Assessment of the possibilities to derive relationships between stress factors and forest condition for The Netherlands

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ABSTRACT

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In a definition study the possibilities to derive relationships between stress factors and forest condition in The Netherlands are surveyed. First the present knowledge on forest health and stress factors is discussed. Next different monitoring networks are compared and available data are described. Then, relevant effect and predictor variables are discussed. Finally a statistical method is proposed for examining the relationship between forest condition and stress factors. Minimum sets of predictors were selected which have to be included in the statistical models to perform a useful examination.

Keywords: air pollution, biotic stress, crown condition, defoliation, meteorological stress, statistical methods, stress factors

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Contents

Annexes

Preface

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 (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.

The department of Nature of The Netherlands Ministry of Agriculture, Nature Management and Fisheries (IKC-N), asked the DLO Winand Staring Centre (SC-DLO) to conduct the study on The Netherlands scale (reports 147 and 148) in co-operation with the DLO institute for Forestry and Nature research (IBN-DLO), the National Institute for Public Health and the Environment (RIVM) and the Centre for Biometrics Wageningen (CBW, formerly DLO Agricultural Mathematics Group).

From these institutes and from the IKC-N, an expert-panel was installed, covering a broad field of experience related to forest condition. The expert-panel consisted out of: Ir. W. Daamen (Maatschap Daamen, Schoonderwoerd & de Klein), Dr. Ir. W. de Vries (SC-DLO), Dr. J.W. Erisman (RIVM), Ir. P.R. Hilgen (IKC-N), Ir. J.M. Klap (SC-DLO), Ir. A.F.M. Olsthoorn (IBN-DLO), Drs. J.H. Oude Voshaar (CBW), Ir. P.J.H.M. Reuver (IKC-N), Dr. Ir. J. van den Burg (IBN-DLO), Drs. E.P. van Leeuwen and Ir. C.M.A. Hendriks.

The project co-ordination was done by SC-DLO, the project management was in hands of Ir. C.M.A. Hendriks.

Summary

Aim of this report is to give an overview of:
(i) relevant stress factors and related key parameters affecting forest condition in The Netherlands;
(ii) available data to derive such key parameters;
(iii) methods to derive relationships between forest condition, as expressed in defoliation and discoloration, and environmental factors such as air pollution and meteorological conditions with their inherent limitations.

The most important stress factors affecting condition of Dutch forests and related key parameters to which this study is focused are presented in Table I.

Table I Relation between stress factors and key parameters

Stress factor	Key parameters
Stand characteristics	tree species, provenance, stand age, crown coverage
Site characteristics	soil type, groundwater table
Water stress	relative transpiration, precipitation deficit, soil moisture supply
Frost stress	average minimum winter temperature, average minimum January temperature, minimum temperature April, minimum temperature May, minimum temperature June
Nutrient stress	foliar N, P, K, Mg, Ca contents and ratios to N
Pests and diseases	percentage of damage, number of insects/fungi, percentage affected trees
Air pollution	air concentrations and deposition of SO_x, NO_x, NH_x and O_3
Toxic elements	ratio of dissolved base cations (Ca, Mg, K) to Al concentrations, heavy metal contents in solid phase

Tree species have different susceptibilities for the various stress factors. This implies that the critical level above which damage appears differs per tree species.

There are many indices that can be determined to indicate forest condition, e.g. defoliation, discoloration, crown transparency, tree growth, canopy closure, crown form, defoliation type, dead shoots in conifers, flowering in Scots pine, fruiting, secondary shoots in spruce, epicormic branches on oak, leaf size of beech and presence of insects and fungal pathogens. Defoliation and discoloration, however, are the only two systematically recorded indices covering a longer period of time (10 years) and space (The Netherlands, Europe). Therefore, defoliation and discoloration are the most appropriate indices for use in a time series survey.

In The Netherlands there are two systematically surveyed national monitoring networks on forest health. These monitoring networks consist out of the old monitoring network, covering the period 1984 to 1994 with about 3000 stands in total, and the new monitoring network covering the period from 1995 to present with 200 stands.

For the old monitoring network site specific recorded data are available on some stand characteristics, defoliation and discoloration, and on pests and diseases. No information is available on the chemical composition of the soil or the foliage, nor on site characteristics and site specific meteorological conditions, deposition and air concentrations of air pollutants. However, meteorological and air pollution parameters can be derived from models. The number of stands is large viz. 3000.

The new monitoring network comprises less stands (200) but more information is available for these stands. Information is available on stand and site characteristics, and the chemical soil and foliar composition. Further, site specific meteorological conditions, deposition and air concentrations of air pollutants can be estimated with models.

The relationships between forest condition and stress factors for both the old and the new monitoring network can be surveyed on the temporal variation as well as on the spatial variations. Both data sets however have their own advantages and drawbacks. For the old monitoring network a information is available over a long time series (10 years) and many stands (3000) but relatively little site-specific data is available. For the new monitoring network more site-specific data is available but for a shorter time series (3 years) and less stands (200). This latter implies that a reduction of relevant parameters affecting forest condition must be made.

The relationship between the forest condition indices and stress factors can be studied by use of multiple regression. The computer program GENSTAT provides an appropriate procedure (SELECT) with which the survey can be executed. This procedure calculates all possible combinations of predictor variables and supplies criteria on base of which the best explaining models can be selected. To obtain meaningful results the total number of sample plots should be at least 3 to 4 times the number of predictors that are included in the model. Due to interaction between tree species and key parameters, the relationships can best be studied per tree species. The number of relevant key parameters (42), however, is much larger than allowed by the number of sample plots per tree species in the new monitoring network. Therefore a selection of the most relevant predictors was made. This minimum set could not be reduced further than about 15 predictors. This means that within the new monitoring network only for pedunculate oak (n=51) and Scots pine (n=42) enough sample plots are recorded to perform a survey per tree species. For the old monitoring network this problem is less pressing because of the larger number of sample plots.

Four options are drawn up for the survey on the relationships between crown condition and stress factors for the old and the new monitoring network. For both networks an option is developed to perform a survey per tree species (A and C) and for all tree species together (B and D). It is recommended to execute first the per tree species analysis. Based on the result from such a per tree species analysis it must be decided whether an analysis for all tree species will useful. If a survey for all tree species will be executed, interaction terms should be included in the model because the tree species specific sensitivity for the different stress factors.

1 Introduction

1.1 Background

Forest condition in The Netherlands is monitored annually since 1984, following an international standard (UN-ECE, 1989). The monitoring is carried out by the department of Nature of The Netherlands Ministry of Agriculture, Nature Management and Fisheries (IKC-N). In the period 1984-1994, forest condition was monitored in the old monitoring network, containing some 3000 stands. In 1995 a new monitoring network was established, containing 200 stands. However the number of stands was reduced, the amount of information that was gathered on these stands increased. Besides monitoring the forest condition, the survey of the new monitoring network aims to gain more insight in possible causes of changes in the forest condition.

The most important tree species of which the crown condition is recorded are: Scots pine (*Pinus sylvestris* L.), Corsican pine (*Pinus nigra var. maritima* (Aiton) Melville), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Norway spruce (*Picea abies* (L.) Karsten), Japanese larch (*Larix kaempferi* (Lamb.) Carrière), pedunculate oak (*Quercus robur* L.) and beech (*Fagus sylvatica* L.). In the monitoring period large fluctuations in the crown condition of the species have occurred, especially in that of pedunculate oak and beech (Fig. 1).

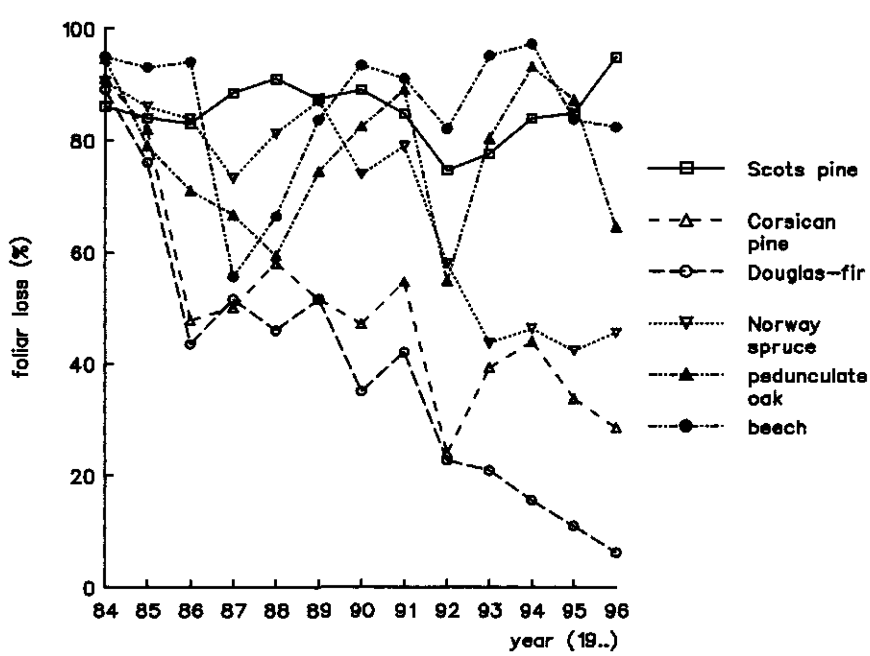

Fig. 1 Forest vitality of six tree species in The Netherlands since 1984

For Corsican pine, Norway spruce and Douglas fir a permanent negative trend in the development of the condition has been observed since the beginning of the monitoring in 1984 (Hilgen, 1995). In 1985 Corsican pine and Douglas-fir both showed a strong decline in condition. After this decline the condition decreased more slowly. At this moment, Corsican pine and Douglas-fir are the least vital tree species in The Netherlands forest: 64% of the Corsican pine stands and even 89% of the Douglas-fir stands are little or not vital (Hilgen, 1995). Norway spruce showed a strong decrease in condition in 1992 and 1993, whereafter the condition, with 58% of the stands being little or not vital, became comparable to that of Corsican pine. It is remarkable that both pedunculate oak and beech show periods with a strong decrease in condition (1987 and 1991 respectively) but also show periods with a strongly increasing condition (Fig. 1). In 1992 for the first time a decrease in condition for all tree species was recorded. In 1993, however, the condition of all tree species, except that of Douglas-fir and Norway spruce, improved. Smits (1992) stated that the dry growing season of 1992 together with four preceding dry years, was the cause of this decrease. Also Hilgen (1995) holds meteorological conditions as an important determining factor for the fluctuations of the forest condition.

In the annual reports of the forest condition inventory (e.g. Smits & Van Tol, 1993; Hilgen, 1994) the effect of possible stress factors, such as weather and air pollution, is mentioned only as a short comment. Until now, these factors have not been quantified and related to the forest condition. Hendriks et al. (1994) investigated the relationships between forest condition and chemical composition of soil, soil solution and deposition of 150 forest stands in The Netherlands. These 150 forest stands formed part of the national monitoring network. No significant relation was found between foliar loss and deposition. Deposition however, showed a clear correlation with the foliar nutrient status and the chemical soil moisture composition (Leeters et al., 1994). Foliar nutrient status, viz. the foliar N/P ratio and foliar N content, was correlated to the defoliation class (Hendriks et al., 1994; Olsthoorn & Maas, 1994). Also relationships between N emission and foliar N content are found (Van den Burg & Kiewiet, 1989). This implies indirect relationships between emissions, deposition, soil nutrient status and defoliation. In the research of Hendriks et al. (1994) the possible effect of weather, ozone, soil moisture supply and suitability of the soil have not been taken into account. Also no allowance was made for the effects of pests and diseases.

In the report on the forest condition of 1995, Hilgen (1995) announced a survey on the relationship between forest condition and its key factors. Preceding such a survey, it is necessary to (i) define key factors affecting the forest condition, (ii) check the availability and quality of necessary data, and (iii) assess possible methods to investigate such relationships and test hypotheses on causes of changes in forest condition, assuming that the vitality indicators represent the state of tree health adequately.

1.2 Aim

Aim of this research was to give an overview of:

(i) relevant stress factors and related key parameters affecting forest condition in The Netherlands;

(ii) available data to derive such key parameters;

(iii) methods to derive relationships between forest condition, as expressed in defoliation and discoloration, and environmental factors such as air pollution and meteorological conditions with their inherent limitations.

1.3 Method

In order to assess a methodology to derive possible relationships between stress factors and forest condition in The Netherlands, a definition study on this topic (this study) was carried out by an expert-panel on forest condition in the first half year of 1996. The experts covered a wide field of experience such as forest management, forest health inventarisation and monitoring, forest nutrition, forest hydrology, forest soils, soil acidification, (effects of) deposition, air pollutants and statistics.

Draft documents were prepared for discussion in the expert-panel, which were based on literature and on an inventarisation of data availability. Aim of the discussions was to use the broad cross-section of expertise related to forest condition in order to achieve a collective agreement on possible methods for analyzing forest condition data. An important part of the discussion was devoted to the selection of stress factors and selection of parameters that are best expressing these stress factors.

1.4 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. Furthermore, an overview is given of the relevant stress factors in relation to forest condition. For each stress factor, possible key parameters are given which can be used when surveying the relationship between forest condition and stress factors. In Chapter 3 the availability an quality of data is discussed, together with possibilities to estimate missing parameters. Possibilities to relate effect parameters for forest condition to relevant key factors are given in Chapter 4. In Chapter 5 the results are discussed and the most important conclusions are given.

2 Stress factors and related key and effect parameters

2.1 Introduction

Before describing methods that aim to relate forest condition to environmental stress factors, including air pollution, it is important to have insight in:

— Relevant natural and anthropogenic stress factors affecting forest condition.
— The interaction between natural and anthropogenic stress factors.
— The occurrence of chronic or acute effects related to the temporal frequency of data on stress factors (intra- and inter-annual).
— Differences in sensitivity of tree species to the stress factors considered.
— The occurrence of threshold (critical) values for stress factors, either related or unrelated to tree species.
— Relevant effect parameters describing the forest condition in relation to stress factors

In general, one can state that the condition of a forest is influenced by the availability of water and nutrients on the one hand versus toxic compounds, frosts, heath, and the occurrence of pests and diseases on the other hand. These general stress factors, however, should be specified in key parameters.

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

2.2 Stress factors

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 inputs) and acidification (increased Al and heavy metal concentrations).

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, a multiple stress theory has thus received increasing attention. It became increasingly clear that spatial patterns of different types of decline exists, each with different causes, and that large-scale forest declines as a result of air pollution have not been demonstrated (Innes, 1993). 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 Kam et 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 Table 1 the relation between stress factors and key parameters is given. In the following sections the various stress factors and key factors are discussed in detail.

Table 1 Relation between stress factors and key parameters

Stress factor	Key parameters
Stand characteristics	tree species, provenance, stand age, stand height, crown coverage, stand history, forest management
Site characteristics	soil type, groundwater table
Water stress	relative transpiration, precipitation deficit, soil moisture supply
Frost stress	average minimum winter temperature, average minimum January temperature, minimum temperature April, minimum temperature May, minimum temperature June
Nutrient stress	foliar N, P, K, Mg, Ca contents and ratios to N
Pests and diseases	severeness of damage, number of insects/fungi, percentage affected trees
Air pollution	air concentrations and deposition of SO_x, O_3, NO_x and NH_x
Toxic elements	dissolved Al concentrations, BC/Al ratio, heavy metal contents in solid phase

2.2.1 Stand and site characteristics

In a research on the effects of acid deposition on 150 forest stands in The Netherlands it was found that defoliation strongly increased with increasing stand age (Hendriks, 1994). Besides the aging 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 UN-ECE/CEC. Thus, tree species and stand age are parameters that always have to be included in any analysis of forest condition.

Differences in soil type and groundwater table on the national scale were relative unimportant for the explanation of the defoliation class (Hendriks et al., 1994). A significant negative relation 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 groundwater table are larger, e.g. sandy soils and clay soils. Because no important effect is expected the soil type and groundwater table can be omitted in the analysis. Besides, important soil characteristics are also represented by the soil nutrient contents and soil moisture concentrations, while soil water characteristics can be discounted in the water stress parameters.

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. An incorrect species choice was made for only a small fraction of the sites involved in the national forest health inventory (Hendriks, unpublished). 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. Although provenance might be a relevant parameter, we have no information about it. It is also impossible to overtake species provenance from any forest administration or from phenotypical characteristics.

Former land use and forest management also may affect the present vitality. Olsthoorn & Maas (1994) found a relation between the occurrence of *Fomus annosus* (Fr.) Cooke on douglas fir and former agricultural land use. Landmann & Bonneau (1995) mention the importance of forest management (normal ageing, formerly very dense stands, and substitution of natural forest species by more productive species) to which they, together with climate (droughts and frosts), award most differences in forest condition of forests in the French Vosges. Although of great importance, no information is available about forest management. As substitute the percentage crown coverage can be used in combination with stand age, indicating thinning intensity.

2.2.2 Water

Meteorological stress is considered to be very important with respect to forest condition. Innes (1993) mentioned that the most alarming and frequent observations of a decrease in forest condition in Central Europe coincided with the dry years 1982 and 1983. 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).

Potential and actual (evapo)transpiration (E_{Tp}, ET_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 (φ_p) are often used as tree specific parameters to indicate drought stress of forests (Federer, 1980; Schulze et al., 1989; Cienciala, 1994; Mather, 1994; Bréda et al., 1995; Fife & Nambiar, 1995). To calculate these parameters detailed characteristics on tree species, stand, soil and meteorology have to be known. In such research the required data are mostly gathered by intensive field measurements in one or some forest stands. This implies limited application possibilities at a regional or (inter-)national scale, at which usually only more rough data are available.

For some tree species a linear relation between transpiration and dry matter production exists (Van den Burg, 1987). The variation in the amount of transpiration by the forest canopy is strongly determined by the soil moisture supply (De Visser, 1993; Tiktak & Bouten, 1994; Bréda et al., 1995). Thus, parameters like soil moisture supply and precipitation deficit seem also usable as indicators for drought stress. Both parameters, however, do not take into account any vegetation effects on evaporation.

In a correlative study on forest condition and environmental factors, Mather (1994) used mean annual potential evapotranspiration, mean annual precipitation and mean monthly soil moisture deficits for March, June, July and August as parameters to predict water stress. Mean annual potential evapotranspiration and mean monthly soil moisture deficits were calculated with the Meteorological Office Rainfall and Evapotranspiration System (MORECS) (Thompson et al., 1981) for a 40 x 40 km^2 grid over Great Britain. MORECS uses the Penman-Monteith equation (Monteith, 1965) for evapotranspiration to estimate weekly and monthly evaporation and soil moisture deficit. These are calculated using daily weather data for deciduous and coniferous forest. Using these grid data, site specific data were derived by inverse quadratic distance weighting, after which a correction for soil type was made. In his study, Mather (1994) found that most of the changes in forest condition, as expressed by crown density, could be attributed to the effects of water stress as indicated by potential evapotranspiration and soil moisture deficit.

In theory drought stress of a vegetation will be better correlated with relative transpiration (E_{Ta}/E_{Tp}) than with relative evapotranspiration (ET_a/ET_p) because the latter includes also evaporation of intercepted precipitation and soil evaporation. Correction of evapotranspiration for interception and soil evaporation gives transpiration, being a more specific parameter indicating drought stress of forests.

Although relative transpiration seems an adequate parameter to indicate drought stress, especially because its detailed physical relationship, it is not clear whether it also gives the best results when used in a statistical explanatory model. For statistical modelling, there might be other, more simple indicators which give equal or better correlations with drought stress. Andersson & Harding, (1991) compared models of varying complexity to calculate transpiration and soil moisture deficit. They concluded that the most successful models used simple procedures for calculating required parameters. Therefore it seems useful to examine several drought indicating parameters with different levels of complexity. In descending order of complexity the drought indicating key parameters that can be computed are relative transpiration, precipitation deficit, and soil moisture supply in combination with precipitation amounts. In Section 3.6 it is explained how these key parameters can be derived from meteorological data.

Besides the key parameter itself, also the period for which it is calculated makes a difference. For instance, in a year with a severe drought period in the spring and a wet summer period, relative transpiration may indicate no or only a slight drought stress when it is calculated as an annual mean or a growing season mean, while the monthly means of the spring months show severe transpiration reduction. For our study monthly means for the growing period, which is about from 1 April to 1 October, seem to be adequate.

2.2.3 Frost

While high temperatures mainly affect transpiration rates, and through that depletion of available soil water, low temperatures can cause damage in cases of winterfrost and late night-frosts in spring (Hellinga, 1982).

In general, winterfrosts hardly causes detrimental effects on a large scale in The Netherlands (Hellinga, 1982). At very low temperatures and with prolonging 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 ($T_{min,jan}$) and during the winter period ($T_{min,win}$) can be used as key parameters 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 flow 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 ($T_{min,apr}$), May ($T_{min,may}$) and June ($T_{min,jun}$) can be used as key parameters for late night-frosts.

2.2.4 Nutrient

Parameters which can be used to evaluate the nutrient status of forests are the nutrient composition of the foliage and the soil (Lambert et al., 1983; Kaupenjohann et al., 1989). Key parameters in this context are the foliar N, P, K, Mg and Ca contents. The nutrient status of forests can be evaluated using criteria given by Van den Burg & Schaap (1995) and the Commission on Forest Fertilization (CAD-BLB, 1990). Also ratios of the nutrients compared to N supplies additional information about the state of nutrition (see Section 2.6).

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 prolonging high levels of N deposition stimulated growth up to levels where other nutrients, like P, become limiting (Mohren et al., 1986). Also growth dilution of Mg can take place, resulting in yellowing of older needles (Oren et al., 1988). However, discoloration can also be the result of absolute deficiencies (Landmann et al., 1995). Discoloration in fir and spruce seems to be most common on nutrient poor but productive sites (Landmann et al., 1995). In The Netherlands in most forests a nutritional imbalance is evident (Mohren et al., 1986;

Van den Burg & Kiewiet, 1989; Hendriks et al., 1994, Van den Burg & Olsthoorn, 1994).

2.2.5 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 pest 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 practise 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).

As key parameters in fact only the percentage of insect and fungal damage can be selected, because these are the only two available for the monitoring plots. These parameters are somewhat unspecific, because they do not supply information on the insect species or fungus causing damage. This is of importance, because different species may respond different to stress. Another important drawback is that at the time of the recording period the major part of the insects is disappeared (caterpillars have become butterflies) and regrowth of shoots often has occurred. This can seriously hamper a proper estimation of the foliar loss.

Besides key parameter, pests and diseases can also be considered to be an effect parameter in cases when infection or attacks take place in forests of which the condition is already weakened because of other stress factors such as drought.

2.2.6 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 Eerden, 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, 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 Sudetes 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 Fichtelgebirge, 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 soil acidification, eutrophication and an increase in susceptibility to plagues and diseases (Lekkerkerk et al., 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). 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. (1994) 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
It seems that at high altitudes forest decline can be related to ozone and acidic mist (Prinz et al., 1987; Ashmore et al., 1988). 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 did not accounted for the episodic course. 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.

Many other pollutants may reach forests from nearby emission sources. Some of these, such as fluoride, may cause extensive damage, even in very low concentrations. The impact of other pollutants on forest condition are still uncertain.

Summarizing, most relevant key parameters for air pollution stress are the total deposition of S and N, related to indirect soil mediated effects and the exposure to O_3. Other, less relevant parameters, are the ambient concentrations of SO_x, NO_x and NH_3.

2.2.7 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. 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 to aluminium ratio (BC/Al).

Because in the field harmful effects of a high Al concentration in the soil moisture on forest condition is not demonstrated, it does not seem a very useful parameter for our purpose. There is, however, also some doubt about the BC/Al ratio, this parameter can be included in an analysis because it accounts for neutralizing effects of base cations.

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 mineralization of humus can be hampered and tree roots can be 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) found a significant increase of phytochelatines in red spruce, 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.

De Vries & Leeters (in prep.) showed that in the forest floor of 150 forest stands the contents of Pb, Cd and Ni are raised, while the contents of Cu and Zn were sometimes low. Hence heavy metal contents may cause effects (direct or indirect) on forest condition can therefore be selected as key parameters.

2.3 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 indeed exists 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. Table 2 shows the interactions between natural and anthropogenic stress factors based on a review of cause-effect relationships in forest decline (ICP-forest, 1991)

Table 2 Interactions between natural and anthropogenic stress factors (after ICP-forest, 1991)

Natural stress factor	Anthropogenic stress factor					
	air conc.		deposition		soil	
	SO_2	O_3	S	N	BC/Al	heavy metals
Water stress	+	+	+	+	+	+
Frost stress	+	+	+	+	0	0
Nutrient stress	0	0	+/-	+/-	+	+
Pests	0/-	+	0	+	0/+	0/+
Diseases	0	0	0	+	0/+	0/+

+ : worsening of the stress factor, - : reduction of the stress factor, 0 : neutral to the stress factor

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). Consequently, it is relevant to focus on the interactions between N deposition and natural stress factors, as indicated in Table 2.

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 droughts. 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.

By affecting the nutritional status of trees, especially the N content, N-deposition also plays a role in changing the sensitivity to frost (Aronsson, 1980; Skre, 1988; Timmis, 1974; Van den Burg & Kiewiet, 1989). Through fumigation experiments, Dueck et al. (1991) found that high ambient concentrations of SO_x and NH_x increased frost sensitivity of Scots pine at temperatures of -10 °C.

One of the secondary effects of nitrogen deposition is the occurrence of relative shortage of especially phosphorus, magnesium and potassium (Mohren et al., 1988; 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 increases. On nutrient limited sites, as most Netherlands forests sites are, higher nutrient requirements are not always met by the nutrient availability, so that a (relative) shortage occur.

The infection of the mould *Sphaeropsis sapinea* proved to be related with high nitrogen contents in the needles (Boxman & Van Dijk, 1988, 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 2.4% than at 2.2%. For Corsican pine, Van den Burg & Kiewiet (1989) concluded that affection of *Sphaeropsis sapinea* is low when needle N-content is lower than 1.5%, affection increases when the needle N-content is in between 1.6-1.8% and affection is very strong at needle N-contents above 1.9%. 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 exists 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 flow, by which frost stress becomes a raised risk and transpiration might change (Crammer, 1996). The period of time available for this research is to short to assimilate the effects of climate change.

2.4 Temporal dynamics in stress factors

When deriving a good statistical model, it is essential to know the required temporal resolution of recording or calculation of the key 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). A summary of the required temporal resolution of the various key parameters is given in Table 3.

Table 3 Key parameters with their temporal recording or calculation resolution and the relation with the effect parameters defoliation and discoloration (after Erisman et al., 1996 and Table 7)

Key parameters	Effect parameter		Temporal resolution
	Defoliation	Discoloration	
Tree species	+	-	once
Provenance	+	+	once
Stand age	+	-	once
Stand height	+	+	annually
Canopy closure	+	+	annually
Distance forest edge	+	+	once
Stand history	?	?	once
Forest management	+	?	once
Soil type	+	+	once
Groundwater table	+	+	once
Relative transpiration	+	+	monthly/annually/seasonly
Precipitation deficit	+	+	monthly/annually/seasonly
Soil moisture supply	+	+	monthly/annually/seasonly
T*average minimum winter*	-	+	seasonly
T*average minimum January*	-	+	monthly
T *minimum April*	+	+	daily
T *minimum May*	+	+	daily
T *minimum May*	+	+	daily
Foliar N content	+	+	annually
Foliar P content	+	+	annually
Foliar K content	-	+	annually
Foliar Mg content	+	+	annually
Foliar P/N ratio	+	-	annually
Foliar K/N ratio	-	+	annually
Foliar Mg/N ratio	-	+	annually
Pests	+	-	annually
Diseases	+	+	annually
SO_x concentration	+	+	daily/annually
NH_x concentration	+	+	daily/annually
O_3 concentration	+	+	daily/annually
S deposition	-	-	annually
N deposition	-	-	annually
BC/Al	+	+	annually/monthly
Pb content humus layer	-	+	annually
Cd content humus layer	-	+	annually
Cu content humus layer	-	+	annually
Zn content humus layer	-	+	annually

+ : effect , - : no 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 calculated (age) or fluctuate between known margins (groundwater table).

The water stress factors are of interest at two different temporal resolutions. A reduced relative transpiration will only show effects on defoliation and discoloration after some period of time. It is assumed that effects will occur after one or several months with transpiration reduction. In such cases also effects may be expected for when the relative transpiration is calculated for the period of a year or for the growing season. The precise effect is supposed to work out different for different tree species. Because of the drought tolerance of Corsican pine, for instance, the effect of transpiration reduction will probably be better correlated with a significant annual transpiration reduction than with a significant transpiration reduction for only one month.

Effects of drought can still affect forest condition after some years. Landmann (1993) and Saxe (1993) have stressed the importance of such '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). The concept of such an 'after-effect' is worked out in Section 4.3.

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.

The effects of pests can have direct effects on defoliation when for example caterpillars have partly swallowed the leaf biomass. It is sufficient to know whether pests or diseases have occurred during the growing season.

At present still little is known about effects of the dynamics in the Al concentration of the soil moisture on forest condition. High Al concentrations directly can affect the rootsystem, 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.

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.

2.5 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 is possible when effects of stress factors are similar for all tree species. Literature, however, indicates that the different tree species, monitored in the forest condition programme, do have various sensitivities for the different stress factors. There are stress factors which depend on tree species (e.g. meteorological stress and BC/Al ratio) and factors which seem to be independent of tree species such as nutrient stress (ratios), and heavy metal contents (Table 4).

Table 4 Sensitivity of tree species for several stress factors (after Brechtel et al., 1991)

Tree species	Stress factor						
	water	frost	nutrients	pests and diseases	ozone	BC/Al	heavy metals
Scots pine	+/-	-	+	+	+	+	?
Corsican pine	-	++	+	+	?	+	?
Douglas-fir	+/-	+	+	-	?	-	?
Norway spruce	+	+	+	-	?	+	?
Japanese larch	+	+	+	-	?	++	?
pedunculate oak	+	+	+	+	?	+/-	?
beech	++	-	+	?	+	+/-	?

sensitivity - : little, +/- : moderate, + : high, ++ : very high, ? : unknown

2.6 Critical values for key parameters

In developing a statistical model it is relevant to know whether threshold values or critical values do exist for the various key parameters involved. With reference to the previous section, key parameters can be divided into a tree species specific and a tree species unspecific group of key parameters. For the group of tree species unspecific key parameters an average value can be given for all tree species (Table 5), while a specific value can be given for the group of tree species specific key parameters (Table 6). A discussion of the values used is given in the following.

Growth, vitality and occurrence of visible nutrient deficiency symptoms depend in the first place on foliar contents of the separate nutrients. The nutrients, however, also affect the working of each other (Mohren et al., 1986). This mutual working can be described with nutrient ratios, especially in proportion to nitrogen (Mohren et al., 1986; CAD-BLB, 1990; Van den Burg & Schaap, 1995). In Table 5, critical ratios are given for P, K and Mg. As far as known, the Ca/N ratio does not have any physiological meaning and therefore is not of interest. The Cu/N ratio does only give information for Douglas-fir and Japanese larch, and even then only for cases of nitrogen surpluses. Because of these limitations it is not taken into account in this study.

Table 5 Critical values of tree species unspecific key parameters

Stress factor	Ecosystem component	Key parameter	Unit	Critical value
Nutrients	foliage[1]	P/N	$g\ g^{-1}$	5
	foliage[1]	K/N	$g\ g^{-1}$	25
	foliage[1]	Mg/N	$g\ g^{-1}$	5
	soil solution[2]	NH_4/K	$mol\ mol^{-1}$	5
	soil solution[2]	NH_4/Mg	$mol\ mol^{-1}$	5
Air pollutants	air[3]	SO_x conc.	$\mu g\ m^{-3}\ a^{-1}$	20
	air[3]	NO_x conc.	$\mu g\ m^{-3}\ a^{-1}$	30
	air[3]	NH_x conc.	$\mu g\ m^{-3}\ a^{-1}$	8
	air[3]	AOT40	ppm h	10
Toxic elements	humus layer[4]	Pb content	$mg\ kg^{-1}$	150
	humus layer[4]	Cd content	$mg\ kg^{-1}$	3.5
	humus layer[4]	Cu content	$mg\ kg^{-1}$	20
	humus layer[4]	Zn content	$mg\ kg^{-1}$	300

1) CAD-BLB, 1990
2) Boxman & Van Dijk, 1988
3) Heij & Schneider, 1995
4) Tyler, 1989

In the soil solution the ratios NH_4/K and NH_4/Mg indicate a hampered nutrient uptake when they exceed a threshold of 5 mol mol^{-1} above which yellowing of the foliage can occur (Roelofs et al., 1985; Boxman & Roelofs, 1988).

Based on literature, field and laboratory experiments, Van der Eerden et al. (1995) and Heij & Schneider (1995) give threshold values for SO_x, NO_x, NH_3 and O_3. These values are given in Table 5. For SO_x the threshold value is put on 20 $\mu g\ m^{-3}\ a^{-1}$ above which growth inhibition can occur, principally by indirect effects such as Mg deficiency or root damage. The threshold for NO_x is based on the negative effects of high NO_x concentrations on plant physiological and biochemical processes. For NH_x, the threshold is based on the disturbance of several ecophysiological processes such as metabolic processes of the photosynthesis process, partitioning processes by which different root/sprout ratios occur and change of the transpiration efficiency. From studies in the USA, it is known that some threshold values for O_3 may exist at which O_3 may cause damage to trees (Miller et al., 1989). The UN/ECE Convention on Long-Range Transport of Air Pollution at Egham (UK) and Bern (Switzerland) have resulted in a definition of critical levels of ozone. For forest trees the critical level was defined as an AOT40 of 10 000 ppb h in the months from April to September, integrated 24 hours a day (Kirchner et al., 1995). The mean annual AOT40 in The Netherlands varies between 20 000 and 70 000 ppb h (Erisman & Bleeker, 1995).

The thresholds for heavy metal contents in the humus layer are based on toxicological effects on micro-flora and -fauna (Tyler, 1989). Effect studies of heavy metal contents on tree species mainly comprises effects on roots, which are the plant parts that are directly exposed to the metals. It is not possible to present threshold values for trees because many experiments on the effects of heavy metals are carried out on seedling grown on nutrient solutions or unstratified mineral soils. However, they are known to be sensitive for heavy metals (Faber, 1995).

Tree species specific threshold values can be given for foliar nutrient contents and the BC/Al ratio. For other stress factors to little information was found to give such values.

For N the threshold value is given above which the content is assumed to be too high by which plant metabolic processes can be hampered (Table 6). The upper limit is given because of the very high N deposition in large areas in The Netherlands. Because these high N inputs, in many areas formerly N deficiencies are strongly diminished or vanished.

For P, K and Mg values are given below which a deficiency of these nutrients is likely (Table 6). For these nutrients deficiencies are more common than surpluses (Hendriks et al., 1994).

Table 6 Critical values of tree species specific key parameters

Tree species	Foliar nutrient content[1] (%)				BC/AL ratio[4] (mol mol^{-1})
	N[2]	P[3]	K[3]	Mg[3]	
Scots pine	1.8	0.14	0.5	0.07	1.2
Corsican pine	1.8	0.13	0.5	0.06	1.2
Douglas fir	1.8	0.14	0.6	0.07	0.3
Norway spruce	1.7	0.14	0.6	0.07	1.2
Japanese larch	2.5	0.20	0.7	0.1	2.0
pedunculate oak	2.8	0.14	0.6	0.16	0.6
beech	2.8	0.15	0.6	0.15	0.6

1) source: CAD-BLB, 1990; Van den Burg & Schaap, 1995; 2) upper limit; 3) lower limit
4) source: Sverdrup & Warfvinge, 1993

Sverdrup & Warfvinge (1993) derived a threshold for the BC/Al ratio from literature and field experiments for many tree species. As a threshold they used 20% growth reduction of biomass, root length or root growth. Critical BC to Al ratios are given in Table 6. For Corsican pine no critical value was found in literature. Therefore the same value as for Scots pine is used.

2.7 Effect parameters for forest condition

Forest condition can be studied on different scales, namely on the ecosystem, stand and tree level. This study is focused on the stand level because the available forest condition data of the monitoring networks, ie. 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.

In international respect, defoliation (also termed needle/leaf loss) and discoloration are the two most widespread indices on forest condition (Innes, 1993). In The Netherlands monitoring programme, defoliation, foliage discoloration and crown discoloration are the only effect parameters which are systematically recorded since 1984. By means of key tables an overall value for tree condition is derived from these parameters. Because it are the only systematically recorded parameters, they are also the most designated parameters in assessing the relationship with stress factors. In almost all other European countries these two indices are also 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. It is, however, not clear whether defoliation and discoloration are the best indices on forest condition, even though research do show relations between these two indices and unfavourable circumstances (e.g. Hendriks et al., 1994; Van den Burg & Olsthoorn, 1994)

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 fungal pathogens. 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. Innes (1993) pleads in favour of the use of a number of indices, which will give more insight in the dynamic aspects of forest condition.

Table 7 shows differences in the adequacy of effect parameters indicating forest condition in relation to the considered stress factors and related key parameters. Growth seems to be the effect parameter which is correlated to most stress factors. However, no systematic information for the monitoring plots is available on growth.

Table 7 Relation between different effect parameters indicating forest condition and stress factors

Stress factor	Key parameter	Effect parameters				
		defoliation	discolouration	leaf biomass / LAI	growth / DBH	root biomass / root length
Stand	species	+ (9,10)	+ (4)	+	+ (37,38)	+ (22,29)
	provenance	+ (4,36,39)	?	+ (4)	+ (4,16)	?
	age	+ (9,11)	0 (9)	+	+ (38)	+ (22)
	density	+ (10)	?	?	?	?
	height/dominance	+ (15)	0	+		?
Site	soil type	+ (12)	?	+ (4)	+ (13,37,38)	+ (29,31)
	groundwater table	0	+	0	+ (37)	+ (29)
Meteo	E_{Ta}:E_{Tp}	+ (1,2,30)	0	+	+	+
	Tmin,winter	+ (14)	+	+	+	0
	Tmin,spring	+ (4,14)	0	+	?	0
	Tgrow.season	+ (3)	?	?	+ (13,30)	?
Nutrients	N,P/N etc.	+ (6,35)	+ (4,7)	+	+	+ (31,32)
Pests/ Diseases		+ (4)	+ (4)	+	+	+
Air pollution	SO_x	0 (17)	0 (17)	0	+ (20,33)	+ (20)
	NO_x	0	0	+	+ (28)	+
	NH_x	0	+	+/- (33/26)	+ (33)	+ (26)
	O_3	+ (5)	+ (8,19)	+ (20,34)	+ (20,27)	+ (20,23)
Toxic elements	BC/Al	?	?	?	?	+ (18,25)
	heavy metals	?	?	?	+ (21)	+ (24)

+ = effect of key parameter on effect parameter; 0 = no effect; +/- = both effect and no effect can occur; ? = effect unknown

Given indices (superscript) refer to the references below. In the cases no index is given, the expert group on vitality (Section 1.3) has awarded the most likely effect of the key parameters on the effect parameters.

1 Gruber, 1990
2 Orlov, 1980
3 Kouki & Hakkanen, 1992
4 Innes, 1993
5 Miller & Van Doren, 1981
6 Escudero et al., 1992
7 Lange et al., 1989
8 Ewell et al., 1990
9 Hendriks et al., 1994
10 Innes & Boswell, 1990
11 Innes & Boswell, 1988
12 Neumann, 1989
13 Worrell & Malcolm, 1990
14 Hellinga, 1982
15 Innes & Neumann, 1991
16 Kinloch et al., 1986
17 Lange et al., 1989
18 Schneider et al., 1989
19 Manes et al., 1988
20 Chappelka et al., 1985
21 Breckle & Kahle, 1992
22 Hendriks & Bianchi, 1995
23 Andersen & Hogset, 1991
24 Nuorteva, 1990
25 Sverdrup & Warfvinge, 1993
26 Van der Eerden et al., 1993
27 Lefohn, 1992
28 Wellburn, 1990
29 Van de Burg, 1996
30 Erisman et al., 1996
31 Glinsky & Lipiec, 1990
32 Keyes & Grier, 1981
33 Heij & Schneider, 1995
34 Dueck et al., 1994
35 Van den Burg & Olsthoorn, 1994
36 Innes, 1993
37 Waenink & Van Lynden, 1988
38 Mayer, 1984
39 Oleksyn, 1989

3 Availability and quality of data

3.1 Forest Health Monitoring Networks and available data

In The Netherlands four major monitoring networks on forest health exist, each having their own specific data set and recording period (Table 8). This research is focused on the Old and New Forest Health Monitoring Network (with 3000 and 200 plots respectively). For the completeness also other sets (pre-New and Level 1 and 2) are given.

Table 8 Availability of site specific recorded data of four monitoring networks in The Netherlands

monitoring network	Old	New	Pre-New	Level 1 and 2
monitoring period	1984-1994	1995-present	1990	1987-present
number of monitoring plots	3000	200	150	14
Key parameters				
Defoliation	+	+	+	+
Discoloration	+	+	+	+
Crown transparency	-	+	-	-
Dead branches	-	+	-	-
Tree species	+	+	+	+
Provenance	-	-	-	-
Stand density	+	+	+	+
Stand age	+	+	+	+
Stand height	+	+	+	+
Average DBH	-	-	-	+
Growth	-	-	-	+
Forest edge[1)]	-	-	+	-
Site history	+	+	+	+
Forest management	-	-	-	-
Canopy coverage	-	+	-	-
Ground vegetation[2)]	-	+	+	-
Altitude	-	-	-	+
Soil type	-	+	+	+
Soil profile description	-	+	+	+
Water table depth	-	+	+	+
Meteorological conditions[3)]	*	*	*	*
Pests	+	+	+	+
Diseases	+	+	+	+
Foliar composition[4)]	-	+	+	+
Aerosol concentrations[5)]	*	*	*	*
Deposition fluxes[6)]	*	*	*	+
Soil nutrient content[7)]	-	+	+	+
Soil solution conc.[8)]	-	+	+	+
Heavy metal content[9)]	-	+	+	+

+ = available (field estimations or measurements), - = not available, * = can be estimated using models
1) Distance to, exposition of and land use at nearest forest edge
2) Vegetation type and soil coverage of vegetation
3) Temperature, precipitation, global radiation, wind velocity, relative transpiration
4) Foliar contents of N, P, K, Ca, Mg, Al, Fe, Mn, Zn, Cu ($g\ 100\ g^{-1}$)
5) Air concentrations of SO_4, NH_3, O_3 ($mol\ ha^{-1}\ a^{-1}$)
6) deposition fluxes of SO_x, NH_x, NO_y ($\mu g\ m^{-3}\ a^{-1}$)
7) forest floor: N, P, K, Ca, Mg, Al, Fe and Mn ($mol\ m^{-3}$); mineral soil: total N and P ($g\ kg^{-1}$) exchangeable NO_3, NH_4, PO_4, SO_4, K, Ca, Mg, Al, Fe, Mn, Na, Cl, Si ($mol\ m^{-3}$) and pH-KCl
8) soil solution concentrations: NH_4, NO_3, PO_4, K, Ca, Mg, Al, Fe, Mn, Na, Cl, SO_4 and Si ($mol\ l^{-1}$)
9) heavy metal content in the forest floor: Pb, Cd, Zn, Cu ($mg\ kg^{-1}$)

Old Forest Health Monitoring Network

The old monitoring network contains 3000 sample plots, and the first network that was set up for monitoring forest condition in The Netherlands. In these plots defoliation, discoloration and some stand characteristics were recorded in the period 1984 to 1994 (Table 8). The Old Forest Health Monitoring Network will further be referred to as the 'old monitoring network'. In the old monitoring network 11 (groups of) tree species were monitored of which the stand numbers differed per year (Table 9).

Table 9 Number of sample plots of the old and the new forest health monitoring network in The Netherlands

Tree species	Old network		New network
	1984-1993	1994	1995-present
Scots pine	1180	510	42
Corsican pine	149	76	20
Douglas-fir	130	65	27
Norway spruce	107	63	20
Japanese larch	178	95	13
Other coniferous species	ca. 30	15	-
Pedunculate oak	437	219	51
Beech	99	54	27
Poplar	ca. 112	56	-
Other deciduous species	ca. 192	146	-
Total	ca. 2614	1299	200

New Forest Health Monitoring Network

From 1995 to present forest condition in The Netherlands is monitored in the New Forest Health Monitoring Network, containing 200 sample plots, which were also part of the old monitoring network. Besides defoliation, discoloration and stand characteristics also the chemical composition of the soil solution, mineral soil, humus layer and the foliage are recorded (Table 8). The New Forest Health Monitoring Network will further be referred to as the 'new monitoring network'. In the new monitoring network seven tree species are monitored. Each year the same number of stands are recorded per tree species (Table 9), and within these stands the same trees (25) are recorded.

Pre-New Forest Health Monitoring Network

In 1990 a survey on the effect of acid deposition on 150 forest stands in The Netherlands was carried out (Leeters et al., 1994; Jansen & De Vries, 1994; Hendriks et al., 1994). In these stands many characteristics were recorded (Table 8). Site specific deposition and air concentrations of air pollutants were derived from models in which the recorded site characteristics were used. 124 of these 150 forest stands, are also part of the new monitoring network.

EC and UN-ECE monitoring network on forest health (Level 1 and 2 plots)

The set of 14 forest stands are part of the monitoring network on forest condition of the European Commission and the Economic Commission for Europe of the United Nations (UN-ECE). This international network knows two levels of intensity at which stand characteristics are recorded, the so called Level 1 (extensive monitoring plots) and Level 2 (intensive monitoring plots). The Level 1 and Level 2 networks are geographically two (partly) different networks, but in The Netherlands they completely overlap. Sample plots are positioned on base of a 16 x 16 km^2 gridnet. Since 1987 annual crown assessments have been carried out. In the Level 2 plots a survey on the forest soil condition and foliar composition has been carried out in the periods 1991-1995 and 1991-1996 respectively.

The availability and quality of the data for the old and the new monitoring network are described in the following sections. For missing parameters the possibilities to derive estimates are discussed.

3.2 Vitality data

The old monitoring network (1984-1994)

The sample plots of the old Forest Health Monitoring Network were selected systematically by overlay of a 1 x 1 km^2 gridnet with a forest distribution map. Intersections of this gridnet were selected when it was positioned in forest and when the forest has an size of at least 0,5 ha, crown projection was at least 20%, there were at least 25 dominant or co-dominant trees, and it was not exploited as coppice (Nas & Smits, 1989). Through this overlay and criteria, about 3000 sample points were selected. The total set of 3000 stands was divided in four equal sized subsets indicated by the capitals A to D. Recording of these subsets was carried out by partial replacement by which it was aimed that it was less time-consuming and it would be still possible to describe the annual situation of the forest condition and the change compared to the previous year. So in the first year subset A and B were recorded, in the second year subsets B and C, in the third year subsets C and D and in the fourth year subsets D and A, whereafter it start from the beginning. In the years 1984 and 1988 all 3000 sample plots were recorded.

In the period 1984 to 1988 the recordings were executed by follow-workers of The Netherlands Forest Service. In the first two years the recordings were executed in the region of labour of the fellow-workers. After the suspicion of influence of the recorders, the fellow-workers were pooled and a circulation scheme was established. In the period 1989-1991 and 1992-1994 by the engineering companies Heidemij and the combination Oranjewoud/Eelerwoude respectively.

In the old monitoring network the forest condition in The Netherlands was monitored by recording the parameters defoliation and discoloration of 25 individual trees at each sample plot. In coniferous tree species, defoliation was determined by recording the needle retention, i.e. number of years needles are retained. For Scots pine the standard number of years for needle retention is 1.5 years for trees younger then 40 years and 2 years for trees older then 40 years. For Corsican pine, Norway spruce and Douglas-fir needle retention is 4, 6 and 5 years respectively. After recording, defoliation is calculated out of the recorded needle retention and the standard needle retention, and classified in classes of defoliation. In deciduous tree species defoliation is determined as the percentage of buds not developed to leafs, which is also the percentage of defoliation.

In the period 1984-1991 the percentage was estimated in four classes, which were the same for deciduous and coniferous species. These classes are 1: 0-10%, 2: 10-25%, 3: 25-60% and 4: 60-100% defoliation. From 1992 to 1994 a continuous scale of 5% classes was used.

Discoloration is determined by combination of the percentage crown discoloration and the percentage foliage discoloration, which both were estimated in the same percentage classes as used for defoliation, e.g. 4 classes for the period 1984 to 1991 and 5% classes in the period 1992 to 1994.

Next, the vitality class of the individual trees is calculated by combining the classes for discoloration and defoliation, following an established key table. Finally the vitality of a forest stand is calculated as the mean of the individual vitality classes of the recorded 25 trees. In the annual reports on the condition of The Netherlands forest, vitality is presented in the very broad qualitative classes good health, satisfactory health, poor health and very poor health (e.g. Hilgen, 1994). More detailed information on the recording and calculation of the forest condition is given in Nas & Smits (1989).

Estimated crown parameters are entered in a computer directly in the field. During the annual survey, each week data from the field computers are transported to a central data base and roughly screened on irregularities. From the total number of plots a sample of about 10% is taken and screened in more detail on the reliability of the recorded data. In cases of serious doubts, sample plots were recorded again.

The data from the inventories are available at IKC-N, and can be used for this project. They are stored in a ascii database which contains information on tree species, tree age, year of inventory, number of sample trees per plot and a score for the defoliation and discoloration per tree in 5% classes.

The new monitoring network (1995 to present)

In 1995 the number of stands in which forest condition is recorded was reduced from 3000 to 200 stands. The 200 sample plots were selected out of the set of 3000 plots from the old monitoring network. The selection was mainly done on basis of the fractional distribution of tree species in The Netherlands forest and regional distribution of the plots throughout The Netherlands. Although the number of stands decreased, the information gathered per stand seriously increased (Table 8). Besides defoliation and discoloration (in 5% classes) also crown transparency, number of dead branches, the chemical composition of the foliage, humus layer, mineral soil and soil solution are recorded. In 1996 the vegetation composition will be recorded and in the future also mycorrhiza will be investigated. The intention of the new monitoring network is no longer monitoring only, but also gaining insight on probable causes of changes in forest vitality. The inventories of the new monitoring network are carried out following the same procedure as for the old monitoring network in the period from 1992 to 1994.

3.3 Foliage data

The old monitoring network (1984-1994)
For the 3000 stands of the old monitoring network no systematic collection of data on the chemical composition of the foliage was carried out. In 1990 in 150 stands of the monitoring network the chemical composition of the foliage was analyzed as part of a study on the relationships between the chemical composition of the foliage, mineral soil, soil solution, deposition, stand and vitality characteristics (De Vries & Leeters, in prep.; De Vries & Jansen, 1994; Hendriks et al., 1994; Leeters et al., 1994).

The new monitoring network (1995 to present)
In 1995 for all 200 stands of the monitoring network on forest condition the chemical composition of the foliage was analyzed conform fixed directives (CAD-BLB, 1990; Van den Burg & Schaap, 1995). For deciduous tree species sampling took place during August and September, and for coniferous species during October to December 1995. Chemical composition was analyzed by IBN-DLO. Results were stored in a computer data base by the DLO-Institute for Forest and Nature Research. Because foliar sampling and analysis are both done by one team and laboratory, data may be considered as very consistent. 124 of the 200 stands made also part of the 150 forest stands. Thus for these stands also data of 1990 is available.

3.4 Soil data

The old monitoring network (1984-1994)
For the 3000 sample points of the national monitoring network, site-specific soil information is not available. A possibility to derive soil information is to create a digitized map with the 3000 sample points and to overlay the map with sample points with the Soil Map of The Netherlands on a 1 : 50 000 scale. This gives information on soil type and groundwater table, on the basis of which schematic soil profiles and soil characteristics can be assigned (De Vries, 1993) from which soil intermediate data, such as soil water availability, can be derived.

For the study on the 150 forest stands, besides the foliage also the soil was surveyed. Besides field information on soil type, soil texture, soil organic matter, and groundwater table, also the chemical composition of the humus layer, mineral soil and soil solution was analyzed (De Vries & Leeters, in prep.). Possibly, relations between site characteristics and atmospheric deposition levels on the one hand and the chemical status of the soil on the other hand can be derived from this study and extrapolated to the set of 3000 points (cf. Leeters et al.). Also the information gathered on the set of 200 sample points can be of interest in this case. Soil information gathered this way will be of a different quality than the vitality data, which are gathered through field observations.

The new monitoring network; period 1995 to present

For the 200 sample points recorded in 1995, detailed soil information was gathered on each site. The data give information on composition and texture of the soil, rooting depth, groundwater depth and organic matter. From these data supplementary data, such as soil water supply or soil suitability for tree species, can be derived. Also detailed chemical samples were taken from the humus layer, mineral topsoil and soil solution. Data are available at SC-DLO (Leeters & De Vries, in prep.).

3.5 Estimation of air pollution stress

Deposition data cannot directly be obtained from measurements but can be 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 can be used. The DEADM model has been described extensively in Erisman (1992, 1993, 1995) as well as in Asman & Van Jaarsveld (1992) and the OPS model in Van Jaarsveld (1990; 1995). Site-specific atmospheric deposition estimates can be derived from DEADM calculations using interpolated concentration measurements, except for ammonia, where modelled OPS concentrations can be used. Ozone exposure estimates can be 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 AOT40 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 AOT40 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. As these results are not representative for higher vegetation, calculated AOT40 values are corrected using the actual canopy height at the monitoring sites. For further details on the methods used the reader is referred to Annex 1.

3.6 Estimation of water stress

Relevant water stress parameters are relative transpiration, precipitation deficit and soil moisture supply (Section 2.2.2). Data of these stress parameters are not directly available at the monitoring sites but can be generated by simulation models as discussed in the following sections.

3.6.1 Calculation of the relative transpiration

Calculation of relative transpiration

A procedure to calculate the relative transpiration (RE_T) is illustrated in Fig. 2. The first step in the calculation is that of the potential evapotranspiration (ET_p). Secondly, evaporation of precipitation intercepted by the crowns (E_I) can be calculated using the model of Gash et al. (1995). As a third step soil evaporation (E_S) can be calculated following Van den Broek & Kabat (1996). Next, potential transpiration (E_{Tp}) can be

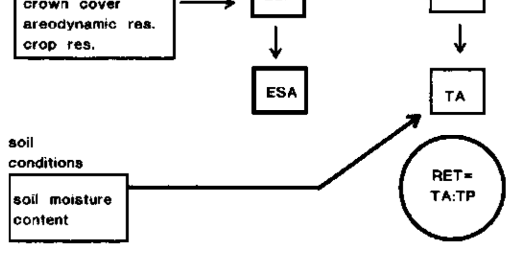

Fig. 2 Procedure to calculate the relative transpiration

calculated by subtraction of E_I and potential soil evaporation (E_{Sp}) from ET_p. Then, actual transpiration (E_{Ta}) can be calculated as a function of E_{Tp} and the soil moisture content (Θ). Finally, RE_T can be calculated by dividing E_{Ta} by E_{Tp}. More details on the calculation of the RE_T are given in Annex 2.

The relative transpiration (RE_T) is calculated for the growing season. Since there is no large difference in the length of the growing season for different regions in The Netherlands, a fixed period can be selected to represent the growing season. For instance April 1th to September 30th, which is a period of 180 days. Both E_{Ta} and E_{Tp} are calculated as the sum of the daily values of their fluxes over the growing season.

Calculation of the evapotranspiration

ET_p can be calculated with a several equations, i.e. Penman (1948), Penman-Monteith (Monteith, 1965), Priestly-Taylor (Priestley & Taylor, 1972) and Makkink (1957). Only the equations of Penman-Monteith and Makkink account for the influence of vegetation on the evapotranspiration regime. The Penman-Monteith equation is the only process-based model that accounts for the influence of vegetation on the evaporation regime (Dunn & Mackay, 1995). This model is often used in combination with interception models such as the models of Rutter et al. (1975) and Gash et al. (1995). The major disadvantage of the Penman-Monteith equation seems to be the need for many meteorological and tree specific data. If these data requirements can be fulfilled, the Penman-Monteith equation seems a very useful choice.

Calculation of the water balance

The daily Θ, which is needed to calculate E_T, can only be calculated when a water balance is kept. The water balance of a forest can be calculated as:

$$\Theta_{i+1} = \Theta_i + P_i - Q_{Si} - E_{Ti} - E_{Ii} - E_{Si} - Q_{Di} \qquad (1)$$

in which:

Θ_i = soil moisture content (mm)
P_i = precipitation (mm)
Q_{Si} = Surface run-off (mm)
E_{Ti} = actual transpiration (mm)
E_{Ii} = interception (mm)
E_{Si} = soil evaporation (mm)
Q_{Di} = drainage (mm)
i = daynumber (-)

Equation 1 is the basis of many hydrological simulation models (e.g. SWATRE, Belmans et al., 1983; SWACROP, Kabat et al., 1992; MUST, De Laat, 1985; SWIF, Tiktak & Bouten, 1992; SOIL, Jansson, 1991). Θ is used as an intermediate pool between storage in the soil and uptake by the trees. In the simulation models mentioned above, soil water fluxes are calculated depending on many soil physical, meteorological and crop specific factors. Because the lack of such site-specific data on the one hand and inaccuracies for the estimates of the other missing parameters on the other hand, the application of such detailed models is not very useful. A simple 'bucket model' (Boughton, 1984; Kalma et al., 1995) seems to be appropriate. With such models, in which Θ at field

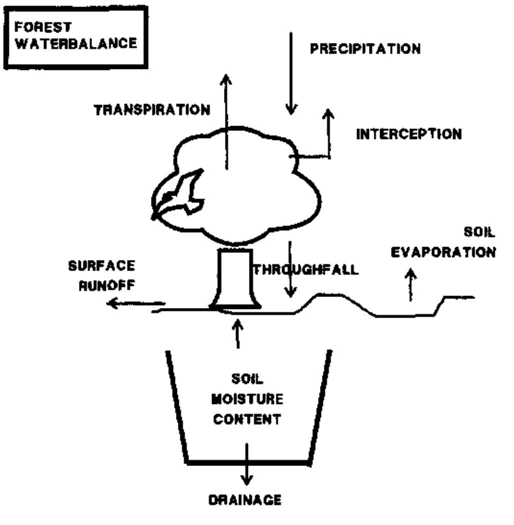

Fig. 3 The bucket model representing the forest water balance

capacity (Θ_{fc}) can be used to define a fixed bucket size, soil moisture contents, run-off, drainage, transpiration, interception and soil evaporation can be estimated (Fig. 3). In Annex 2 a procedure is given by which the separate evaporation terms of Equation 1 can be calculated.

Soil moisture content and drainage
The soils of the plots of the old monitoring network are not described in detail. Soil type can be derived from the Soil Map of The Netherlands, scale 1 : 50 000. Based on expert judgement and on the explanation of the soil map a rough estimate of Θ can be given.

Of the soils of the new monitoring network detailed profile descriptions are made (Leeters & de Vries, in prep.). Based on these profile descriptions Hendriks (unpublished) estimated Θ_{fc} with use of the model KLASSE (Hendriks, in prep.). This Θ_{fc} can be used to set the bucket size, assuming that when the bucket is filled, the surplus of water will percolate to deeper soil layers and can be considered as the precipitation excess. In the bucket model this excess is indicated by the drainage flux Q_D (Fig. 3).

Surface run-off
Surface run-off depends on slope, vegetation and soil texture classes (Driessen, 1986). In forests, however, run-off is often limited because of the presence of a litter layer and interception of precipitation through the crowns and ground vegetation, which causes a lessened precipitation intensity at the forest floor. Therefore we neglect run-off by assuming $Q_s = 0$.

Rates of potential transpiration, interception and soil evaporation
Potential transpiration (E_{Tp}) can be calculated according Equation 2:

$$E_{Tp} = ET_p - E_I - E_{Sp} \quad (2)$$

where:

E_I = evaporation of intercepted precipitation

E_{Sp} = potential soil evaporation

E_I can be calculated with models (e.g. Gash et al., 1995; Rutter et al., 1975), or as a fraction of gross precipitation (e.g. Calder, 1977). Dolman & Moors (1994) however, showed that the fraction of E_I as percentage of gross precipitation differs considerable, depending on tree species, storm intensity, and storm duration, and an error of even more than 100% may occur (Moors et al., 1996). Moors et al. (1996) stated that E_I can be estimated satisfactory only for time periods of one day or shorter, and only process orientated models are used. The model of Gash et al. (1995) fulfils these demands and can therefore be used to calculate E_I. More detail is given in Annex 2.

A commonly used equation to calculate soil evaporation (E_{Sp}) is the equation given by Van den Broek & Kabat (1996), in which E_{Sp} is calculated as a function of ET_p and LAI (Annex 2).

Actual rates of transpiration
Actual transpiration (E_{Ta}) is usually calculated as a function of both E_{Tp} and Θ (Andersson & Harding, 1991; Federer, 1982; Van Keulen, 1986). E_{Ta} can be calculated using a slightly modified version of a model of Van Keulen (1986) in which E_{Ta} equals E_{Tp}, when the available amount of soil moisture is adequate to supply sufficient water to the plant roots. In the model a critical soil moisture content (Θ_{cr}) is used, above which roots can freely take up water from the soil, depending on soil characteristics and atmospheric demands. The modification comprises that a soil specific Θ_{cr} is calculated depending on a critical pressure head (h_{cr}= -1000 cm). In Annex 2 the method to derive E_{Ta} is given in more detail.

3.6.2 Precipitation deficit

When the amount of precipitation (P) and E_{Ta} are know (Section 3.6.1), the precipitation deficit (P_{def}) can simply be calculated as:

$$P_{def} = E_{Ta} - P \quad (3)$$

3.6.3 Soil moisture supply

The soil moisture content Θ can be calculated as explained in Section 3.6.1 and Annex 2. The soil moisture supply capacity is already available through model derivation (Hendriks unpublished).

3.6.4 Meteorological data

No measured site-specific meteorological data are available, neither at the monitoring plots of the old monitoring network nor at the plots of the new monitoring network. Site-specific estimated meteorological data for both the old and the new monitoring network can, however, be obtained through interpolation. A relatively simple interpolation procedure can be used because the relatively little differences in meteorological conditions throughout The Netherlands and the good spatial distribution of weather station over the country for which data are available. Such an interpolation method is included in the model DEADM (Erisman, 1992; 1993; 1995) with which the deposition fluxes can be calculated (Section 3.5). A great advantage of using this interpolation method is that it is already fully integrated in the DEADM model. A large disadvantage of all interpolation methods is the introduction of some inaccuracy in the data. This especially holds for precipitation, because this has a strongly differing spatial pattern over short distances. There is, however, no alternative, because site-specific measured data are not available. In DEADM, interpolation to each forest site is performed using a simple inverse distance weighting procedure from a maximum of four meteorological stations located in the immediate surroundings of the site. Most emphasis in the method is put on data quality by selection of the most representative stations to be used for the interpolation to each site.

Input data for the interpolation program are weather data of twelve weather stations in The Netherlands. These data are available at RIVM for the period 1984-1994. Data comprise daily values for minimum and maximum temperature, precipitation, relative humidity, wind speed and sunshine duration. These data are sufficient for the calculation of actual transpiration and precipitation deficit. For calculation of the after-effect term of the water stress factor (Section 2.2.2), meteorological data of six preceding years are needed, viz. 1978 to 1983. These data are also available at RIVM.

4 Methodology to assess possible relationships between forest condition and stress factors

4.1 General approach

Many environmental factors may affect forest condition (see Section 2.2). In this large-scale national study, effects of stress factors on forest condition can only be estimated or tested properly if all other relevant effects are taken into account. Deleting relevant effects will decrease the precision of the estimates of the remaining effects considerably and result in a lower significance of the tests. Moreover the estimates may loose their interpretation due to confounding. Furthermore, it is necessary to account for the most important interactions between stress factors (see Section 2.3). Finally, since different effects of the stress factors are expected for the different tree species, it is best to have separate models for each tree species in order to avoid numerous model parameters due to interactions between tree species and predictor variables (see Section 2.5). Other aspects that may influence the results of the statistical model chosen, is the temporal resolution (Section 2.4) and the possible use of threshold values (Section 2.6) for the key parameters included in the survey.

Suitable regression models must be able to explain the forest condition on a certain location and in a certain year from all relevant factors. As the response is on a limited scale (0-100%) a logit transformation is needed to make a meaningful use of linear and additive effects. If necessary the ordinal character of the response could be taken into account. Also spatial and temporal correlations should be included in the model (e.g. Baeumler, 1995).

A simple way to test the effect of each stress factor is deleting it from the model. If this deletion diminishes the model explanation significantly, then the effect of the stress factor could be called 'significant'. Successive deletion of non significant terms (backward elimination) was a popular method of predictor selection in the last decades. However as predictors may be exchangeable, there may be more than one 'best' model. Therefore a more thoroughly procedure is necessary to trace alternative models. The procedure SELECT in the computer program GENSTAT provides such a procedure (Oude Voshaar, 1994)(Section 4.9). To obtain meaningful results the total number of degrees of freedom of the potential predictors should not exceed 0.25 of the number of sample plots (Oude Voshaar, 1994).

As the two monitoring networks of 3000 and 200 sample plots, described in Section 3.1, differ strongly in their setup, models have to be fitted separately for the old and the new monitoring network.

4.2 The monitoring networks

4.2.1 The new monitoring network

For the new monitoring network fewer observations but more predictor variables are available compared to the old monitoring network (Table 8). Here a serious problem arises. The number of degrees of freedom of potential predictor variables exceeds 0.25 of the number of observations that is necessary to produce stable models. In the case that the regression is performed per tree species, at most 51 plots (pedunculate oak) are available. On the other hand for the additive model more than 40 degrees of freedom are needed and far over 100 degrees of freedom are needed if all interactions are included. Hence no meaningful selection of predictors can be executed when all predictors a priori are considered as potentially relevant. Thus it should be concluded that a serious survey could only be done if (i) the number of locations is drastically increased or (ii) the number of predictors can be reduced. Option i) is the best option but it provides no solution for this project. Therefore the expert panel has worked out a minimum set of predictors which can be used examining the relationships for the new monitoring network. The minimum options are worked out in two variants, indicated with the capitals A and B and described in Section 4.3. One should be aware of the consequences of excluding predictors from the model, which possibly result in less explanation viz. more noise and a larger exchangeability of predictors.

4.2.2 The old monitoring network

For the old monitoring network a regression model can be fitted for all 1500 observations. The best possible model should account for temporal correlations between the repeated observations on the same site. If possible also spatial correlation between neighbouring sites should be considered. Such models are described by e.g. Baeumler (1995) and Liang & Zeger (1986). These models can also deal with the ordinal character of the response variables. However, these models are not yet operational because additional software has to be developed.

An alternative option is to consider all observations of the 10 year period (1984-1994) as independent observations. Then these observations can be lumped and examined as being one large spot-check with 15 000 observations. In this option, however, temporal correlations are not accounted for. Effects of temporal correlations can partly be substituted by including 'after-effects' for both the predictor variables and effect parameters. For the predictor variables, after-effect terms can be introduced as described in Section 4.3. For the effect parameters after-effect terms can be introduced for instance by making allowance for the annual change in defoliation, or the 10 year trend (slope) in defoliation (e.g. Klap et al., 1997). In principle, the spatial correlation is allowed for by including relevant predictor variables. In our case, however, not all relevant parameters are measured at the plots of the old monitoring network (e.g. meteorological conditions) or are not known at all (e.g. foliar composition, soil chemical composition). Therefore it might be useful to analyze the region effect (by including a region parameter in the model), which might indicate the completeness of the set of predictor variables.

4.3 Predictor selection

4.3.1 Key parameters included

Table 10 gives information on the key parameters and interactions to be included in the statistical models for the new monitoring network (200 stands, option A and B) and the old monitoring network (3000 stands, options C and D). In both cases a difference is made between a model where each tree species is treated seperately (options A and C) and models where all tree species are lumped, while including tree species and their interactions with stress factors in the list of key parameters (options B and D). In the latter case, the number of predictors (total degrees of freedom) increases significantly (Table 10), but this is also true for the number of stands (Table 9). A discussion about the various options is given below.

Option A: new monitoring network per tree species
This option supplies a set of predictors with which a per tree species survey is possible for the set of 200 stands. Because of the number of samples only pedunculate oak (51) and scots pine (42) are eligible. According to Oude Voshaar (1994) the number of degrees of freedom must not exceed 0.25 the sample size. Hence a set of predictors had to be selected with only about 15 degrees of freedom, including that of the estimate. Table 10 shows the result of this selection. The expert panel considered this being the absolute minimum option making a survey on the relationships significant. Unfortunately, no interactions could be taken into account, although the existence is recognized.

Option B: new monitoring network all tree species
The set of predictors in this option should provide a survey of all tree species together for the total of the 200 stands, which can only be meaningful if tree species is included as one of the predictors. Because the sample number in this option is 200, a set of predictors can be chosen with about 50 degrees of freedom. Because the expert panel expects some significant different behaviour of tree species in relation to some stress factors, interaction terms are included. As for these interactions many degrees of freedom are needed, only a few (4) predictors of main effects can be added to the model compared to the per tree species survey (Table 10).

It should be mentioned that not all relevant interaction terms (which may exceed 100) can be included in the statistical model because the maximum number of degrees of freedom than will be exceeded. If, however, all relevant interactions will be included, there is no difference between a per tree species model and an 'all-trees' model. Inclusion of only some interactions implies that other effects are supposed additional, which is not always the case.

It should also be mentioned that the 'all-trees' model will only be useful when the results from the per tree species survey are indicating that roughly the same key parameters are affecting the condition indices. Hence, if different key parameters are affecting the condition indices, an 'all-trees' survey should not be executed.

Table 10 Available relevant key parameters to assess forest condition, their degrees of freedom and selected key parameters for 4 model options (New monitoring network A: survey per tree species, B: survey for all tree species together; Old monitoring network C: survey per tree species, D: survey for all tree species together)

Key parameter	Degrees of freedom	New Network A	New Network B	Old network C	Old network D
Tree species	6	-	+	-	+
Stand density	1	+	+	-	-
Stand age	1	+	+	+	+
Average DBH	1	-	-	-	-
Stand height	1	-	-	-	-
Crown coverage	1	+	+	-	-
Ground vegetation	1	-	-	-	-
Forest edge	1	-	-	-	-
Site history	1	-	+	-	-
Soil type	1	-	-	+	+
Mean highest g.water level	1	+	+	+	+
Mean lowest g.water level	1	-	-	+	+
RE_T*growing season*	1	+	+	+	+
RE_T*preceding years*	1	-	-	+	+
T*av.min,winter*	1	-	-	+	+
T*av.min,jan*	1	+	+	+	+
T*min,spring*	1	+	+	+	+
T*sum,growing season*	1	+	+	+	+
Pests	1	-	+	+	+
Diseases	1	-	+	+	+
Foliar N content	1	+	+	-	-
Foliar P content	1	-	-	-	-
Foliar K content	1	-	-	-	-
Foliar Mg content	1	-	-	-	-
Foliar Cu content	1	-	-	-	-
Foliar Zn content	1	-	-	-	-
Foliar P/N	1	+	+	-	-
Foliar K/N	1	+	+	-	-
Foliar Mg/N	1	+	+	-	-
SO_x concentration	1	-	-	+	+
NO_y concentration	1	-	-	+	+
NH_x concentration	1	+	+	+	+
O_3 concentration	1	+	+	+	+
N deposition	1	-	-	+	+
S deposition	1	-	-	+	+
Soil ratio NH_4/K	1	-	-	-	-
Soil ratio NH_4/Mg	1	-	-	-	-
Aluminium	1	-	-	-	-
BC/Al	1	+	+	-	-
Pb content humus layer	1	-	-	-	-
Cd content humus layer	1	-	-	-	-
Cu content humus layer	1	-	-	-	-
Zn content humus layer	1	-	-	-	-
Interaction terms					
tree spec. x age	6	-	6	-	6
tree spec. x RE_T*grow.seas.*	6	-	6	-	6
tree spec. x RE_T*prec.years*	6-36	-	-	-	6-36
tree spec. x T*av.min,jan.*	6	-	6	-	6
tree spec. x foliar N content	6	-	6	-	6
tree spec. x foliar P content	6	-	-	-	6
tree spec. x BC/Al	6	-	6	-	6
Total degrees of freedom*)	48	15	24	18	24

*) excluding the interaction terms; + = selected; - = not selected

Option C: old monitoring network per tree species
With the predictors mentioned under option C of Table 10 it will be possible to examine the relationship for the 3000 stands per tree species. When the 10 year period of 1984 to 1994 is surveyed, hardly no restriction on the number of predictors will occur. Table 9 shows that the fewest plots were recorded for beech, viz. in 1994 54 plots were recorded. Thus for beech for the 10 year period up to 500 observations are available, allowing more than 100 predictors that can be included in the model, which is ample sufficient.

Option D: old monitoring network all tree species
This option shows the same set of predictors as option C, completed with the most relevant interaction terms in case of an survey for all tree species. The same comments on the usefulness should be made here as mentioned for option B.

4.3.2 After-effects

In Table 10, the effect of water stress in preceding years is included, using one degree of freedom only. In reality the effect may, however, last for several years. In order to avoid that this leads to numerous predictors, it is suggested to combine the terms for water stress of preceding years in one so called 'after-effect' term. Doing so, the degrees of freedom needed can be reduced from a maximum of 6 for Norway spruce to 1 for all tree species (Table 11).

Table 11 After-effect period and formula to calculate the after-effect term of the relative transpiration (RE_T) for seven tree species

Tree species	After-effect period (years)	Formula
Scots pine	2	$(2*RE_{T,i-1} + RE_{T,i-2})/3$
Corsican pine	4	$(4*RE_{T,i-1} + 3*RE_{T,i-2} + 2*RE_{T,i-3} + RE_{T,i-4})/10$
douglas fir	5	$(5*RE_{T,i-1} + 4*RE_{T,i-2} + 3*RE_{T,i-3} + 2*RE_{T,i-4} + RE_{T,i-5})/15$
Norway spruce	6	$(6*RE_{T,i-1} + 5*RE_{T,i-2} + 4*RE_{T,i-3} + 3*RE_{T,i-4} + 2*RE_{T,i-5} + RE_{T,i-6})/21$
Japanese larch	4	$(4*RE_{T,i-1} + 3*RE_{T,i-2} + 2*RE_{T,i-3} + RE_{T,i-4})/10$
pedunculate oak	4	$(4*RE_{T,i-1} + 3*RE_{T,i-2} + 2*RE_{T,i-3} + RE_{T,i-4})/10$
beech	6	$(6*RE_{T,i-1} + 5*RE_{T,i-2} + 4*RE_{T,i-3} + 3*RE_{T,i-4} + 2*RE_{T,i-5} + RE_{T,i-6})/21$

It is obvious that any after-effect term must be related to the effect parameter used (e.g. defoliation). The percentage of defoliation is calculated from the fullness of the needle age classes for coniferous species and fullness of the crown with leaves for deciduous species. If a drought event has occurred by which needles have been lost, the effect on defoliation will be seen for some years, depending on the number of age classes and the sensitivity of the tree species to drought. The monitored tree species can be divided into three rough groups as related to water stress. The less sensitive group contains Scots pine and Corsican pine, moderate sensitive species are Douglas-fir, Japanese larch and pedunculate oak. The most sensitive species are Norway spruce and beech. For the group of less sensitive species a short after-effect period can be introduced, e.g. 2 years, and for the most sensitive group a long after-effect period, e.g. 6 years. But as these periods largely coincide with the needle age classes for the coniferous species, the after-effect period is related to these classes. For deciduous species and Japanese larch the after-effect period is related to the sensitivity to water stress, viz. pedunculate oak and Japanese larch 4 years and beech 6 years (Table 11).

5 Conclusions

Based on the overview of stress factors, related key parameters and the availability of data, as given in this study, it is concluded that the relationships between forest condition and stress factors in The Netherlands can be studied using advanced multiple regression techniques, as for instance supplied by the SELECT procedure of the statistical program GENSTAT.

The forest condition index 'defoliation' can be used as effect parameter in the analyses of relationships between forest condition and stress factors. 'Growth' also seems an usable index. There is, however, no data available on growth of the monitoring plots.

Most relevant stress factors, and related key parameters affecting forest condition are:
— stand characteristics (tree species, provenance, stand age, forest management),
— site characteristics (soiltype, groundwater table),
— water stress (relative transpiration, precipitation deficit, soil moisture supply capacity),
— frost stress (minimum January and April temperature),
— nutrient stress (foliar nutrient contents and ratios),
— pests and diseases (severeness of damage),
— air pollution (air concentrations and deposition of SO_x, NO_x, NH_x and O_3,
— toxic elements (ratio of dissolved base cations to Al in the soil solution).

Not all relevant key parameters are available. For most of the missing key parameters, however, site-specific values can be estimated using models (e.g. meteorological conditions, relative transpiration, precipitation deficit, soil moisture supply capacity and air concentrations and deposition of SO_x, NO_x, NH_x and O_3). In some cases, a substitutive key parameter can be used indicating a missing key parameter (e.g. crown coverage for forest management). In some cases there are no alternatives for a missing parameter (e.g. provenance), through which it can not be included in the analyses.

The use of model derived data and the substitution or absence of key parameters in the regression analyses, due to a lack of information or restrictions on account of the degrees of freedom, will introduce uncertainties in the results. Despite these uncertainties, it is believed that the proposed analyses of relationships between forest condition and stress factors will be meaningful. It is recognized, however, that inaccuracy of the data and the absence of parameters may lead to a higher percentage noise in the regression analyses.

The available data sets for the new and the old monitoring network differ in:
— available data (e.g. foliar composition),
— scale levels (e.g. soil type),
— number of plots (200 and 3000 respectively),
— time series (1995 to present and 1984-1994 respectively).

Both data sets have their own advantages and drawbacks. The new monitoring network has the advantage of the availability, or the possibility of model derivation of, site-specific data. Disadvantages are the short time series and the relatively little monitoring plots. The latter implies that a reduction of relevant parameters affecting forest condition must be made. Advantage of the old monitoring network is that data are available for a long time series and for many plots. Disadvantage is the relatively little site-specific data that are available for the monitoring plots. This leads to the conclusion that:
— a meaningful study on the temporal variation in forest condition can only be executed for the old monitoring network,
— spatial variation in forest condition can best be studied for the new monitoring network, although it can also be meaningful for the old monitoring network.

6 Recommendations

It is recommended to perform a study on the relationships between forest condition and stress factors for both the old and the new monitoring network on forest health. The results of such a study will increase the knowledge on factors affecting crown condition and contribute to policy making. It also will enlarge the insight in methodological problems, related to the survey on the relationships, and possibilities to solve these problems. This is of great importance, because little experience exists on such methods.

It is recommended to perform studies for both the new and the old monitoring network because the differences in datasets and because it provides a solid base for evaluation of both monitoring networks. Results may contribute to an optimalization of the setup of the monitoring network.

Further, an survey on the relationship between crown condition data of one year only (e.g. 1995) and stress factors is useful for the new monitoring network because of the availability of detailed site-specific data and development of the regression method. Such a research can increase insight in spatial patterns affecting forest condition and in the effect of dominating stress factors within one year. Temporal variation, however, will not be accounted for.

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Annex 1 Estimation of deposition fluxes and ozone exposure

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:

$$F = V_d(z)\ c(z) \qquad (1)$$

where:
c(z) is the concentration at height z;
$V_d(z)$ is the dry deposition velocity at height z (Chamberlain, 1966).

In Equation 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 parametrised.

V_d is represented by the inverse of three resistances:

$$V_d=(R_a+R_b+R_s)^{-1} \qquad (2)$$

The three resistances represent the three stages of transport. The aerodynamic resistance (R_a) represents the resistance against turbulent transport of the component close to the surface, the quasi-laminar sublayer resistance (R_b) accounts for the transport of the component by molecular diffusion through a laminar layer adjacent to the surface, and the surface resistance (R_s) accounts for the uptake at the surface. R_a mainly depends on the local atmospheric turbulence, whereas R_b depends on both turbulence characteristics and molecular diffusion of the component considered. R_s 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 (z_0) less than 0.5 m is calculated using a parametrisation by Wesely et al. (1985), and for forests and other areas with a z_0 above 0.5 m 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, 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).

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 grid 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.

The DEADM model has been developed to estimate deposition fluxes on a small spatial scale (Erisman, 1992; 1993; 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 50 m 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., 1994). Resistances are modelled using observations of meteorological parameters and parametrisation of surface exchange processes for gases and aerosols (Erisman et al., 1994). 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 (V_d) for each grid and each month, and multiplying the monthly average diurnal variations of V_d and concentration. In this way the most important correlations between V_d 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 about 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., 1994). 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. (1994). Base cation input is estimated by multiplying the annual average concentrations and the deposition velocities (Erisman et al., 1994).

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 50 m 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) (Fuhrer & Achermann, 1994). In The Netherlands observed 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 4 m above the ground. As these results are not representative for higher vegetation, calculated AOT40 values are 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 50 m) 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 (O_x, sum of O_3 and NO_2) instead of observed ozone concentrations. The O_x 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 O_x-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.

Annex 2 Calculation of the relative transpiration

Soil moisture deficit

From the sites of the new monitoring network a detailed soil profile description is available which can be used to calculate soil water contents. In some studies the soil component of the water balance is very simplified. Cramer & Prentice (1988) consider a uniform soil over the northern part of Europe, containing 150 mm soil water at the beginning of the growing season. Andersson & Harding (1991) and Harding et al. (in prep.) also use the 'bucket' model, as given in Section 3.5, but initialized the soil water content by measurements at the site. Since no additional soil physical characteristics will be measured for the forest water balance, information on available soil water has to be derived from the profile descriptions available only for the 200 sites. Based on these profile descriptions, Hendriks (unpublished) has calculated the soil moisture content at field capacity (Θ_{fc}), which can be used as initial soil moisture content. In case of the 3000 sites, a more rough estimation of the available soil moisture content must be made, principally based on soil type and groundwater table which can be derived from the soil map of The Netherlands, scale 1 : 50 000.

Potential evapotranspiration

Evapotranspiration of forests can be estimated using various formulas or empirical relations. The latter are only valid for certain regions or scales. Most models need detailed meteorological data, daily or even hourly measured. Although rather complex and a high requirement of parameters, the Penman-Monteith (1965) equation is very commonly applied. In general, it gives reliable estimates of the evapotranspiration. The equation can be given as:

$$\lambda E_{\text{Penman-Monteith}} = \frac{sA + \rho_a c_p (e_s - e_a)/r_a}{s + \gamma(1 + r_s/r_a)} \quad (\text{W m}^{-2}) \qquad (1)$$

in which:
λ = latent heat of vaporization (J kg^{-1})
E = evaporation rate (kg m^{-2} s^{-1})
A = available energy (W m^{-2})
s = slope of the saturation vapour pressure-temperature curve (hPa °C^{-1})
γ = psychrometer coefficient (hPa °C^{-1})
ρ_a = density of dry air (kg m^{-3})
c_p = specific heat at constant pressure (kJ kg^{-1} °C^{-1})
e_s = saturated vapour pressure (hPa)
e_a = vapour pressure at temperature T_a (hPa)
r_a = aerodynamic resistance (s m^{-1})
r_c = crop canopy resistance (s m^{-1})

where γ is 0.65 hPa $°C^{-1}$, ρ_a is 1.2047 kg m^{-3} and c_p is 1.004 kJ kg^{-1} $°C^{-1}$.

λ can be calculated following Harrison (1963) as

$$\lambda = 2501 - 2.3601*T \quad (kJ\ kg^{-1}) \qquad (2)$$

Where T is the average daily air temperature in °C.
The available amount of energy, A, can be calculated as:

$$A = R_n - D - G - M - \mu A \quad (W\ m^{-2}) \qquad (3a)$$

in which (all in W m^{-2})
R_n = net radiation
D = advection
G = soil heat flux
M = energy storage in the forest
μA = energy absorbed for photosynthesis

Following Dolman & Moors (1994) μA, M and G are small in relation to R_n and therefore can be neglected. Also following Dolman & Moors (1994) it is supposed that no advection takes place by which D can be taken zero. So A can be approximated as

$$A = R_n \quad (W\ m^{-2}) \qquad (3b)$$

Net radiation R_n can be calculated as:

$$R_n = R_{sh} - R_l \quad (W\ m^{-2}) \qquad (4)$$

in which:
R_{sh} = net downward short-wave radiation (W m^{-2})
R_l = net upward long-wave radiation (W m^{-2})

Net downward short-wave radiation can be estimated as the solar radiation R_s at the earth's surface. R_s can be calculated using the Angstrom equation as adapted by Penman (1948):

$$R_s = R_a * (a + b * n/N) \quad (W\ m^{-2}) \qquad (5a)$$

in which:
R_a = extraterrestrial radiation (W m^{-2} day^{-1})
a + b = empirical constants
n = measured number of hours of bright sunshine (h day^{-1})
N = possible number of hours of bright sunshine (h day^{-1})

The constants a and b are related to the clear sky transmittivity and for general use, values of 0.25 and 0.50 are recommended by Doorenbos & Pruitt (1977). Supit (1994) shows that a and b differ per region, mainly on the large scale. For The Netherlands the variation is limited, a and b vary between 0.192 and 0.218 and between 0.569 and 0.583 respectively. For The Netherlands the average value of six weather stations given by Supit (1994) can be used, which for a and b is 0.201 and 0.576 respectively.

Because from the meteorological data base no radiation values are available R_a will be corrected with the fractional cloud cover C following Brutsaert (1982) who indicated that C + n/N should equal unity. Substituting this in formula 5a give:

$$R_s = R_a * (a + b * (1-C)) \qquad (5b)$$

in which:
C = fraction visual cloud cover (-)

Extraterrestrial radiation, R_a, is a function of latitude and date only if radiation from the sun is assumed to be constant. De Bruin (1977) developed the procedure ASTRO to calculate R_a, which is given by the empirical formulas 6 to 12.

$$R_a = 430.673*A'^2*(D*\sin(B)*\sin(L')+\cos(L')*\cos(B)*\sin(D)) \qquad (6)$$

in which
- L' = function of latitude
- A', B = functions of day number
- C = function of latitude
- D = variable depending on C

The functions can be written as

$$L' = 0.01745333*L \qquad (7)$$

in which L is latitude and

$$A' = A - 1.35512 + 0.0335*\sin(A) + 0.00035*\sin(2*A) \qquad (8)$$

and $A = 0.01745333*L$ (9)

$$B = \sin^{-1}(0.397949*\sin(A')) \qquad (10)$$

$$C = -\tan(L')*\tan(B) \qquad (11)$$

$$D = \pi \quad \text{for } C \leq -1.0 \qquad (12a)$$
$$D = \cos^{-1}(C) \quad \text{for } 0 < C < 1 \qquad (12b)$$
$$D = 0.0 \quad \text{for } C \geq 1 \qquad (12c)$$

Net long wave radiation, R_l, can be estimated following Weiss (1982).

$$R_l = C_{clouds}\,(L_d + L_o) \qquad (13)$$

where:

C_{clouds} = a cloudiness correction
L_d = downward long wave radiation
L_o = outward long wave radiation

The long wave outward radiation, L_o, can be estimated using Equation 9.

$$L_o = \varepsilon_{surface}\ \sigma\ T_k^4 \tag{14}$$

in which:
$\varepsilon_{surface}$ = the emissivity of plant and ground surface (-)
σ = Stefan-Boltzmann constant (W m^{-2} K^{-4})
T_k = average daily air temperature (K)

For green vegetation Burman & Pochop (1994) give as common value for $\varepsilon_{surface}$ 0.97. The Stefan-Boltzmann constant σ equals $5.6703*10^{-8}$ W m^{-2} K^{-4}. The downward radiation flux, L_d, can be estimated following Brutseart (1975).

$$L_d = \varepsilon_{sky}\ \sigma\ T_k^4 \tag{15}$$

with

$$\varepsilon_{sky} = 1.24[10*e_a/T_k]^{1/7} \qquad \text{for } C_{clouds} \leq 0.7 \tag{16a}$$

and

$$\varepsilon_{sky} = 0.97*\varepsilon_{sky} \qquad \text{for } C_{clouds} > 0.7. \tag{16b}$$

The cloud correction C_{clouds} can be estimated as

$$C_{clouds} = (0.4 + 0.6*R_s/R_{so}) \tag{17}$$

where R_s can be calculated using Equation 4b and the clear day solar radiation R_{so} can be estimated following Heermann et al. (1985).

$$R_{so} = A\ \exp\text{-}[(D\text{-}C)/B]^2 \qquad (\text{W m}^{-2}) \tag{18}$$

in which
A = peak value of radiation (W m^2 day^{-1})
C = calender day number of the day when maximum solar radiation occurs
D = calender day number of the day under consideration
B = curve width determination factor

Maximum solar radiation occur at day 172, while A and B can be determined with

$$A = 31.25 + 0.001113*z \tag{19}$$

and

$$B = 270 - 3.008*L \tag{20}$$

where z is elevation above sea level in meter and L is latitude in degrees.

This completes the equations needed for calculation of net radiation.

Further the Penman-Monteith equation contains the term for the slope of the saturation vapour pressure-temperature curve, s, which can be calculated as:

$$s = e_s(T)*[7.5*237.3/(T+237.3)^2]*\ln 10 \quad (\mathrm{Pa}\ ^\circ\mathrm{C}^{-2}) \qquad (21)$$

in which the saturated vapour pressure, e_s, is expressed in hPa and temperature, T, in °C. e_s can be calculated using equation 22.

$$e_s = e_s(0)*10*[7.5/(T+273.3)] \quad (\mathrm{mbar}) \qquad (22)$$

where $e_s(0)$ is 6,107 mbar and T is in °C. Transformation of mbar to hPa can be done by dividing by 1013 (1 atmosphere = 1000 hPa = 1013 mbar). The actual vapour pressure can be simply calculated using the relative air humidity, given in the data base, and the calculated e_s following

$$e_a = e_s * RH/100 \quad (\mathrm{kPa}) \qquad (23)$$

The aerodynamic resistance, r_a, can be calculated following Monteith (1965).

$$r_a = 1/(k^2*u_s) * [\ln\{(z-d)/z_0\}]^2 \quad (\mathrm{s\ m^{-1}}) \qquad (24)$$

in which
k = von Karman constant (-)
u_s = wind velocity above the crop (m s^{-1})
z = height of measurement (m)
z_0 = roughness length (m)
d = zero plane displacement (m)

The roughness length and zero plane displacement depend on the crop height following

$$z_0 = 0.1*H \quad (\mathrm{m}) \qquad (25)$$
$$d = 0.7*H \quad (\mathrm{m}) \qquad (26)$$

The wind velocity at crop height can be calculated as

$$u_s = c_u * u \quad (\mathrm{m\ s^{-1}}) \qquad (27)$$

in which
c_u = correction factor to estimate the wind velocity at crop height (-)
u = wind velocity at height of measurement, usually 2 m (m s^{-1})

The correction factor c_u can be estimated following Van Dam & Hendriks (1994).

$$c_u = \frac{\ln\{(H+2-d_c)/z_{o,c}\}\ln\{(100-d_m)/z_{o,m}\}}{\ln\{(100-d_c)/z_{o,c}\}\ln\{(HU_m-d_m)/z_{o,m}\}} \qquad (28)$$

in which
H = crop height (m)
HU_m = height of measurement of the wind speed (m)

and the subscripts c and m indicate the difference for the parameters between the crop and the meteo station. d_m usually is taken about 0.02 m and $z_{o,m}$ 0.03 m.

Crop resistance r_c (s m^{-1}) is the resistance to the transport of water vapour through the stomata to the ambient air. r_c depends on light intensity, vapour pressure deficit, temperature, ambient CO_2 concentration, leaf water potential and soil water deficit (Van Roestel, 1984; Stewart, 1988). Stewart (1988) developed a model to estimate r_c. The model however requires rather detailed data which are not available for the forest health monitoring plots. De Laat (1985) proposed the use of a basic crop resistance (r_b) which, for forests, is adapted depending on the saturation deficit of air using the following equation.

$$r_c = r_b \qquad \text{for } \Delta e \leq 3 \text{ mbar} \qquad (29a)$$

and

$$r_c = r_b + 25(\Delta e - 3) \qquad \text{for } \Delta e > 3 \text{ mbar} \qquad (29b)$$

in which
r_c = crop resistance (s m^{-1})
r_b = basic crop resistance (s m^{-1})
Δe = vapour pressure deficit (mbar)

Vapour pressure deficit can be calculated as

$$\Delta e = e_s - e_a \qquad (30)$$

in which all terms are as explained before and expressed in mbar.

As a value for r_b De Laat (1985) used 80 s m^{-1} for both coniferous and deciduous forest. In literature some tree species specific values of r_b are found of which a selection was made for the use in Equation 29 (Table A2.1). For Corsican pine the same value of r_b was chosen as for Scots pine. This is based on fact that Stewart (1984) found the same values for Corsican pine and Scots pine, but that the values found are considered as low. The chosen values for the other tree species follow logically from the values showed in Table A2.1.

Table A2.1 Values of the basic crop resistance (r_b in s m^{-1}) for 7 tree species as found in literature and as used in this study

Tree species	r_b Literature	r_b Used
Scots pine	120[1], 90-100[2], 45[3]	100
Corsican pine	45[3]	100
Douglas fir	86[1], 90-100[2], 40[4], 60[5], 86[6]	90
Japanese larch	86[1]	80
Norway spruce	40[1], 50[2], 52[8], 54[9]	50
Sitka spruce	50[2], 40[7]	50
pedunculate oak	50[1]	50
white oak	44[10]	-
beech	85[1]	85
poplar	71[1]	-

1) Dolman & Moors, 1994; 2) Jarvis, 1981; 3) Stewart, 1984; 4) McNaughton & Black, 1973; 5) Tan & Black 1976; 6) Spittlehouse & Black, 1982; 7) Milne, 1979; 8) Calder, 1977; 9) Bringfelt; 10) Federer, 1980.

Actual transpiration, E_{Ta}

Actual transpiration, E_{Ta}, equals the potential level, E_{Tp}, in case of no limitations of the soil moisture supply. Because on most forest sites a soil moisture deficit is more commonly than a surplus, actual transpiration will be reduced. Actual transpiration can be calculated using the forest water balance as explained in Section 3.6.1. E_{Ta} can be calculated as a function of available soil moisture. Based on literature, Rutter (1968) showed that actual transpiration will reduce when the soil moisture content will become less than 0.40 of the maximum capacity. This relation, however, does not take into account any differences between soil types and atmospheric demand. Van Keulen (1986) developed a simple model, based on soil moisture contents and transpiration rate, that overcomes these limitations. In this model a critical soil moisture content is used below which water uptake by plant roots is hampered. As long as the critical soil moisture content is not exceeded, E_{Ta} equals E_{Tp}. The critical soil moisture content can be calculated on base of a depletion fraction of the soil moisture content. By Van Keulen (1986) this depletion fraction is, however, the same for all soil types. In stead of the use of a critical soil moisture content a critical pressure head (h_{cr}) can be used. Van Roestel (1984) suggests a pressure head (h) of -1000 cm above which actual transpiration is reduced. With the model of Van Keulen (1986) it is calculated that for a h_{cr} of -1000 cm the soil water depletion fraction for the texture classes fine sand, loam, light clay and peat is 0.60, 0.52, 0.44 and 0.46 respectively. These depletion fractions can be used to calculate critical soil moisture contents by multiplication of the depletion fraction and the maximum available soil water content. When the critical soil moisture content (Θ_{cr}) is exceeded, actual transpiration is assumed to decrease from 1, at Θ_{cr}, to 0 at the wilting point (h= -16000)(Van Keulen, 1986). Thus E_{Ta} now can be calculated as:

$$E_{Ta} = E_{Tp} \qquad \text{for } \Theta_i \geq \Theta_{cr} \qquad (31a)$$

and

$$E_{Ta} = E_{Tp}*(\Theta_i/\Theta_{cr}) \qquad \text{for } \Theta_i < \Theta_{cr} \qquad (31b)$$

where:

Θ_i = soil moisture content at day i (mm)

Θ_{cr} = critical soil moisture content

Θ_{cr} can be calculated as:

$$\Theta_{cr} = (1\text{-}p)*\Theta_{fc} \qquad (32)$$

where:

Θ_{fc} = soil moisture content at field capacity (mm)

p = soil water depletion fraction (-)

The soil water depletion factor can be considered as a function of the maximum transpiration rate (E_{Tp}). Doorenbos & Kassam (1979) give indicative p-values for different groups. On the average, the p-values decrease 66% going from E_{Tp} = 2 mm d^{-1} to E_{Tp} = 10 mm d_{-1}. We also applied this reduction of p in our model. With the model of Van Keulen (1986) we calculated a basic p-value (p_b) for the different soil types for h=-1000 cm and E_{Tp} = 2 mm (Table A2.2).

Table A2.2 Soil water depletion fraction (p) above which actual transpiration is reduced

Soil texture class	Depletion fraction p
sand	0.63
loam	0.49
clay	0.42
peat	0.46

Now p can be calculated as:

$$p = p_b\text{-}((p_b\text{-}(0.33*p_b))/8)*(E_{Tp}\text{-}2) \quad (\text{-}) \qquad (33)$$

Interception

Interception can be calculated using the model of Gash (1995).

First the amount of precipitation must calculated to which is needed to saturate the crown, P'.

$$P' = -(R*S/E)*\ln[1-(E/R)] \text{ (mm d}^{-1}) \qquad (34)$$

in which

R = mean rainfall rate (mm h^{-1})

E = mean evaporation rate during rainfall (mm h^{-1})

S = canopy storage capacity (mm)

For small rain-showers when $P \leq P'$ interception, E_I, can be calculated as

$$E_I = (1-p-p_{tr})P \quad (35)$$

in which
P = daily precipitation (mm d^{-1})
p = free throughfall coefficient (-)
p_{tr} = stem flow coefficient (-)

For showers of rain when $P > P'$, interception can be calculated as

$$E_I = (1-p-p_{tr})*P'+(E/R)*(P-P') \quad (mm\ d^{-1}) \quad (36)$$

Interception of the trunk is often small and therefore frequently neglected. In the adapted form for sparse forest, the storage capacity of the canopy S is calculated per unit area of cover as S_c=S/c where c is the canopy cover. Mean rainfall and evaporation rate have to be calculated for the period that the crown is saturated. For The Netherlands constant values for E and R can be used because they are little variable over such a relative small area. As proper constants 2.0 mm h^{-1} can be taken for E and 0.2 mm h^{-1} for R. The storage capacity depends on tree species. Dolman & Moors (1994) give values for S for several tree species which are shown in Table A2.1. Given figures in Table A2.3 may be considered as average values for 'normally' managed forest with a relative high canopy coverage.

For deciduous tree species the summer value and for coniferous tree species the whole year value of the free throughfall coefficient (p) can be calculated as:

$$p_s = 1-CP/100 \quad (37)$$

in which:

p_s = summer value (in case of deciduous tree species) or whole year value (in case of coniferous tree species) of the free throughfall coefficient
CP = crown coverage percentage (%)

The crown coverage is recorded for the plots of the new monitoring network.

Then also the winter value of p must be adapted for deciduous tree species, which can be done following:

$$p_w = p_s * p_{wt} / p_{st} \quad (38)$$

in which:

p_w = winter value for deciduous tree species of the free throughfall coefficient
p_s = summer/whole year value for p as calculated with Equation 37
p_{wt}= winter value for deciduous tree species of the free throughfall coefficient as given in Table A2.3

p_{st}= summer value for deciduous tree species of the free throughfall coefficient as given in Table A2.3

Next, also the storage capacity must be adapted to the calculated troughfall coefficient, which can be done following:

$$S = S_t * p / p_t \quad (39)$$

in which:

S_t = storage capacity of the crown as given in Table A2.3
p = free throughfall capacity as calculated with Equation 37
p_t = free throughfall capacity as given in Table A2.3

Table A2.3 Storage capacity of the crown (S) and free throughfall coefficient for several tree species

Tree species	S (mm)		p (-)	
	summer	winter	summer	winter
pedunculate oak	0.9	0.3	0.3	0.8
red oak	0.7	0.2	0.3	0.8
poplar	1.0	0.3	0.2	0.8
beech	1.0	0.3	0.1	0.8
Japanese larch	1.0	0.3	0.1	0.8
Scots pine	1.0		0.1	
Norway spruce	2.8		0.1	
Douglas fir	2.4		0.05	

Soil evaporation

According to Van den Broek & Kabat (1996) potential soil evaporation E_{Sp} can be calculated based on Beer's Law for the absorption of the radiation flux by the canopy:

$$E_{Sp} = e^{(\kappa * LAI)} ET_p \quad (mm\ d^{-1}) \quad (40)$$

in which:
κ = extinction coefficient for net radiation
LAI = leaf area index (-)

Actual soil evaporation, E_{Sa}, can be calculated as a function of time since the last rainfall event following Black et al. (1969):

$$E_{Sa} = \omega(\sqrt{(t_d+1)} - \sqrt{(t_d)}) * E_{Sp} \quad (41)$$

in which:
t_d = time since last rainfall (d)
ω = an empirical parameter ($d^{-1/2}$)

Following Tiktak et al. (1995) ω can be taken 0.33.

The crown coverage percentage or relative LAI, needed in equation 37, can be calculated depending on a maximum LAI, differing for each tree species, and the defoliation class DC, given in 5% classes.

$$LAI = (1\text{-}DC)*LAI_{max} \qquad (42)$$

Since LAI is not recorded in the monitoring programme, a maximum LAI can be derived from Dolman & Moors (1994) (Table A2.4).

Table A2.4 Maximum leaf area index (LAI) for several tree species during summer and winter

Tree species	LAI summer	winter
Scots pine	6.0	4.5
Corsican pine	6.0	4.5
Douglas fir	5.0	4.5
Norway spruce	12.0	11.0
Japanese larch	5.5	0.0
pedunculate oak	4.0	0.0
beech	5.5	0.0