218
oa	51	124	125	170	168	216	218
mean	200	124	134	166	170	215	218

A1.16 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: mean minimum temperature in january (°C)

tree species	n	min	5%	50%	mean	95%	max
be	27	-4.9	-4.9	-4.8	-4.8	-4.7	-4.7
cp	20	-4.8	-4.8	-4.7	-4.7	-3.9	-3.2
df	27	-4.8	-4.8	-4.8	-4.8	-4.7	-4.6
ns	20	-4.8	-4.8	-4.8	-4.8	-4.7	-4.7
sp	42	-4.9	-4.8	-4.8	-4.8	-4.7	-4.6
jl	13	-4.8	-4.8	-4.8	-4.8	-4.8	-4.8
oa	51	-4.9	-4.9	-4.8	-4.8	-4.6	-4.6
mean	200	-4.9	-4.8	-4.8	-4.8	-4.6	-3.2

A1.17 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: mean minimum temperature in april (°C)

tree species	n	min	5%	50%	mean	95%	max
be	27	-1.60	-1.52	-0.30	-0.48	0	0
cp	20	-1.20	-1.05	0.00	-0.21	0	0
df	27	-1.60	-1.43	-0.50	-0.54	0	0
ns	20	-1.60	-1.60	-0.90	-0.66	0	0
sp	42	-1.60	-1.54	-0.70	-0.64	0	0
jl	13	-1.60	-1.60	-1.30	-1.05	0	0
oa	51	-1.70	-1.60	-0.30	-0.54	0	0
mean	200	-1.70	-1.60	-0.30	-0.57	0	0

A1.18 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: degree-days of the growing season (°C*days)

tree species	n	min	5%	50%	mean	95%	max
be	27	2599	2603	2729	2723	2846	2848
cp	20	2608	2614	2741	2726	2800	2802
df	27	2608	2608	2718	2705	2795	2797
ns	20	2598	2603	2684	2693	2793	2797
sp	42	2598	2616	2727	2715	2800	2804
jl	13	2600	2601	2622	2648	2782	2790
oa	51	2598	2601	2718	2711	2844	2847
mean	200	2598	2608	2721	2708	2800	2847

A1.19 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar N content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	16.6	22.5	25.6	26.0	29.2	29.6
cp	20	9.8	11.1	13.8	14.3	20.4	22.8
df	27	16.3	16.6	18.6	19.4	24.5	29.7
ns	20	13.2	13.8	16.6	17.1	21.2	21.3
sp	42	14.6	15.2	18.5	18.5	21.6	21.9
jl	13	18.7	18.8	21.8	22.6	27.3	27.5
oa	51	22.2	22.8	25.1	25.4	27.9	28.8
mean	200	9.8	13.5	20.9	21.1	28.3	29.7

A1.20 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar P content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	1.00	1.00	1.30	1.26	1.43	1.60
cp	20	0.80	0.85	1.00	1.09	1.35	1.40
df	27	0.90	0.99	1.20	1.20	1.51	1.60
ns	20	1.00	1.00	1.25	1.27	1.55	1.60
sp	42	1.00	1.00	1.30	1.32	1.60	1.60
jl	13	1.00	1.01	1.30	1.33	1.87	1.90
oa	51	1.00	1.00	1.50	1.49	1.80	2.00
mean	200	0.80	1.00	1.30	1.31	1.70	2.00

A1.21 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar K content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	5.1	5.1	7.2	7.7	10.8	10.9
cp	20	4.9	5.0	5.9	5.9	6.8	6.9
df	27	5.2	5.4	6.6	6.6	7.7	7.7
ns	20	4.2	4.4	5.8	5.8	7.2	7.4
sp	42	5.0	5.4	6.0	6.1	6.8	7.0
jl	13	4.9	4.9	6.4	6.5	8.3	8.4
oa	51	5.9	6.5	8.8	8.9	11.9	13.8
mean	200	4.2	5.1	6.6	7.1	10.4	13.8

A1.22 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Ca content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	2.5	2.9	4.7	5.4	11.5	12.1
cp	20	0.4	0.5	1.0	1.2	2.6	2.7
df	27	1.0	1.7	2.5	2.5	3.5	3.5
ns	20	1.2	1.4	2.4	2.5	4.2	4.2
sp	42	1.0	1.2	1.9	1.8	2.8	2.9
jl	13	2.5	2.5	3.1	3.4	6.0	6.2
oa	51	2.2	3.0	4.8	5.2	8.2	10.6
mean	200	0.4	1.0	2.8	3.4	7.5	12.1

A1.23 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Mg content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	0.7	0.7	1.3	1.28	1.9	2.0
cp	20	0.5	0.55	0.8	0.9	1.4	1.4
df	27	0.7	0.78	1.4	1.33	1.6	1.6
ns	20	0.6	0.6	0.8	0.79	1.05	1.1
sp	42	0.5	0.6	0.7	0.72	0.9	1.0
jl	13	1.0	1.03	1.4	1.48	2.05	2.1
oa	51	1.1	1.3	1.6	1.65	2.1	2.4
mean	200	0.5	0.6	1.2	1.19	1.95	2.4

A1.24 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Na content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	0.10	0.10	0.20	0.21	0.37	0.80
cp	20	0.10	0.10	0.15	0.56	4.25	6.60
df	27	0.10	0.10	0.10	0.14	0.21	0.30
ns	20	0.10	0.10	0.10	0.12	0.20	0.20
sp	42	0.10	0.10	0.20	0.16	0.20	0.20
jl	13	0.20	0.20	0.30	0.34	0.60	0.60
oa	51	0.10	0.10	0.10	0.14	0.30	0.30
mean	200	0.10	0.10	0.20	0.21	0.35	6.60

A1.25 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar S content (g kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	1.10	1.10	1.80	1.77	2.23	2.40
cp	20	0.70	0.75	0.90	0.95	1.30	1.40
df	27	1.00	1.09	1.50	1.44	1.74	2.00
ns	20	0.90	0.90	1.10	1.10	1.45	1.60
sp	42	1.00	1.00	1.20	1.20	1.44	1.50
jl	13	1.20	1.20	1.40	1.44	1.87	1.90
oa	51	1.20	1.40	1.70	1.67	2.00	2.30
mean	200	0.70	0.90	1.40	1.41	2.00	2.40

A1.26 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Cu content (mg kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	3.5	5.5	7.1	7.4	10.4	11.2
cp	20	1.4	1.6	4.3	4.2	6.6	7.0
df	27	2.1	2.6	4.2	4.1	5.8	8.3
ns	20	1.3	1.6	2.8	2.8	3.6	3.7
sp	42	2.1	2.5	3.7	3.7	4.8	4.9
jl	13	2.5	2.6	4.0	4.0	5.2	5.2
Oa	51	5.4	5.9	7.5	7.6	9.8	10.7
mean	200	1.3	2.4	4.5	5.3	8.8	11.2

A1.27 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Zn content (mg kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	16	19	29	32	52	47
cp	20	28	29	42	44	62	63
df	27	18	18	26	27	42	49
ns	20	16	17	24	24	33	38
sp	42	30	33	44	47	63	146
jl	13	18	18	21	23	40	42
oa	51	18	19	24	25	38	43
mean	200	16	19	28	32	54	146

A1.28 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Mn content (mg kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	52	146	567	753	1614	1731
cp	20	48	48	97	124	272	306
df	27	106	125	230	368	1170	1635
ns	20	98	98	184	304	1264	1390
sp	42	83	104	213	234	597	830
jl	13	81	83	136	159	304	312
oa	51	127	188	565	621	1334	1784
mean	200	48	88	250	412	1311	1784

A1.29 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Fe content (mg kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	80	83	114	123	218	218
cp	20	33	36	52	56	99	108
df	27	48	53	88	89	145	171
ns	20	41	42	56	62	98	103
sp	42	34	42	64	66	105	119
jl	13	45	45	58	67	120	123
oa	51	67	74	113	126	211	248
mean	200	33	43	82	91	186	248

A1.30 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Al content (mg kg^{-1})

tree species	n	min	5%	50%	mean	95%	max
be	27	48	50	110	112	186	226
cp	20	69	72	292	269	392	394
df	27	166	169	244	258	342	350
ns	20	58	61	98	114	209	225
sp	42	130	136	208	204	268	284
jl	13	45	49	168	168	245	249
oa	51	36	45	74	79	134	139
mean	200	36	50	151	162	334	394

A1.31 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar P/N ratio (100%*P/N)

tree species	n	min	5%	50%	mean	95%	max
be	27	3.91	3.97	4.81	4.90	5.92	7.83
cp	20	4.46	4.65	7.70	7.88	11.51	13.31
df	27	4.04	4.54	6.44	6.31	8.07	8.10
ns	20	6.60	6.64	7.40	7.45	9.02	9.20
sp	42	5.05	5.38	7.08	7.20	9.12	9.55
jl	13	4.73	4.75	5.44	6.18	9.82	9.95
oa	51	3.75	4.36	5.91	5.84	7.15	7.37
mean	200	3.75	4.24	6.54	6.46	9.10	13.31

A1.32 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar K/N ratio (100%*K/N)

tree species	n	min	5%	50%	mean	95%	max
be	27	21.49	22.31	28.48	29.52	38.59	38.95
cp	20	28.12	29.11	41.29	42.30	56.04	57.32
df	27	24.93	26.72	33.70	34.17	40.96	45.64
ns	20	24.15	24.33	35.10	34.59	46.61	46.97
sp	42	25.09	27.12	32.40	33.05	40.76	42.93
jl	13	18.18	18.22	30.71	29.44	38.28	38.51
oa	51	23.42	27.34	35.41	35.44	44.78	49.89
mean	200	18.18	24.78	33.93	34.19	46.07	57.32

A1.33 Values of minimum, mean, maximum, 5, 50, and 95 percentiles for stands of seven tree species in 1995: foliar Mg/N ratio (100%*Mg/N)

tree species	n	min	5%	50%	mean	95%	max
be	27	2.75	2.78	4.64	4.93	6.95	7.40
cp	20	3.20	3.55	5.44	6.44	11.94	13.31
df	27	2.70	3.91	7.50	6.99	8.91	8.99
ns	20	2.82	2.82	4.74	4.76	7.50	7.58
sp	42	2.59	2.88	3.95	3.97	5.37	5.94
jl	13	4.58	4.61	6.48	6.75	10.47	10.70
oa	51	4.10	5.04	6.28	6.50	8.62	8.91
mean	200	2.59	2.98	5.39	5.64	8.59	13.31

A1.34 Criteria used for assessment of the mineral nutrient status of 200 forest stands in 1995

Tree species	Criterion (foliar content, g kg^{-1})				
	High	Low			
	N	P	K	Ca	Mg
beech	>28.0	<1.4*)	<6.0	<4.0	<1.5
Corsican pine	>18.0	<1.2*)	<5.0	<1.0	<0.5
Douglas-fir	>18.0	<1.4	<6.0	<2.5	<0.7
Norway spruce	>17.0	<1.5*)	<6.0	<2.0	<0.7
Scots pine	>18.0	<1.4	<5.0	<1.5	<0.7
Japanese larch	>25.0	<2.0	<7.0	<3.0	<1.0
pedunculate oak	>28.0	<1.3	<6.0	<3.0	<1.5

*) value established in 1996 after revision of a former value. High = optimum supply; no reaction after N fertilization. Low for P, K, and Mg = nearly always a positive growth reaction after fertilization with P or K; positive reaction of leaf or needle colour after fertilization with Mg; the criterion for Mg equals the threshold of visual Mg deficiency symptoms. Low for Ca: limited growth for all tree species or even visual Ca deficiency symptoms (Scots pine, Corsican pine).

A1.35 Percentage of stands with 'high' N, or 'low' P, K, Ca or Mg status of leaves or needles in 1995

Tree species	% of stands with				
	High	Low			
	N	P	K	Ca	Mg
beech	37.0	74.1	14.8	29.6	74.1
Corsican pine	5	65	5	45	-
Douglas-fir	66.7	88.9	14.8	4.07	-
Norway spruce	45	75	55	30	15
Scots pine	59.5	54.8	-	21.4	26.2
Japanese larch	38.5	100	76.9	38.5	-
pedunculate oak	3.9	13.7	2.0	3.9	25.5

A1.36 Percentage of stands with 'low' P/N, K/N or Mg/N status of leaves or needles in 1995

Tree species	% of stands with low ratio of X/N		
	P/N	K/N	Mg/N
beech	55.6	14.8	63.0
Corsican pine	10	-	40
Douglas-fir	7.4	3.7	7.4
Norway spruce	-	10	70
Scots pine	-	-	85.7
Japanese larch	23.1	23.1	15.4
pedunculate oak	17.6	2.0	3.9

Annex 2 Estimation of site-specific atmospheric deposition and ozone exposure

Site-specific deposition estimates of acidifying components and base cations

In this Annex the methods used to estimate deposition fluxes of acidifying components and base cations as well as ozone exposure at each site for the period 1984-1995 are described in further detail. The dry deposition flux of gases and particles from the atmosphere to a receptor surface is governed by i) the concentration in air, ii) turbulent transport processes in the boundary layer, iii) the chemical and physical nature of the depositing species and iv) the efficiency of the surface to capture or absorb gases and particles. The flux of a trace gas is given as:

$$F = V_d(z)\ c(z) \qquad [A2.1]$$

where:
c(z) = the concentration at height z;
Vd(z) = the dry deposition velocity at height z (Chamberlain, 1966).

In equation A2.1, z is the reference height above the surface, here taken as 50 m. If the surface is covered with vegetation, a zero-plane displacement (d) is included: z = z-d. The absorbing surface is often assumed to have zero surface concentration, and the flux is therefore viewed as being linearly dependent on the atmospheric concentration gradient.

The parametrisation of the dry deposition velocity is based on a description with a resistance analogy or Big Leaf Model (see e.g. Thom, 1975; Hicks et al., 1987; Fowler, 1978; Erisman et al., 1994b)). In this resistance model the most important deposition pathways by which the component is transported to and subsequently taken up at the surface are parametrisized.

Vd is represented by the inverse of three resistances:

$$V_d=(R_a+R_b+R_s)^1 \qquad [A2.2]$$

The three resistances (Eq. A2.2) represent the three stages of transport. The aerodynamic resistance (Ra) represents the resistance against turbulent transport of the component close to the surface, the quasi-laminar sublayer resistance (Rb) accounts for the transport of the component by molecular diffusion through a laminar layer adjacent to the surface, and the surface resistance (Rs) accounts for the uptake at the surface. Ra mainly depends on the local atmospheric turbulence, whereas Rb depends on both turbulence characteristics and molecular diffusion of the component considered. Rs depends on the component and receptor characteristics. The latter can be split up into several other resistances such as e.g. stomatal, mesophyll, cuticular, surface and water-layer resistance (Erisman, 1992).

Deposition velocities of particles composed of SO_4, NO_3, NH_4, and Na, Ca, Mg, and K are calculated using the following parametrisations. For acidifying compounds, the particle dry deposition velocity for low vegetation and other areas with a roughness length (z0) less than 0.5m is calculated using a parametrisation by Wesely et al. (1985), and for forests and other areas with a z0 above 0.5m using a parametrisation based on the model of Slinn (1982) which was recently tested with micro-meteorological measurements performed at the Speulder forest in The Netherlands (Ruijgrok et al., 1994; Erisman et al., 1994a). The dry deposition velocity for base cation particles is calculated using the latter parametrisation. It includes both turbulent exchange and sedimentation of coarse particles (Ruijgrok et al., 1994).

Deposition in The Netherlands and the contribution of different source categories or countries are calculated using the DEADM (Dutch Empirical Acid Deposition Model) and OPS (Operationele Prioritaire Stoffen) models. These models have been described extensively in Erisman (1992; 1993) and Erismanet al. (1995) (DEADM) and Asman & Van Jaarsveld (1992), and Van Jaarsveld (1990; 1995) (OPS). Site-specific atmospheric deposition estimates are derived from DEADM calculations using interpolated concentration measurements, except for ammonia, where modelled OPS concentrations are used. Ozone exposure estimates are obtained using the method presented by De Leeuw & Van Zantvoort (1995).

OPS

The statistical transport model OPS was developed at RIVM to calculate dispersion and deposition of substances of SO_x, NO_y, NH_x and heavy metals in The Netherlands (Van Jaarsveld, 1990). The OPS model is able to describe both short- and long-distance transport, and average concentrations and depositions can be computed for time scales ranging from 1 day to more than 10 years (Van Jaarsveld, 1995). It can account for both point sources of various heights and area sources of various shapes and heights. The sources need not be distributed on a regular grid system. The model yields realistic results both within area sources and near point sources, as well as at long distances from sources. The receptor system is therefore determined by the resolution of the emissions. The concentrations and depositions in The Netherlands are described on a 5 x 5 km^2 grid system, whereas those in Europe are estimated on a 50 x 50 km^2 gid system. Computations are made for a limited number of meteorological situations (classes) with a representative meteorology for each class. Among the discretisations, a total of 12 wind-direction sectors and 6 atmospheric stability classes are distinguished. The basis for the model is formed by the Gaussian plume formulation for a point source. It is assumed that the plume is reflected only once at the surface and at the top of the boundary layer. Moreover, it is assumed that at larger distances from the source the plume is vertically distributed homogeneously over the whole boundary layer, apart from an attenuation near the surface due to dry deposition (Van Jaarsveld, 1995; Asman & Van Jaarsveld, 1992). The OPS model is used to calculate the annual average ammonia and ammonium concentration and deposition field over The Netherlands. These fields are input for DEADM, which model is used to calculate the total deposition.

DEADM

The DEADM model has been developed to estimate deposition fluxes on a small spatial scale (Erisman, 1992; 1993; Erisman & Draaijers, 1995). DEADM calculates deposition fluxes of the most important acidifying components and base cations for each two hour period using the inferential method based on information obtained mainly from measurements. To obtain site-specific dry deposition estimates for sulphur and oxidised nitrogen species, ambient concentrations obtained from interpolation of measurements of SO_2, SO_4, and NO, NO_2, NO_3 and HNO_3 made within the National Air Quality Monitoring Network (LML, RIVM, 1994) are combined with parametrised dry deposition velocities. For reduced nitrogen species concentration fields calculated by the OPS model are used. Concentrations at 50m above the surface are used. At this height it is assumed that concentrations and meteorological parameters are not influenced by surface properties to a large extent. Dry deposition velocities of gases and particles at this height are calculated for each site using detailed stand information, routinely available meteorological information and the inferential technique (Erisman et al., 1994a). Resistances are modelled using observations of meteorological parameters and parametrisation of surface exchange processes for gases and aerosols (Erisman et al., 1994a). Hourly measured values of temperature, wind speed, relative humidity, global radiation, and amount and duration of precipitation at 12 stations in The Netherlands are interpolated over the country on a 10 x 10 km^2 grid. For the set of 3000 stands not all characteristics, such as tree height and canopy coverage, required to characterize roughness length and turbulence intensity are recorded. For these stands, information on tree species and stand age can be used to estimate missing values. For the set of 200 stands more stand characteristics and site information are known allowing more accurate site-specific deposition modelling. The resulting two-hourly deposition values are summed to obtain annual fluxes. Occult deposition and deposition of large particles are not taken into account due to lack of information. Wet deposition, obtained from interpolation of precipitation concentration and amount measurements made within the LML, is added to the dry deposition to estimate total deposition at each site. For a description of the theoretical background of the model and for details of the model and model parameters the reader is referred to Erisman (1992).

As the OPS model has been modified with the same parameters and inputs as currently used in DEADM, NH_x dry deposition estimates resulting from the OPS model are directly used to calculate detailed deposition estimates in DEADM. In DEADM the monthly and daily variations in NH_3 concentrations derived from LML measurements as proposed by Bleeker & Erisman (1995) have been taken into account. The equations they reported for 1993 and other years were incorporated in DEADM to describe the monthly average diurnal variation for each site. The dry deposition for each site is calculated by averaging the diurnal variation of the deposition velocity (Vd) for each grid and each month, and multiplying the monthly average diurnal variations of Vd and concentration. In this way the most important correlations between Vd and concentration are taken into account. For each year the annual average concentrations were obtained with the OPS model using meteorological statistics and emission estimates for that year. The estimates of dry deposition of NH_x with DEADM and OPS were compared for different years and found to be equal within $\pm$ 5%. DEADM was so used to estimate the site specific deposition data.

The model is extended with a module to estimate dry deposition of base cations (Erisman et al.1994a). A problem with generalisation of the results obtained for base cations is that there is a serious lack of measured or estimated base cation concentrations in The Netherlands, as elsewhere in Europe. In order to estimate regional dry deposition of base cations, the method using scavenging ratios as explained in Eder & Dennis (1990) is used. This approach is based on the premise that cloud droplets and precipitation efficiently scavenge particles resulting in a strong correlation between concentrations in precipitation and the surface-level air (Eder & Dennis, 1990). This assumption will only be valid for well-mixed conditions at sufficient distance from sources. Factors that will influence the magnitude and variability of scavenging rations include particle size distribution and solubility, precipitation amount and rate, droplet accretion process and storm type (Galloway et al., 1993). Event scavenging ratios can range several orders of magnitude even for single species at a single location, but scavenging ratios have been found reasonably consistent when averaged over one year or longer (Galloway et al., 1993). For this reason, annual mean precipitation concentrations are used to infer annual mean air concentrations of Na^+, Mg^{2+}, Ca^{2+} and K^+. First, monthly mean air concentrations of Na^+, Mg^{2+}, Ca^{2+} and K^+ were inferred from wet deposition amounts measured at the sites of the National Air Quality Monitoring Network (LML, RIVM, 1994), using the long-term averaged scavenging ratios obtained from simultaneous measurements on air quality and wet deposition at the Speulder forest research site. Second, these monthly mean air concentrations were averaged over the year. Deposition velocities are estimated for every two hours at each site using the parametrisation reported in Ruijgrok et al. (1994) and Erisman et al. (1994a). Base cation input is estimated by multiplying the annual average concentrations and the deposition velocities (Erisman et al., 1994a).

Ambient air concentrations of acidifying components and base cations derived from the procedure described above will reflect the average situation. Sub-grid concentration gradients are likely to exist, especially when point sources and/or many scattered sources such as agricultural fields and unpaved roads are present. In emission areas, surface-level air concentrations will be larger compared to concentrations at 50m height, whereas in background situations, surface-level concentrations will be lower due to dry deposition.

Site-specific estimates of ozone exposure

For forest trees a critical level of ozone has been defined which is expressed as the cumulative exposure over a threshold of 40 ppb. This index is referred to as AOT40 and should not exceed 10 000 ppb h (accumulated over six month, 24 hours a day) (Führer & Achermann, 1994). In The Netherlands, observed ozone concentrations and AOT40 levels are mapped on a 5 x 5 km^2 resolution (De Leeuw & Van Zantvoort, 1995). The spatial interpolation procedure is based on measurements made within the LML. At urban stations, as a result of the chemical interaction between ozone and nitrogen oxides (for which increased levels due to locally enhanced emissions can be found), ozone concentrations are generally lower than at rural stations. As the exceedances of the critical levels for forest trees are evaluated, only results of the rural stations have been used. Corrections for missing data have been made by means of i) a correction proportional to the number of missing hours, ii) a spatial interpolation of ozone concentrations using measurements from the other stations and subsequently calculation of AOT40 using the interpolated data, and iii) an interpolation in time using the time series measured at the station itself (De Leeuw & Van Zantvoort, 1995). The AOT40 values are calculated by interpolation of the hourly ozone measurements to a 5 x 5 km^2 grid followed by accumulation of AOT40 values at grid level. The AOT40 values at each monitoring site will be obtained by overlaying the locations of the sites with the AOT40.

The calculations are based on measurements made at a height of 4m above the ground. As these results are not representative for higher vegetation, calculated AOT40 values should be corrected using the actual canopy height at the monitoring sites. Furthermore, the relation between the ozone concentrations at measuring height and canopy height depend on meteorological conditions and local conditions (roughness length, vegetation type and probably also the local NO_x emission density both at the measuring location and at the receptor site). Therefore a procedure similar to DEADM (Erisman, 1992) is recommended. In such a procedure, the (hourly) measured concentrations are interpolated in the vertical to a certain reference height above the surface (taken as 50m) using the local conditions at the monitoring site. In the receptor the concentrations are extrapolated downwards from this reference height to the desired height taking into account the local conditions at the receptor.

Errors in the interpolated ozone fields are mainly caused by the chemical interactions of ozone with NO_x. Variations in the NO_x concentration caused by low level sources like traffic will introduce a shift in the photo-stationary state and through that in ozone concentrations. The quality of the interpolated fields can be improved by interpolating the observed oxidant concentrations (Ox, sum of O_3 and NO_2) instead of observed ozone concentrations. The Ox concentration is a more conservative quantity than the ozone concentration because it is not sensitive for shifts in the photo-stationary state. The ozone concentrations in each 5 x 5 km^2 grid cell can be estimated from the interpolated Ox-levels when the photo-stationary equilibrium constant in combination with the NO_x concentrations are available on this scale. The applicability of both methods mentioned to improve the quality of the results will be investigated in the near future.

Evaluation of model results

An extensive uncertainty analysis on the DEADM deposition estimates has been published by Erisman (1992; 1993). The uncertainty analysis comprised comparison of modelled fluxes with measurements, comparison with other model results and estimation of uncertainty ranges using the error propagation method. In this Section, the uncertainty analysis performed by Erisman (1992; 1993) will be used to determine uncertainty ranges in deposition estimates.

Figure A2.1 shows a comparison between monthly average modelled dry deposition velocities of SO_2, NH_3, NO_2 and SO_4^{2-} -aerosol measured at Speuld (36 m above the surface) and calculated with DEADM (50 m above the surface) for 1993. The agreement is reasonably good, with an average deviation of about 25%.

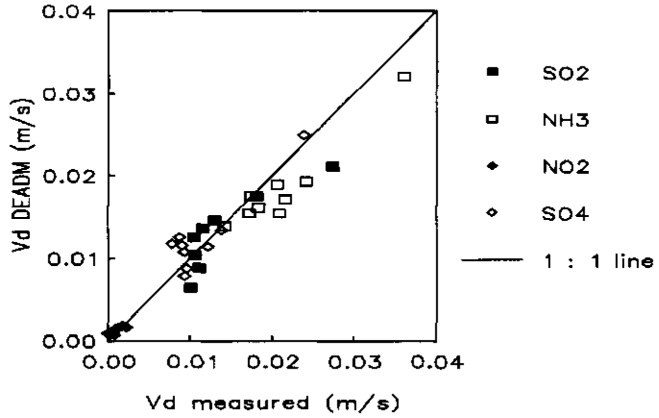

Fig. A2.1 Comparison of monthly Vd values calculated with DEADM (50 m height) and measured in Speulder forest (36 m height) for 1993 (m s-1)

Calculated SO_4^{2-} aerosol Vd values are somewhat higher than those derived from measurements. Monthly average modelled Vd values of SO_2 and NO_2 are in good agreement with those based on measurements with no systematic differences. NH_3 dry deposition velocities calculated with DEADM (OPS) are smaller than those derived from measurements at Speulder forest. DEADM calculations are representative for the area surrounding Speulder forest, whereas measurements are representative for more local surface characteristics. It must be noted that the comparison of modelled Vd with those derived from measurements in Speulder forest is not fully independent because parametrisations of Vd used in DEADM are partly based on data from Speulder forest. Annual average fluxes derived from measurements and calculated using DEADM for the Speulder forest are listed in Table A2.1 (Erisman et al., 1994a). Agreement is reasonable, keeping in mind that DEADM results are 1 x 1 km^2 grid averages (5 x 5 km^2 for NH_3 and NH_4^+), calculated with parameters such as land use, forestry statistics, etc. derived from long-term statistics.

Table A2.1 Average dry deposition fluxes based on measurements (November 1992 - September 1993) and calculated using DEADM (January 1993 - September 1993) for the Speulder forest (mol ha^{-1} a^{-1})

Component	Measurements	DEADM results
SO_2	488	509
SO_4^{2-} aerosol	189	146
Dry SO_x	677	655
NH_3	1409	816a
NH_4^+ aerosol	563	685a
Dry NH_x	1972	140a
NO_2	136	190
HNO_2	96	109
HNO_3	144	126
NO_3- aerosol	388	216
Dry NO_3	764	614

a): 5 x 5 km^2 estimates

Modelled values are compared to observations at different locations in The Netherlands in Table A2.2. Model estimates of the NH_3 dry deposition flux over heathland (Elspeet and Assel) are higher than the fluxes obtained from measurements. At the Speulder forest site, NH_3 fluxes as estimated by the model are lower than measured fluxes (see also Table A2.1). It must be emphasised that the model resolution for NH_3 fluxes is 5 x 5 km^2. Variations of the flux within such a grid can be as large as a factor of 4 (Asman et al., 1989; Asman and Van Jaarsveld, 1992). The location of the area where measurements are made relative to the NH_3 sources in the grid determines whether the depositions will be higher or lower than the average over the grid. Table A2.2 probably just gives an indication of this variation rather than a real comparison. Generally, agreement is reasonable. It can be concluded that fluxes obtained using the model and those derived from measurements show differences in the order of 20%.

Table A2.2 Flux measurements and estimates by different methods and for different locations in The Netherlands in mol ha^{-1} a^{-1} (For intercomparison, the estimates have been presented in more significant figures than those consistent with their accuracy)

Location	Component	Height (m)	Year	Reference	Measured flux	Estimated flux
Speuld	SO_2	30	1988	Duyzer et al.(1994)	590	530
	NO_x	30		Duyzer et al. (1994)	360	400
Speuld	SO_2	30	1989	Duyzer et al. (1994)	540	584
	NO_x	30		Duyzer et al. (1994)	270	440
	NH_3	30		Duyzer et al. (1994)	1860	1645
Elspeet	SO_2	4	1989	Erisman et al. (1993)	350	510
	NH_3	4		Erisman et al. (1993)	810	980
Assel	NH_3	1.5	1987	Duyzer et al. (1989)	550	975
Cabauw	HNO_3	200	1986	Erisman et al. (1988)	220	180
Zegveld	SO_2	4	1988	Erisman et al. (1993)	590	484

In Table A2.3, uncertainty ranges are listed based on error propagation methods. The uncertainty in dry deposition, resulting from uncertainty in both concentrations and dry deposition velocities, wet deposition and total deposition are listed separately. These estimates are not related to 'hard facts', but merely reflect some sort of 'expert judgement'.

The uncertainty range in the flux is calculated by the relative uncertainty Qa in Vd and c, according to Equation A2.3. Uncertainty in the total flux is estimated using the absolute uncertainty Sa (Eq. A2.3). If the variables are correlated, an extra term must be added: R times the product of individual errors, where R is the correlation coefficient between the variables. However, no correlation between the variables is assumed because these are taken into account in DEADM by calculating the flux for each two hours in a year.

$$a = b + c \qquad S_a = \sqrt{S_b^2 + S_c^2 + 2\,R\,S_b\,S_c}$$
$$a = b * c \qquad Q_a = \sqrt{Q_b^2 + Q_c^2 + 2\,R\,Q_b\,Q_c} \qquad [A2.3]$$

Worst case estimates are derived taking into account full correlation (R = 1 in Equation A2.1) (Erisman, 1993). Worst case estimates are about a factor of two higher than the systematic uncertainty estimates. The uncertainty in the total potential acid deposition in The Netherlands as a whole therefore lies somewhere between 15 and 30%. The largest uncertainty is found in deposition of nitrogen compounds.

It must be noted that, in general, the uncertainty in the deposition estimates becomes larger when the spatial scale on which the estimates are mapped becomes smaller. Therefore, uncertainty numbers for site-specific estimates will be somewhat larger than the numbers presented here. On the other hand, site-specific estimates are calculated using locally known roughness lengths, resulting in somewhat improved results compared to these numbers.

Finally, uncertainty in the ozone concentrations mainly arises from the spatial interpolation procedure. It is estimated that the ozone concentrations at the 5 x 5 km^2 level have an uncertainty of ca. 30% (De Leeuw & Van Zantvoort, 1995). They also (very roughly) estimate that for forests (assuming a canopy height of 10 m) the concentrations at canopy level are about 25% higher than the 4m values obtained from the monitoring network.

Table A2.3 Total systematic uncertainty (%) in yearly average total deposition flux on different spatial scales for all individual components (1993)

Component	Flux	5 x 5 km^2			Country average (mol ha^{-1} a^{-1})		
		c/c	Vd/Vd	F/F	c/c	Vd/Vd	F/F
Dry SO_2	530	20	30	36	15	20	25
Dry SO_4^{2-}	45	20	40	45	15	30	34
Wet SO_4^{2-} a)	195	22	-	-	20	-	-
Total SO_x	770	25	-	-	15	-	-
Dry NO	0	30	200	200	20	100	102
Dry NO_2	210	30	50	58	20	50	54
Dry HNO_2	50	50	60	78	40	40	57
Dry HNO_3	100	50	60	78	40	30	50
Dry NO_3^- a)	65	40	40	57	25	30	39
Wet NO_3	320	-	-	25	-	-	20
Total NO_y	745	-	-	40	-	-	25
Dry NH_3	1250	40	30	58	30	20	36
Dry NH_4^+	60	40	40	71	40	30	50
Wet NH_4^+ a)	680	-	-	40	-	-	30
Total NH_x	1990	-	50	-	-	30	-
Total Acid	4270	-	35	-	-	15	-

a) Wet deposition is calculated on a 10 x 10 km^2 scale.

Annex 3 Results of simple regression analysis of foliar loss

Table A3.1 Simple regression equations for foliar loss (classes) in 1995

Tree species	*n*	Equation		R^2_{adj} (%)
beech	27	no significant equations		-
Corsican pine	20	21.00 - 2.333	*K	31.8
	20	15.88 - 0.2007	*K/N	37.7
	20	24.81 - 0.419	*O_3	19.8
	20	10.94 - 0.00521	*SO_x	19.2
	20	17.75 - 2.77	*ln(age)	16.2
Douglas fir	27	5.93 + 0.0225	*psum	11.9
	27	38.9 - 0.01075	*tgsum	12.3
	13	12.292- 0.0685	*Ptot	45.4
	27	0.06 + 9.35	*fungi	23.7
Norway spruce	20	-9.70 + 1.019	*N	44.4
	20	-6.47 +11.14	*P	36.4
	20	16.59 -11.28	*Mg	15.7
	20	15.53 - 1.649	*Mg/N	34.3
	20	-4.04 + 0.01881	*SO_x	33.0
	13	-4.81 + 6.44	*Norg	33.7
	20	1.86 + 4.29	*insect	38.0
Scots pine	42	0.972+ 0.0401	*age	14.7
	35	-4.83 + 2.050	*ln(age)	14.8
Japanese larch	13	-42.6 + 0.01733	*tgsum	30.0
	13	-4.68 + 0.352	*N	37.7
	13	8.46 - 0.1770	*K/N	37.5
	13	0.733+ 0.1015	*Ptot	77.8
pedunculate oak	51	2.146+ 0.02341	*age	28.4
	23	-2.14 + 1.436	*ln(age)	32.2
	51	0.56 + 0.341	*K	14.1
	51	6.54 - 1.774	*Mg	10.8
	51	0.03 + 0.1017	*K/N	16.4
	51	6.01 - 0.368	*Mg/N	8.6
	51	1.880+ 0.712	*insect	15.4

These preliminary results from the simple regression per tree species can be summarised as follows:

Corsican pine

The relationship between the foliar K content or K/N ratio and foliar loss seems plausible; other parameters explain only little of which the atmospheric O_3 concentration and the SO_x deposition are the best, both explaining about 19% of the defoliation.

Douglas-fir

The relationship between psum and foliar loss presumably is an indirect one because it is not very plausible that increased precipitation during the growing season would have intensified needle loss of Douglas-fir also, the relationship between tgsum and foliar loss is not clear. This relationship suggests that increased warmth during summer would decrease needle loss.

Norway spruce

Foliar N, P and Mg contents play a significant role. Presumably, the relation between the foliar Mg/N ratio and needle loss might be a direct one, because it is in agreement with observations in Central Europe that needle loss is intensified by a poor Mg status.

Japanese larch
Due to the low number of surveyed stands, it can not be decided which of the significant relations between foliar loss and predictor variables is a direct one. A higher foliar K/N ratio coincided with lower foliar loss, which might be a plausible and direct relation. The relationship between foliar loss is curious, because it seems to imply that foliar loss increases on soils with a higher P-total value.

Scots pine and pedunculate oak
Stand age seems to play a main role; foliar loss is higher at increasing stand age. Two observations are also remarkable: in the first place, no significant relation was found between the soil moisture availability class and foliar loss. In the second place, no significant relationships between foliar loss and predictor variables could be established for beech. A possible explanation for this lack of significant relationships for beech might be the mitigation of these relationships due to the initiation and production of an heavy cone crop in 1995 (Hilgen 1995).

Annex 4 Second best models explaining foliar loss of pedunculate oak and Scots pine

Table A4.1 Equations explaining foliar loss of pedunculate oak; 'age' included as ln(age), insect damage included as insect25

Equation		p	R^2_{adj}
1. fol.loss =	-223		69.8
	+24.00*ln(age)	<0.001	
	-0.739*crown%	0.003	
	+28.85*insect25	<0.001	
	-82.8*tmin1	0.013	
	-0.0899*tgsum	0.017	
2. fol.loss =	-100.6		67.7
	+22.64*ln(age)	<0.001	
	-0.839*crown%	0.001	
	+28.86*insect25	<0.001	
	+0.2586*psum	0.005	
3. fol.loss =	-620		63.2
	+30.40*ln(age)	<0.001	
	+30.94*insect25	<0.001	
	-95.3*tmin1	<0.001	
4. fol.loss =	-258.1		57.7
	+20.57*ln(age)	0.002	
	-1.083*crown%	<0.001	
	+0.954*psum	<0.001	
	+0.01322*AOT40	0.004	
5. fol.loss =	-643		43.1
	+33.46*ln(age)	<0.001	
	-115.5*tmin1	0.010	

Table A4.2 Equations explaining foliar loss of Scots pine

Equation		p	R^2_{adj}
1. fol. loss =	23.32		14.4
	- 0.2113*crown%	0.008	
2. fol. loss =	-1.05		11.3
	+ 0.1785*age	0.017	
3. fol. loss =	16.9		15.6
	+ 0.1837*age	0.012	
	- 254*P/N	0.092	

Annex 5 Results of simple regression analysis of crown transparency

Table A5.1 Simple regression equations for crown transparency (in classes 1-21) in 1995

Tree species	*n*	Equation			R^2_{adj}
beech	27	n.s.			-
Corsican pine	20	8.54	-0.0618	* age	24.1
	20	16.12	-2.77	* ln(age)	22.2
	20	11.63	-5.44	* P	16.9
	20	25.12	-0.369	* O_3	19.7
	20	9.19	-0.00501	* SO_x	23.9
Douglas-fir	27	9.51	-3.28	* P	18.7
Norway spruce	13	-0.09	+2.389	* Norg	45.9
	20	2.540	+0.0955	* Ptot	54.9
	20	1.944	+1.818	* insect	47.6
Scots pine	42	5.506	-0.01723	* age	8.8
	42	8.29	-0.954	* ln(age)	10.8
	42	8.13	-2.76	* P	11.8
	42	7.56	-0.427	* P/N	12.8
	35	7.267	-1.390	* Norg	18.4
Japanese larch	13	9.69	-0.1835	* K/N	35.6
	13	1.872	+0.0978	* Ptot	62.9
	13	1.48	+2.055	* insect	24.7
pedunculate oak	51	3.316	+0.02737	* age	21.7
	51	1.99	+1.708	* ln(age)	25.6
	51	2.984	+0.768	* insect	9.5
	51	1.09	+0.420	* K	11.9
	51	9.57	-2.864	* Mg	17.1
	51	0.89	+0.1125	* K/N	10.8
	51	9.00	-0.636	* Mg/N	16.1
	51	3.348	+0.000770	* NH_x	9.8
	51	17.97	-0.318	* O_3	12.7
	51	2.618	+0.00347	* SO_x	9.4
	51	3.019	+1.032	* Ntotdep	11.3

These results can be summarised as follows:

Corsican pine

With increasing stand age and foliar P, the crown transparency becomes less, which is plausible for P but not for stand age. Increasing air pollution (O_3 and SO_x) also seem to increase crown density, which is not an acceptable hypothesis.

Douglas-fir and Scots pine

A negative correlation between foliar P and crown transparency. With increasing stand age the crown transparency decreases, which means that with increasing age, crowns are more dense. Pedunculate oak is characterized by a relatively large number of significant equations which explain a significant part of the variance of the crown transparency, but neither of the R^2_{adj}-values - except age - is very convincing.

Annex 6 Second best models explaining crown transparency of pedunculate oak and Scots pine

Table A6.1 Multiple linear regression models explaining logit crown transparency (%) of pedunculate oak (Model A: all predictors included in the statistical model; Model B: fungal damage excluded; C: insect and fungal damage excluded)

Model	Equation			p	R^2_{adj}
A	1	logit cr.transp. =	-19.47		61.0
			+0.624 * ln(age)	<0.001	
			+0.623 * insect25	<0.001	
			-0.407 * fungi	<0.001	
			-2.934 * tmin1	0.003	
B	2	logit cr.transp. =	-4.02		46.7
			+0.455 * ln(age)	0.010	
			-0.016 * crown%	0.032	
			+0.641 * insect25	<0.001	
	3	logit cr.transp. =	-16.42		45.8
			+0.668 * ln(age)	<0.001	
			+0.654 * insect25	<0.001	
			-2.12 * tmin1	0.052	
C	4	logit cr.transp. =	- 7.92		39.2
			-0.030 * crown%	<0.001	
			+0.021 * psum	0.003	
			+0.0004* AOT40	0.001	
	5	logit cr.transp. =	-18.67		39.9
			+0.648 * ln(age)	<0.001	
			-2.89 * tmin1	0.015	
			+0.0003* NH_x	0.024	

Table A6.2 Multiple linear regression models explaining logit crown transparency (%) of Scots pine

Equation			p	R^2_{adj}
1	logittra =	+19.4		43.55
		-0.005 * age	0.046	
		-0.042 * psum	0.008	
		-5.89 * tmin1	<0.001	
		-0.015 * tgsum	0.035	
		-1.638 * P	<0.001	
		-0.0002 * NH_x	0.037	

Annex 7 Relationships between foliar N content, N deposition and NH_3 air concentration

The relationships presented in Table A7.1 and A7.2 are derived through simple linear regression and are therefore to be considered as indicative.

Table A7.1 Indicative relationships between foliar N content of five tree species and total atmospheric N deposition (Ntotdep) in 1995.

Tree species	*n*	Equation	$R^2_{adj.}$	p
beech	27	n.s.		
Corsican pine	20	8.47+0.00233*Ntotdep	26.7	0.012
Douglas-fir	27	n.s.		
Norway spruce	20	13.1+0.001389*Ntotdep	37.1	0.016
Japanese larch	13	16.65+0.002255*Ntotdep	43.5	0.008

n.s. : not significant at the p = 0.05 level

Table A7.2 Indicative relationships between foliar N content of five tree species and atmospheric NH_3 concentration (NH_3) in 1995.

Tree species	*n*	Equation	$R^2_{adj.}$	p
beech	27	n.s.		
Corsican pine	20	$12.97+0.2213*NH_3$	30.5	0.007
Douglas-fir	27	n.s.		
Norway spruce	20	n.s.		
Japanese larch	13	$19.76+0.605*NH_3$	46.4	0.006

n.s. : not significant at the p = 0.05 level

Annex 8 Preliminary relationships between foliar nutrient contents and soil fertility

Table A8.1 Preliminary relationships between 1995 foliar nutrient content and 1990 soil fertility parameters for five tree species of the New Monitoring Network for Forest Health (The relationships are to be considered as preliminary because they are derived through multiple regression on a limited data set containing soil fertility data from 1990 only)

Nutrient	Tree species	Equation		$R^2_{adj.}$	p
N	beech	n.s.			
	Corsican pine	12.03	+0.1431*Ptot	34.0	0.021
	Douglas-fir	15.08	+9.51*NH_4-exc.	56.3	0.002
	Norway spruce	n.s.			
	Japanese larch	20.57	+6.93*N_{org}	37.7	0.017
			-3.25*pH-KCl		0.015
P	beech	1.387	-0.00739*Al-exc.	55.4	0.001
	Corsican pine	0.655	+0.1028*pH-KCl	38.2	0.014
	Douglas-fir	n.s.			
	Norway spruce	n.s.			
	Japanese larch	n.s.			
K	beech	n.s.			
	Corsican pine	n.s.			
	Douglas-fir	n.s.			
	Norway spruce	n.s.			
	Japanese larch	n.s.			
Ca	beech	4.989	+4.03*Mg-exc.	22.7	0.034
			-0.1115*Al-exc.		0.045
	Corsican pine	n.s.			
	Douglas-fir	n.s.			
	Norway spruce	3.775	-6.68*K-exc.	63.4	0.034
	Japanese larch	3.052	+0.03081*Ca-exc.	65.9	<0.001
Mg	beech	0.683	+0.366*Mg-exc.	16.3	0.085
	Corsican pine	n.s.			
	Douglas-fir	n.s.			
	Norway spruce	1.082	-0.557*NH_4-exc.	19.4	0.074
	Japanese larch	1.218	+0.582*Mg-exc.	46.5	0.006
Al	beech	548.4	-4.30*Ptot	52.6	0.017
			-44.5*pH-KCl		0.051
	Corsican pine	n.s.			
	Douglas-fir	n.s.			
	Norway spruce	n.s.			
	Japanese larch	n.s.			
Fe	beech	n.s.			
	Corsican pine	20.8	+1.94*Ptot	50.4	0.004
	Douglas fir	59.1	+1.145*Ptot	20.9	0.066
	Norway spruce	-42.3	+28.8*pH-KCl	30.5	0.029
	Japanese larch	40.2	+1.078*Ptot	36.6	0.017
Mn	beech	n.s.			
	Corsican pine	244.3	-37.7*pH-KCl	58.5	0.031
			+1983*Mn-exc.		0.005
	Douglas-fir	45.8	+8450*Mn-exc.	71.4	<0.001
	Norway spruce	51.1	+11775*Mn-exc.	93.5	<0.001
	Japanese larch	54.5	-78.0*pH-KCl	68.7	<0.001
			+193.8*Norg.		<0.001

Table A8.2 Indicative relationships between 1995 foliar nutrient contents and 1995 soil fertility data for five tree species of the new monitoring network of forest condition (The relationships are to be considered as preliminary because they are derived through multiple regression on a limited data set containing soil fertility data from 1990 only)

Tree species	Nutrient	Equation	$R^2_{adj.}$	p
beech	N	n.s.		
	P	n.s.		
	K	n.s.		
	Ca	3.507 +3.959*[Ca]	81.1	<0.001
	Mg	0.786 +2.858*[Mg]	34.4	<0.001
	Fe	n.s.		
	Mn	329.6 +25848*[Mn]	56.0	<0.001
	Al	n.s.		
Corsican pine	N	13.08 +2.0*[NO_3+NH_4]	27.9	0.010
	P	n.s.		
	K	n.s.		
	Ca	1.446 +0.3862*ln([Ca])	63.4	<0.001
	Mg	1.206 +0.2195*ln[(Mg])	52.7	<0.001
	Fe	n.s.		
	Mn	n.s.		
	Al	n.s.		
Douglas-fir	N	17.84 +1.711*[NO_3+NH_4]	35.0	<0.001
	P	n.s.		
	K	n.s.		
	Ca	n.s.		
	Mg	n.s.		
	Fe	n.s.		
	Mn	200.2 +13278*[Mn]	78.3	<0.001
	Al	n.s.		
Norway spruce	N	15.55 +1.75*[NO_3+NH_4]	45.7	<0.001
	P	1.211 +5.64*[PO_4]	22.4	0.020
	K	n.s.		
	Ca	2.059 1.194*[Ca]	45.8	<0.001
		3.415 +0.627*ln([Ca])	46.3	<0.001
	Mg	n.s.		
	Fe	n.s.		
	Mn	n.s.		
	Al	n.s.		
Japanese larch	N	n.s.		
	P	n.s.		
	K	n.s.		
	Ca	2.482 +2.46 * [Ca]	55.7	0.002
	Mg	n.s.		
	Fe	43.62 +740 * [Fe]	49.6	0.004
	Mn	n.s.		
	Al	68.5 +283.9 * [Al]	63.4	<0.001