Relationships between crown condition and its determining factors in The Netherlands for the period 1984 to 1994

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ABSTRACT

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In the period 1984 to 1994 forest condition in The Netherlands was estimated by recording defoliation and discoloration on 3000 plots. In this study the defoliation classes for this eleven years period was related to possible stress factors such as deposition, soil chemistry and soil moisture. The data for most stress factors is site specifically model derived since no measured data is available. The assessment of the relationship is performed with a split plot analysis. Results show that deposition, climatic, stand, site and biotic factors contribute significantly to the explanation of defoliation, however, percentages accounted for are low.

Keywords: forest condition, stress factors, oak, Scots pine, Douglas-fir, time series analysis

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Contents

Preface

This study can be seen as a synthesis of 10 years monitoring forest condition in The Netherlands. The data on forest condition for the period 1984 to 1994 was not analyzed before. The value of the data set is especially the relative long period for which it is available. With the present state of computer models it is possible to estimate the missing site, climatic, and environmental parameters to which the condition had to be related, since they were the most important missing factors in the monitoring program. With this study the period in which the forest condition was monitored on a large scale (3000 sample points) can be considered as finished. Several studies on forest condition have been executed now, and the moment seems there to make an overview on the state of research on forest condition in The Netherlands.

In previous years a lot of experience was gained in methods how to establish relationships between forest condition and stress factors. In this study the gained experience was used very constructive and was deepened in a professional way. At this point I would like to thank Jan Oude Voshaar who has done a lot of conceptual thinking about tackling this refractory matter. Later on Michiel Janssen and Paul Goedhart took over on a very thoroughgoing way. Many thanks to them all.

Summary

Forest condition
Since 1984 forest condition in the Netherlands is monitored annually through recording defoliation and discoloration. In the period 1984-1994 forest condition was monitored on 3000 plots, of which annually about 1500 were recorded. From 1995 until present, forest condition is monitored on about 200 plots.

The hypothesis that forest condition is affected by multiple stress now is generally accepted and it becomes increasingly clear that the stress factors operate at various spatial and temporal scales. Because of this variation in time and space, time series analysis of forest condition is an important step forward in the understanding of forest ecosystems and their relation to the environment. Air pollution and meteorological factors are regarded as important stress factors of which the continuous load may cause effects over a period of several years. Until now, however, the relationship between forest condition and stress factors was examined for a period of one year only. Therefore, time series analysis of forest condition in relation to possible stress factors is an very important piece of the jigsaw puzzle called forest condition.

Aim
The aim of this study is to examine the effects of temporal variation in stress factors on the development in forest condition in the Netherlands. As index for the forest condition, the defoliation class is used. The relationship is assessed between defoliation class and (1) stand characteristics, (2) site characteristics, (3) nutritional conditions, (4) meteorological conditions, (5) air pollution and (6) biotic conditions for the period of 1984 to 1994.

Method
In the national monitoring network on forest condition 29 tree species were monitored. For most of these species only little stands were monitored. A meaningful analysis of relevant stress factors can only be performed when the number of plots is about four times the number of explaining variables. For only eight of the 29 tree species that were recorded, the number of plots matches this criterion. Out of these eight species oak, beech, Douglas-fir and Scots pine were selected for the analysis. Oak and beech were selected because it are important deciduous tree species having a prominent role in Dutch forests areas. Douglas-fir and Norway spruce were selected because they show a significant negative trend in crown condition over the period 1984 to 1994. It is expected that because of this strong negative trend the possible correlated trends in environmental and meteorological factors will be stronger than for other species for which the trends are less clear or absent.

In the national monitoring network on forest condition the defoliation class and discoloration class are the most important indices representing forest condition.

From literature it follows that the defoliation class can be selected as effect parameter to be used in the time series analysis, however, it must be noticed that forest condition is not equal to defoliation only. Defoliation and discoloration, however, are the only two available parameters. Of these two parameters, defoliation showed the best opportunities to be related to stress factors.

The number of relevant stress factors which possibly may affect the defoliation class is enormously. Therefore a first selection had to be carried out to achieve a reduction of the number of relevant predictors. For this purpose first an informal assessment of relevant predictors was executed. As a second step, a detailed analysis of three selected tree species was executed. Selection of the tree species was based on the performance in the informal analysis.

The informal assessment is carried out with forward and backward selection of parameters using multiple linear regression analysis. By means of the SELECT procedure in GENSTAT 5 the best subset of predictor variables is selected from all possible models explaining the response variable, which in our case is mean defoliation class. The SELECT procedure is almost equal to the RSELECT procedure that has been applied in previous studies on forest condition. The backward selection resulted in a large number (29-57) of significant variables which hampers the selection for input variables in the SELECT procedure. The results of the forward and backward selection did not bring the clearness which it was hoped to bring to the foundation of the choice for which tree species a further detailed analysis would be useful. The large number of predictors, especially the number of meteorological parameters, hampers the interpretation of these models and obstructed a proper execution of an optimal model selection with the SELECT procedure of GENSTAT. Through forward selection a confirmation of the results of the backward selection analysis was obtained, hoping it would facilitate the interpretation of the models. However the number of significant variables was seriously reduced by the forward selection, it was difficult to compare both selection methods in search of the optimal model. The models found through forward selection in general were quite plausible, but they unfortunately make only little sound.

Results

On the base of the results of the backward and forward selection of predictors only, it is difficult to make a well-founded selection of tree species for which a more detailed analysis will be useful. Therefore some additional criteria, such as knowledge about effects on a species, and the importance of a species for Dutch forestry were used for the selection. As tree species for the detailed analysis of the defoliation oak, Scots pine and Douglas-fir were selected. For the selected tree species a detailed regression analysis is performed. In this analysis, effects, combination and the possibility of non-linear functions of variables are tested iterative.

Oak

The detailed split-plot analysis of the oak data resulted in an explaining model that contains 10 different predictors. Four of the predictors showed to be non linear related to the defoliation class. The percentage variance accounted for ($R^2_{adj.}$) calculated with this model for oak is 22.59%.

The defoliation class of oak could is found to be significantly correlated to stand parameters (age), air pollutants (SO_x, NO_x, NH_x), site parameters (N/P ratio, soil moisture availability), meteorological parameters (relative transpiration, maximum summer temperature) and biotic parameters (insect damage).

As expected, defoliation increases with increasing stand age. For all three air pollution predictors (SO_x, NO_x, NH_x) defoliation increases with an increasing air pollution load. The defoliation increases with an increasing N/P ratio. This is probably associated to the level of N deposition. A low precipitation and high temperature induces a low relative transpiration. Remarkably, the relative transpiration in the year of the recording of the defoliation is positively correlated to defoliation, meaning more defoliation with a higher relative transpiration. On the contrary, the relative transpiration in the three previous years of the recording is negatively correlated, which is as expected. This means that defoliation increases with a decreasing relative transpiration.

Scots pine

The detailed split-plot analysis of the Scots pine data resulted in an explaining model that contains 14 different predictors, of which 11 show a non-linear correlation to defoliation. The percentage variance accounted for ($R^2_{adj.}$) for Scots pine calculated with this model is 33.73%. The large number of significant predictors is connected with the large number of plots (5394) for Scots pine.

Significant relationships were found between the defoliation class of Scots pine and stand predictors (age), air pollutants (SO_x, NO_x, NH_x), site predictors (N/P ratio, C/N ratio, soil moisture availability, basic cations) meteorological predictors (precipitation sum in the growing season, average winter temperature, relative transpiration) and biotic predictors (insect and fungal damage).

With increasing stand age defoliation increases. All tested air pollution components were found to be very significant. For SO_x and NO_x defoliation increases as expected with increasing deposition. For NH_x, however, it is the other way around, which might be due to a fertilising effect. For the C/N and N/P ratio defoliation increases with increasing amounts of nitrogen. Defoliation decreases with an increasing fraction of basic cations in the soil solution. The precipitation in the growing season, the average winter temperature, and the relative transpiration all are significantly and positively correlated to defoliation of Scots pine, meaning an increase in defoliation with higher predictor values. Increasing winter temperatures are correlated with decreasing defoliation. As for oak, relative transpiration in the year of recording for Scots pine is found to be positively correlated with the defoliation class, meaning more defoliation for higher relative transpiration values, which was expected the other way round. Defoliation was found to decrease with increasing soil moisture availability. Finally, also insect and fungal damage significantly contributed to the explanation of the defoliation class. As expected, insect damage is positively correlated with the defoliation class. As found in other studies, fungal damage is negatively correlated with defoliation class which was not expected on the forehand.

Douglas-fir

The detailed split-plot analysis of the Douglas-fir data resulted in an explaining model that contains 7 different predictors, of which 2 show a non-linear correlation. The percentage variance accounted for ($R^2_{adj.}$) for Douglas-fir calculated with this model is 23.85 %.

Significant factors, explaining defoliation class for Douglas-fir are air pollutants ($SO_{x,}$ $NO_{x,}$ NH_x) and meteorological factors (minimum temperature of the growing season, average winter temperature, precipitation during the growing season, relative transpiration). Remarkably stand and site characteristics were not significant related to defoliation.

Remarkably, in non of the analysis (detailed and informal backward and forward) a significant relationship between stand age and defoliation of Douglas-fir could be demonstrated, while for the other species age was found to contribute significantly. All three air pollution components are significantly related to defoliation. For SO_x and NH_x a non-linear relationship is found, while for NO_x a linear correlation showed to best significancy. Remarkably, SO_x and NH_x are negatively correlated to the defoliation class, suggesting that defoliation decreases with increasing deposition levels. This might be due to the negative trend in defoliation of Douglas-fir and the negative trend of SO_x deposition over the same period by which the correlation found might be a coincidental relationship. For NH_x the fertilising effect might be the reason. An increase in defoliation occurs with a decrease in minimum temperature of the growing season. In contrast to Scots pine, defoliation increases in Douglas-fir with increasing average winter temperature. Concerning precipitation; the more precipitation the less defoliation. The relative transpiration was found to be positively correlated to the defoliation class, while, on the forehand, a negative correlation was expected.

Discussion

In general, this is the first Dutch study in which temporal effects op the variation in stress factors are incorporated in an analysis of forest condition. Missing data, however, seriously hampered the time series analysis. Because of to many gaps in the data base, a split plot analysis with a constant auto-correlation of defoliation in time had to be used as method for time series analysis, possibly overestimating the time effects. Other sources of uncertainties are the modelled and interpolated data on deposition and meteorological conditions. Precipitation levels and ozone are regarded as important stress factors. Ozone could not be included since it was recorded not earlier than the beginning of the nineties. Interpolation of precipitation levels is possibly biased due to large spatial variation. Nevertheless, in general it can be said that the split-plot analysis resulted in plausible models for oak and Scots pine. The model for Douglas-fir is less plausible because of unexpected effects of air pollution components an relative transpiration. Although the models are quite satisfactory, the percentages variance accounted for are rather low.

Conclusions

Despite the low percentages variance accounted for, it is quite encouraging that the hypothesis that air pollution and meteorological stress are important factors affecting defoliation is underlined by the results of this study. Besides air pollution and meteorological variables also stand characteristics (stand age), site characteristics (element ratios such as N/P ratio) and biotic characteristics (insect and fungal damage) are important factors affecting defoliation. In contrast to other studies, period of afforestation and type of former land use were not found to be important factors affecting forest condition.

This study convincingly demonstrated that air pollution and meteorological conditions affected defoliation of the species involved. Furthermore, the results showed that temporal variation in defoliation is even more pronounced than spatial variation in defoliation. This clearly indicates the importance of temporal aspects in forest condition analysis.

1 Introduction

1.1 Forest condition as issue

The condition of forests became a major concern in the eighties, in the Netherlands as in Europe. Since then programs have been set up to monitor forest condition and to identify causes of forest decline. Initially, forest decline was mainly attributed to a single factor, i.e. air pollution. At present, it becomes increasingly clear that forest decline is caused by multiple stress factors, which operate at various spatial and temporal scales.

Several factors have been recognised to influence forest condition (Innes, 1993; Hendriks 1997a). Stand characteristics (tree species, provenance, tree density), site characteristics (soil type, nutrient availability), meteorological characteristics (drought, frost) and pest and diseases are regarded as the traditional factors. Air pollution, eutrophication and acidification are seen as the more recent, anthropogenic factors. Interaction between the traditional an anthropogenic factors can occur and then can be classified as antropogenic.

On a spatial scale, the magnitude and impact of these factors may differ due to differences in site characteristics, climate and exposure. Although Hendriks et al. (1994) concluded that soil type and groundwater table were relative unimportant parameters explaining defoliation, they expected that in studies with a greater number of plots soil characteristics such as nutrient content and soil chemistry are important parameters of forest condition.

On a temporal scale, especially meteorological characteristics, air pollution, eutrophication and acidification are of importance. The impact of these factors may be revealed after a certain period (after-effect), last longer (chronic) or gradually build up to critical loads (acute). For example, Landmann (1993) and Saxe (1993) found that the effects of drought may last 7-10 years.

In a study on the relationship between stress factors and forest condition in 1995, Hendriks et al. (1997b) concluded that forest condition is influenced by multiple stress factors. For pedunculate oak, important predictors of defoliation in 1995 were stand age, insect damage and temperature. For Scots pine the best explaining model contained stand age and foliar P/N ratio. Ozone and drought had a negative effect by affecting foliar loss (oak) and foliar composition (Scots pine and oak). The effects of other air pollutants (SOx, NHx and NH_y) were less pronounced. From this study it was concluded that time series analysis could give more insight in forest condition developments due to yearly variations in forest condition and the occurrence of after-effects.

1.2 Monitoring forest condition in the Netherlands

Forest condition in the Netherlands is recorded since 1983. In 1984 a monitoring program was initiated to follow the condition according to standardised procedures (Van den Tweel and den Boer, 1986, Smits, 1993). This program lasted till 1994. The forest condition was assessed by estimating foliar loss, foliar and crown discoloration, and recording some stand characteristics and the occurrence of pest and diseases. Eleven (groups of) species were monitored in 3000 plots of which the plot numbers differed per year. In 1995, a more detailed monitoring program was started. In this program the main focus was to identify causes of forest decline. This was done by recording defoliation, crown discoloration and transparency on the one hand and insect and fungal damage, chemical composition of the soil, foliage nutrient composition, vegetation and mycorrhizas on the other hand.

1.3 Aim

The aim of this study is to examine the effects of variation in stress factors on crown condition in the Netherlands with a special emphasis on temporal effects. More specifically this study focused on the relationships between crown condition and meteorological factors, air pollution factors, stand characteristics, site characteristics and biotic factors in the period from 1984 to 1994 using time series analysis.

1.4 Method

In several studies the forest condition in the Netherlands was analysed (e.g. Hendriks et al 1994, Hendriks et al 1997, Olsthoorn and Maas, 1994, Oosterbaan and Nabuurs, 1991). These studies pointed out that meteorological and air pollution factors are important factors affecting crown condition. The temporal effects of these factors however, were not investigated before. Hendriks et al. (1997b) convincingly assessed the negative effects of air pollution, drought and temperature on forest condition. However, the above mentioned stress factors operate at various temporal scales, indicating the importance of including temporal effects, as mentioned by Hendriks et al. (1997a). In this study a time series analysis is used to assess the effects of multiple stress factors on crown condition in the Netherlands for the period 1984 to 1994. The time series analysis was only applied to oak, Scots pine and Douglas-fir.

2 Data and methods

2.1 Selection of tree species

In the national monitoring network on forest condition 29 tree species were monitored. For most of these species only little stands were monitored. Since an analysis of relevant stress factors can only be performed if enough plots are available, most tree species can not be included in the analysis. Following Oude Voshaar (1994) the number of plots must be at least four times the number of predictors in the regression analysis. Since the number of relevant predictors is up to 25, at least 100 plots are required. Only eight tree species match this criterion. These species are oak, beech, poplar, Scots pine, Corsican pine, Douglas-fir, Norway spruce and Japanese larch. In order to make a further selection of species, an informal analysis was carried out. The method of this analysis is described in section 2.3.

2.2 Selection of effect and predictor variables

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 broadleaf species, 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. Hendriks et al. (1997a) presented an overview of the relation between different effect parameters indicating forest condition and stress parameters. From this overview it is concluded that defoliation as such is a useful parameter to be related to stress factors. However, the accuracy with which defoliation is or can be recorded is very important for the level of success in the regression analysis. Hendriks et al. (1997b) found relationships between defoliation and stress factors. In the latter study, however, defoliation data was available in 5% classes, while in this study defoliation data is available in only four classes (0-10%, 11-25%, 26-60% and 61-100% defoliation).

Discoloration shows to be a less useful parameter (Hendriks et al.1994, Hendriks et al. 1997a) which probably has to deal with the inaccuracy when recording discoloration from the ground.

In the National Survey on Forest Health defoliation and discoloration were recorded as most important indices to represent forest condition. Based on the conclusions above it was decided to use only defoliation as effect parameter. But still then it has to be decided how the defoliation parameter can be used best in the regression analysis.

Because the defoliation is recorded in non-equidistantial classes (0-10%, 11-25%, 26-60% and 60-100%), no logit transformation of the classes is necessary. Actually, the classes of defoliation are a somehow comparable with a logit transformation for the lower defoliation percentages. Because the number of observations with defoliation percentages above 60% is limited, logit transformation on the upper side (60-100%) is less important than on the lower side (0-25%).

As effect parameter the defoliation classes itself can be taken, which means that the number of trees in classes 1, 2, 3 and, or in class 4 can be related in separate analyses to the explaining factors. Another alternative is to use the mean or the median of the number of trees for all classes. The use of the mean seems the most appropriate because it gives a more accurate estimation of the defoliation than the original recorded classes.

Apart from the mean, also relative defoliation parameters can be used as effect parameter. The change of the defoliation class compared to that of the previous year of the recording can be used as such a relative parameter and also the trend of the defoliation over a certain period. In a study on the relationships between forest condition and stress factors Klap et al. (1997) found that the change and the trend in defoliation were significantly less successful effect parameters that the actual defoliation itself. This is probably due to the fact that changes and trends are less sensible to stress factors.

Considering the results from previous studies, the mean defoliation class is selected as effect parameter to be used in the time series analysis.

2.3 Selection of forest stands and derivation of site-specific stress factors

2.3.1 Data validation procedure and selection of useable data

The data included in the data collection phase included existing data bases with crown condition measurements and a limited set of stand characteristics (e.g. X and Y co-ordinates and tree species) and a large set of additional data from external data bases.

Amount and location of plots

The provided data file with crown condition variables included 21273 records, which referred to 3754 different locations, based on the X and Y co-ordinates. The plots were located at the intersections of a 1x1 km^2 gridnet, whenever these intersections were covered with forest. Codes for 29 different tree species were found, including 00 for unknown or not recorded species. Three plots (with 4 records in total) were excluded because they, on the base of the co-ordinates, seem to be located outside the Dutch borders or in the North Sea which is probably due to an error in the co-ordinates. The X-co-ordinate for the plot (213;388) was set to 212.9, in order to be it within the Dutch borders.

Presence and quality of values for response variables

2952 records were excluded since they consisted completely of 0's or missing values for the variables NAALD(1…4) (defoliation class), KLEUR(1…4) (discoloration class) and VIT(1…5) (vitality class). Through this action, 278 plots were completely excluded. Further selection was applied on the remaining 18317 records (3473 plots). One negative value for VIT4 and 7 negative values for VIT5 were treated as 0.

The total numbers for NAALD (1…4), KLEUR((1…4) and VIT (1…4 and 1…5) were compared. VIT(1…4) and VIT(1…5) were analysed separately, since the class VIT5 was meant for trees that had died in the previous year, although the recording of dead trees seemed not to be done very consistently. The total numbers per plot generally equalled 25, but was sometimes less. The total numbers for NAALD and KLEUR were the same for all records, except 2. For another 157 records, the total number for VIT (1…4) differed from the total numbers found for NAALD or KLEUR. For even more records (1509), the total number for VIT (1…5) differed from the total numbers for NAALD or KLEUR.

The reason for these differences could only be checked for part of the data, since the source files were only available for the years 1988 onwards. This was a serious limitation since most data were collected in the first years, especially in 1984. Furthermore, the values for VIT have been derived by different methods in the various years: either by direct assessment or by calculation from the results for NAALD and KLEUR. Therefore, the VIT data are less suitable for a time series analyses. Moreover, the results for VIT5 should be excluded from this analysis, since there is no direct relationship with the results for NAALD and KLEUR. The variable VIT5 has been renamed to Mort (= Mortality), since this name is more clearly related to the special features of this variable. The consistency of this variable, however, remains limited, since it is not clear whether dead trees or trees that had died since the latest assessment were always recorded in the same way.

Presence and quality of values for biotic stress factors

The sources gave information of the observation of several natural biotic stress factors, such as fungi and insects and on the level of infestation. Since the beginning of the recordings, the way of recording the insect an fungal damage have been changed several times. In some years, species that had to be recorded were added or removed from the forms or the classes in which the measure of damage had to be recorded were adapted. Hence the raw data could not be used. Because of the importance of biotic stress factors, a rough index for insect and fungal damage was developed, based on the recorded data. Three types of damage were distinguished: fungal damage, bark beetle damage and damage by other, mainly leaf eating, insects. The measure of damage for all categories was divided in four classes: 1: no damage, 2: < 40% of trees have damage, 3: 40-50% of trees have damage, 4: = 61% of trees have damage.

Check of consistency of assessed stands

In principle, the assessed stands are uniquely characterized by their position (X and Y co-ordinates). The only change in stand could be related by the replacement of one stand by another, subsequent stand on the `same' spot, e.g. after a clear-cut. However, it became clear that in several cases different stands had been assessed at the same spot. Therefore, the species and the year of germination (or plantation) had to be added as additional characteristics. Minor deviations were allowed, when the data from one plot were clustered into stands (combinations of location, species and year of germination). As a side effect, this strategy could lead to the exclusion of results if erroneously a wrong species or year or germination were filled in. This is, however, merely due to the poor check of the correctness of the selected stands during the field assessments.

Time series analysis can only be applied when the time series of one plot is recorded for the same stand and tree species. For some plots however, different tree species were recorded during the recording period. In a limited number of cases, the tree species could be `corrected', in order to have the same tree species in all years a certain plot has been assessed. This was possible in the case of two species that are hard to distinguish and in combinations of known tree species with `unknown/not recorded' or with `other conifers' or `other broadleaves', if also the year of germination was comparable. The combinations for which such an approach was applied were Corsican with Austrian Black Pine and Japanese with European Larch. Furthermore, it was checked whether the code ZE (Zwarte Els, Black Alder) was used, when Pedunculate Oak (Zomer Eik; EI) was meant. The tree species has been `corrected' for a total of 163 records.

Besides the tree species, the recorded `year of germination' (kiemjaar) was used to cluster observations into groups of annual observations which were probably done at the same stand. Years of germination before the year 1700 (including the year 0) were treated as errors. A variation within 10 years (i.e. maximum difference was 9 years) was allowed for considering different observations as one stand. The combination of species and year of germination resulted in the characterization of one or more stands per plot. The maximum number of stands distinguished at the same plot equalled five. However, most of such stands referred to only one or two annual assessments. The data for one plot had to be excluded, since no year of germination was recorded. On the other hand, several observations without year of germination could be attributed to a known stand at the same plot by using the dominant height as a way of comparison.

Consecutively all data were excluded for all stands for which only one or two annual observations were available, because (i) these stands were more likely to be the result of one or more errors in the observed species or year of germination and (ii) time series consisting of only one or two annual observations are of no use in a time series analysis.

It was assumed that data that passed the selection criteria and ended up in the data base, was reliable enough to perform a time series analysis on (considering the possibilities to check this). The resulting data base includes data for 2873 stands at 2639 plots (Annex 1). The total number of annual observations equals 13765, which is about two third of the original data base (21273 records). The data for 1115 of the originally included plots did not pass the criteria. At 234 plots, two stands were distinguished. These two stands were of a different species at 122 of these plots. The two stands at the remaining 112 plots were of the same species, but differed only in year of germination. The largest number of stands per plot equalled two. Furthermore, it is remarkable that none of the stands have been assessed for the whole period of time that the recordings have been carried out (1984-1998). Always at least one year is missing.

The value of these numbers can be compared with the number of observations for a reliable statistical analysis. Since the analyses have to be carried out per tree species, the numbers per tree species are most important. Only when the species have a very similar ecological behaviour, the analysis of more than one species together can be considered. The stand level is the highest level of variation for the analysis of separate tree species, since the annual observations at the same plot are probably intercorrelated. Considering the number of degrees of freedom required for the correlative model, the number of stand required for statistical analysis should at least be around 100. Eight species fulfil this requirement: Scots Pine, Corsican Pine, Douglas Fir, Norway Spruce, Japanese Larch, Oak, Beech and Poplar.

The completeness of the series of annual observations is an important condition for a proper time series analysis. As noted, the number of observations per stand varied considerably and none of the stands had a complete time series. In principle, it is possible to carry out a time series analysis with only three annual observations. However, the possibilities to assess statistically significant temporal relationships strongly depend on the number of annual observations at the same stand. In principle, the time series analysis can be done for all the species with enough stands that haven't been mentioned earlier (since all stands have at least 3 annual assessments). However, the best results can be expected for the species with a considerable number of long time series (e.g. at least 6 observations for at least 100 stands). This is only the case for Scots Pine and Oak. If less strong conditions are applied (e.g. at least 5 observations for at least 70 stands), there are also sufficient data for Corsican Pine, Douglas Fir and Norway Spruce. If a species is included in the time series analysis, based on these criteria, also the stands of the same species with a shorter time series can be included in the analysis.

2.3.2 Stress factors and other predictor variables derived from overlay with digitilized maps and grid-oriented data bases

Several stress factors and other important predictor variables can be estimated most precisely by applying overlay techniques with maps or grid-oriented data bases with the relevant information. Main objective with this part of the work was, to use the most detailed maps or data bases available, which also covered the entire country. Within this project, two main sources of such information were available:

- the Digital Soil map of the Netherlands (scale 1 : 50,000) (De Vries & Denneboom, 1992), which is polygon-oriented data base with information on soil type and ground water table, according to Steur & Heijink (1991)
- the 4th Forest Statistics of the Netherlands (Nederlandse Bosstatistiek, 1985), which is grid-oriented (250x250 m^2 and 1x1 km^2) with information on the forests in these grids, including information on forest history, stand characteristics and ownership. Since most plots were located at the km intersections, the values from the cell located south west of the plot are selected (related to the way a stand is selected).

De following characteristics were directly derived form the mentioned data bases and stored for use as predictor variable or for the estimation of additional stress factors:
- soil type (the most detailed level of available soil types)
- ground water table class (the most detailed level of available classes)
- the period in which the considered plot was afforested (<1800, 1800–1850, 1850–1900, 1900–1950 and >1950)
- the land use type previous to forest (old forest, agriculture, waste land, unknown), combined with the way of transition (plantation, spontaneous, unknown).

The average purity of the information from the soil map is generally estimated on 70% (Steur & Heijink, 1987). However, the inaccuracies in the mapping units generally consist of closely related soil types and groundwater tables. The degree of inconsistency might decrease considerably, after a clustering in larger groups of related types is applied (see later-on). The uncertainty of the information from the Forest Statistics is related to the generalisation of the information to the grids of 250x250 m^2 and 1x1 km^2. Stand-dependent characteristics such as tree species are generally much stronger affected, since the average size of the forest stands is generally smaller than the grid size.

Besides the direct information from these data bases, this information was also used to derive stress factors that could be estimated with the help of this information. This included information on chemical and physical soil characteristics and a characterization of the climax vegetation (potential natural vegetation). The potential natural vegetation was estimated from soil type information and information of the forest history cf. The AlBos model (De Vries & Hendriks, 1996). A transfer function was applied to estimate the available water capacity (VLV) of the root zone in five classes, based on the soil type and the water table class (De Vries & Hendriks, 1996). Regression analysis was applied to estimate the various soil chemical variables from the soil type, the water table class, the tree species, the available water capacity and the position (based on the distance to the coast and a SW-NE-component). The soil types and ground water table classes were clustered according to the methods used in the model Smart (Kros et al. 1995). The soil chemical data were derived from three country-wide surveys on the chemical soil composition under forests (De Vries & Leeters, 1998; Leeters & De Vries, in prep.; Klap et al., 1998). The soil type information from the map coincided with the field estimations for 77 to 84 %, depending on some variations in the way of clustering.

The estimations for the soil chemical composition were applied on the top 30 cm of the mineral soil, and were limited to solid phase variables (no soil solution variables). It was considered that these variables were constant through the entire period of observation and that they are affected less by short-term variations in hydrological and meteorological conditions or in atmospheric deposition. The selected variables are directly related to the acidity and nutritional status of the soil. The nutrient variables can be considered as reasonable alternatives for the foliar chemistry as predictor variable for crown condition. Table 1 gives an overview of the selected variables and the selected regression model by (backward) step-wise regression. The percentages of explained variance indicate that the predicted values are generally very useful, possible except for the values for oxalate-extractable P and exchangeable K.

Table 1 Applied regression models for the extra/interpolation of soil chemical variables

Variable	Model	% R^2_{adj}	Sign. [1)]
Org. matter	SoilType + Lime + TreeSpecies + GrWatTable +DisSwNe + DisCoast	87.0	***
pH(KCl)	SoilType + Lime + GrWatTable + DisCoast	72.0	***
$CaCO_3$	Lime + TreeSpecies + DisCoast	68.8	***
C/N	SoilType + TreeSpecies + GrWatTable	57.1	***
N/P	SoilType + Lime + GrWatTable + AvWater + DisSwNe	60.1	***
P_{ox}	SoilType + TreeSpecies + GrWaterTable	42.7	***
% Ca_{exch}	SoilType + Lime + TreeSpecies + AvWater + DisCoast	66.9	***
% K_{exch}	SoilType + DisCoast	20.3	***
% Mg_{exch}	SoilType + TreeSpecies + DisCoast	61.2	***
% BC_{exch}	SoilType + Lime + TreeSpecies + DisCoast	74.2	***

[1)] Significance: – = P>0.1; * = P<0.1; ** = P<0.01 ; *** = P<0.001

2.3.3 Site-specific estimates for meteorology and air pollution

The estimation of meteorological variables was completely based on bi-hourly measurements at the 12 regular meteorological stations of KNMI (Royal Dutch Meteorological Institute). The variables considered included temperature, precipitation, wind speed, wind direction, global radiation and relative humidity. All these variables were interpolated to the considered stands and plots, using standard interpolation techniques. It has been considered to include precipitation data from the much denser precipitation monitoring network, instead, because the interpolated values of precipitation are more reliable when based a nearby meteorological station. This, however, appeared not to be feasible within the short period of the project. Moreover, the use of these data was anyhow limited by its financial requirements. The interpolated meteorological variables were (i) used in the models by which the atmospheric deposition was estimated and (ii) aggregated to monthly and seasonal key parameters on meteorological stress.

Estimation of atmospheric deposition

Site-specific estimates of the deposition of acidifying compound (SO_x, NO_y and NH_z) were calculated using the model DEADM. This model combines estimates for the wet deposition of these compounds with modelled estimates for the dry deposition. The dry deposition model uses data on the ambient concentrations of theses gases, combined with an estimation of the deposition velocity using stand characteristics and meteorological conditions. The results of the deposition model DEADM have been validated by ECN by comparing model estimates with field measurements of the throughfall for the 14 sites that are within the Pan-European Intensive Monitoring Programme (Erisman et al., 1997). The results of this validation shows, that in most cases the model offers very valuable estimates. The largest deviations are related to stands with a mixed species composition, since only the known main species is considered in the model, whereas other species sometimes also have a strong effect on the deposition velocity. The most important source of possible errors is thus the lack of information on the species composition and the structure of the considered stands (and their surroundings), since only the main species (and its age) is given.

Estimation of drought stress using a water balance model

Site-specific estimates for the occurrence of drought stress were calculated be extending the model DEADM with a sub-routine, which calculated a daily moisture balance of the forest ecosystem. This subroutine was originally developed for the use with the model EDACS (for the European scale; Klap et al., 1997). Special effort was made to combine the daily basis for calculations of the water balance model with the bi-hourly basis of DEADM. Drought stress is estimated as the relative transpiration (RET), which is the seasonal mean value of the ratio of the estimated actual transpiration and the maximal transpiration under certain meteorological conditions. The monthly precipitation sums are also calculated from the bi-hourly precipitation values, to provide alternative predictor variables that are more in line with those applied on the 1995 crown condition data. Validation of the model is currently carried out, using the data of ca. 300 sites distributed over North-, Central and Western-Europe.

Estimation of temperature stress indicators

The bi-hourly temperature data are aggregated in two steps into more useful predictor variables. In a first step daily mean, minimum and maximum values are calculated. In a second step, these daily values are aggregated into monthly and seasonal key factors. For all months, the average minimum value, the average mean value and the average maximum value were calculated. Besides, the daily values were used to calculate the following seasonal/annual key parameters:

- winter index (= sum of daily mean temperatures < 0^{o}C in the winter season),
- late frost index (= lowest minimum temperature in spring period from April 1 onwards),
- growth index (= sum of daily mean temperature above certain limit, i.c. 5^{o}C and 10^{o}C) and
- heat index (= sum of daily maximum temperatures above a certain high limit, i.c. 30^{o}C).

These values have not been validated. However, it is expected that the results are very close to the reality, since the aggregation procedure strongly diminishes the effects of possible outlyers in the interpolation procedure. The strongest deviations in the interpolation procedure could be expected for the precipitation, due to its relatively strong spatial variability. The spatial variability of precipitation (and temperatures) at a longer time resolution, however, is generally considerably smaller.

2.4 Statistical methods

2.4.1 Exploration of the data

Exploration of the data is performed to facilitate a proper application of the statistical methods. Insight in the level and the variation of relevant variables makes it possible to judge the results of the statistical models. Depending on level and range, effects of variables on defoliation may be expected, demonstrated and explained or not. Insight in the data is gained by calculation of the frequency distribution for each variable. Based on maximum, minimum, 5%, 95% median values (annex 4), and the standard deviation, the variation of the variables is described and the expectation about a possible effect in the regression analysis is given (section 3.4).

2.4.2 Assessment of the relationships

The establishment of relationships between defoliation and explaining variables has been worked out in two steps. The aim of first step was to assess rough relationships on the base of which a choice can be made for which of the tree species a further, more detailed, analysis of the relationship seems useful. This more detailed assessment of relationships is carried out in the second step of the analysis.

2.4.2.1 Random part of the statistical model

In the statistical analysis one would like to account for random location effects and also for temporal correlation within locations. Random location effects allow for differences between locations in climate, soil, cultivation methods and so on that are not accounted for by the predictor variables. If such unmodelled effects are not accounted for, it might for instance happen that low defoliation measurements at a location over several years would be wrongly considered as independent evidence of advantageous location values, while the low defoliation may in fact be triggered by the same unmodelled cause all the time. With respect to temporal correlation within locations, it is likely that defoliation measurements at the same location will be correlated, with correlation decreasing over time. A so-called first-order autoregressive model within locations was therefore added to the random location effects. The autoregressive part of the model assumes that the correlation between measurements within the same location which are k years apart equals ρ^k, with ρ the autocorrelation parameter. This completes the random part of the model. The model was fitted using the REML facilities of Genstat (1997). However the REML procedure did not converge, which appears to be due to the large number of location-time combinations at which observations are missing. Fortunately, Diggle et al (1994) note that for short time series autoregressive models may well be replaced by a uniform correlation model. So the autoregressive part of the model was omitted, while retaining the random location effects. This model is known as the split-plot model and it assumes that the correlation ρ between observations within locations is constant, irrespective of the time gap between observations. The split-plot model was also fitted using the REML facilities of Genstat.

2.4.2.2 Fixed part of the statistical model: selection of predictor variables

There are various methods for choosing a regression model when there are many predictor variables, see e.g. Montgomery and Peck (1992). The fitting of all possible models, which is the method of choice, within a REML context is not feasible due to the computational burden. Therefore an iterative stepwise selection procedure, similarly to stepwise regression in ordinary linear regression, was implemented for the split-plot model. Every step consists of the following two parts.

1. For all the predictor variables in the current model the Wald test for deleting a predictor is calculated. If one or more of these Wald tests are not significant, the predictor with the largest p-value is deleted from the model. This is repeated until no more predictors can be deleted from the model.
2. All the predictor variables which are not in the current model are added one at a time. This results in a Wald test for inclusion of such predictor variables. If one or more of these tests are significant, the predictor with the smallest p-value is added to the model.

The stepwise procedure ends when the current model is not modified in the above two steps. The significance level used throughout this study is 5%. Quadratic effects of predictors was always tested with the corresponding linear effect in the model.

The predictor variables that are included in the model (annex 2) are selected partly on the base of the results of an informal assessment of relevant predictor variables, which is described in next section, and partly on literature and expert knowledge. Especially for the meteorological predictor variables a manner was found to limit the number of variables. The meteorological variables were clustered for two relevant periods such as the growing season (April to September) and winter period (December previous year to March in year of recording). Besides these two periods also total sums (precipitation), averages, minima and maxima (all temperature) were used for the period between two moments of recording (August previous year to July year of recording). Based on literature and expert knowledge for most predictor variables a non-linear relationship was expected with defoliation. For most variables, the exact type of relationship is not known, but a relationship with some kind of optimum or maximum/minimum is expected. Therefore a quadratic term of all predictor variables was included in the model, for testing the non-linearity.

2.4.2.3 Informal assessment of relevant predictor variables

The stepwise selection procedure for the split-plot model is very computer intensive, especially when there are a large number of predictor variables as is the case in this study. Therefore, prior to the split-plot analysis, an informal assessment of the relationships between defoliation class and predictor variables was carried out using ordinary linear regression. This analysis disregards the random structure of the data and is possibly too optimistic about the significance of predictor variables. The results should therefore be interpreted with caution.

The informal assessment of the relationships between defoliation class and explaining variables is carried out with methods for multiple linear regression analysis. Originally, it was the intention to apply the SELECT procedure of the statistical language GENSTAT (Genstat 5 committee 1997). By means of this procedure the best subset of predictor variables can be selected from all possible models explaining the response variable, which in our case is mean defoliation class. The SELECT procedure is almost equal to the RSELECT procedure that has been applied in earlier crown condition studies (i.e. Hendriks et al. 1997). The most important differences between SELECT and RSELECT are the possibility to include factors having more than one level (i.e. soil type and period of afforestation) and the number of variables (only 15 variables in the SELECT and 27 in the RSELECT procedure) that can be included freely in search for the optimal model selection.

Because only a limited number of variables can be included in the SELECT procedure, a selection of the variables had to be made. When 15 variables are included as free variables, at most 12 variables can be included as forced. Hence the total number of variables that can be included in the SELECT procedure is 27. The total number of relevant variables, however, is much larger, namely 84, and even 105 when the levels of the factors (soil type, soil moisture supply, period of afforestation, former land use) are counted separately. It will be clear that a significant reduction of variables is required for inputting to the SELECT procedure. At first, for each tree species separately, a backward regression analysis is applied. The principle of backward selection is deleting non-significant terms from the model including all variables. Then a model, containing only significant terms remains. The significant variables then can be included in the SELECT procedure. However, the number of significant variables, found through the backward selection, was much higher as expected (up to 57 for beech), by which other reducing steps were necessary, for only 27 variables could be included in the SELECT procedure.

At first a selection was made on the base of the plausibility of the combination of variables, the state of the correlation (positive or negative) and the student t-statistics. A logical set of variables was selected for which the sign of the correlation was plausible and the t-value was up to 4. Then a separation was made which variable had to be included free and which had to be included forced in the SELECT procedure. As forced variables, variables were selected for which a stable significant correlation with defoliation was demonstrated in earlier studies (Hendriks et al. 1997, Klap et al

1997). Remaining variables were included as free variables. With this set of variables, which was different per tree species, the SELECT procedure was performed.

The results of the SELECT procedure with this strongly reduced set of variables were somewhat disappointing. Therefore, as a next step, a forward selection was applied. The forward selection lead to a serious reduction in the number of variables (at most 19 for Scots pine), which was the purpose. The reduction of the percentage variation accounted for, however, was also seriously compared to the percentages found in the backward analysis. Based on these percentages it was concluded that a SELECT procedure with the variables found from the forward selection would not be very useful.

On the base of the results from this informal analysis no well-founded selection of tree species could be made. Therefore additional criteria were formulated (section 3.4).

3 Results

3.1 Informal assessment of relationships between defoliation and explaining factors.

The objective of this informal assessment is to provide criteria on the basis of which a choice can be made for which of the tree species a detailed analysis will be the most useful. The method to do so is described in paragraph 2.4.2, where the results of the backward and forward selection are described respectively.

3.2 Backward selection of variables

The first thing that strikes, when considering the results of the backward selection (annex 1 table A1.1), is the large number of variables that are demonstrated to be significant. The number varies from 29 for Japanese larch to 57 for beech. This large number is rather unexpected and hampers the selection for input variables in the SELECT procedure. In order to see whether a further reduction of the number of variables is possible, the models found are discussed per tree species.

Confounding or interaction with other variables may have influenced the results found. Interaction terms have not been included in the model, mainly to keep it simple in this informal phase of the analysis. The possible omission of relevant variables or, contrarily, the excess of variables or the little specific character of the variables may also influence the results. Some variables are missing because we don't have data on them (e.g. foliar nutrient content, air concentrations of air pollutants etc.). Concerning a possible excess, it is unknown whether meteorological data can best be fitted as monthly values or generalised annual or seasonal data or a combination of annual indices and monthly data.

A general result for all tree species is the significance of monthly meteorological variables. However, not much can be said about the influence of these variables because the correlations found are alternately positive and negative without a clear pattern like for instance a seasonal one.

The annual temperature sums above 5^{o}C and above 10^{o}C (ETS5 and ETS10 resp.) are found to be very significant for almost all tree species. It is, however, difficult to interpretate the meaning of these indices because the sign of the correlation is opposite (resp. positive and negative). Plant physiological processes may be repsonsible for this type of correlation.

3.3 Forward selection of variables

Compared to the backward selection, a large reduction of significant variables has been achieved through forward selection for all tree species, however, the percentage variation accounted for also decreased significantly for all tree species, varying from 2.1% for Scots pine to 16.5% for beech (annex 1 table A1.2). The reduction of the number of significant variables has mainly taken place for the monthly meteorological variables. For beech even no significant monthly meteorological variables were found to be significant in the forward selection, while in the backward selection beech had the largest number of significant meteorological variables (annex 1 table A1.1).

3.4 Conclusions of the informal assessment

The results of the backward and forward selection did not bring the clearness which it was hoped to bring to the foundation of the choice for which tree species a further detailed analysis would be useful. The backward selection of variables resulted in models with very large number of predictors, which hampers the interpretation of these models and obstructed a proper execution of an optimal model selection with the SELECT procedure of GENSTAT.

Through forward selection a confirmation of the results of the backward selection analysis was obtained, hoping it would facilitate the interpretation of the models. However the number of significant variables seriously reduced by the forward selection, it was difficult to compare both selection methods in search of the optimal model. The models found through forward selection in general were quite plausible, but they unfortunately make only little sound.

On the base of the results of the backward and forward selection of predictors only, it is difficult to make a well-founded selection of tree species for which a more detailed analysis will be useful. Therefore some additional, and more subjective, criteria were used for the selection. As tree species for detailed analysis of the defoliation, oak, scots pine, and Douglas-fir were selected.

Comparing the score for the percentage variance accounted for (annex 1 table A1.1 and A1.2) it is found that Douglas-fir and Japanese larch in both the forward and backward selection have the lowest $R^2_{adj.}$ For this reason a further analysis is considered not to be useful for these species.

The highest percentages accounted for are found for Norway spruce, Scots pine and Corsican pine. Selection of these species will induce the omission of the deciduous species, which is considered as undesirable. Therefore Corsican pine is dropped for further analysis because it is also a pine species, just like Scots pine, but the number of stands is much smaller than for Scots pine, and the mean $R^2_{adj.}$ of the forward and backward selection was poorer for Corsican pine than for Scots pine.

Thus, for the third tree species a choice has to be made between oak and beech. If the number of stands is considered, oak has an advantage, having up to four times the number of stand of beech. The mean percentage accounted for of the backward and forward selection is about 4% higher for beech. However, this is due to the high $R^2_{adj.}$ of the backward selection, for which a very large number of monthly meteorological variables was needed. If this number is reduced, the $R^2_{adj.}$ decreases below the level for oak, which is demonstrated in the forward selection. An additional factor, to the credit for oak, is the knowledge about relevant predictors from earlier studies (i.e. Hendriks et al. 1997). Therefore, oak will be the third tree species for a detailed selection.

3.5 Detailed relationships between defoliation and explaining factors

3.5.1 Oak

The detailed split-plot analysis of the oak data resulted in an explaining model that contains 14 different predictors, excluding the constant (Table). This set of 14 different predictors consists of 10 different variables. This is because for four of the predictors a linear as well as a square term are included in the model, expressing non-linearity of the variable. This indicates that the relationship of the predictor and the defoliation class can be described with a parabolic function. For the predictors that are included with only a linear term, the square term was not significantly. However, it does not mean that the relationship sure is linear, but that, based on the present data, a linear relationship represented a better fit than the non-linear function.

The percentage variance accounted for ($R^2_{adj.}$) calculated with this model for oak is 22.59%.

Besides the predictors affecting defoliation, also the time effect itself on defoliation was tested. From this variance component analysis resulted that the variance in defoliation is much larger between years than between plots. The variance component for oak plots was 0.0444 and for plot*year it was 0.2644, about six times higher. This means that variance in defoliation of plots in time is larger than variation in space. Hence the temporal variation must be closely related to predictors that also show large variation in time, such as meteorological predictors.

Based on previous studies (e.g. Hendriks et al. 1994, Hendriks et al. 1997, Klap et al. 1997), the demonstrated negative effect of stand age on defoliation class was expected. The maximum of the function is calculated on about 1868 years, which can be interpreted as the physiological maximum for stand age of oak.

Table 2 Relevant predictors explaining defoliation of oak with their values of estimates, standard error, t-value, p-value and the maximum or minimum of the non-linear function

Predictor	Estimate	Standard error	t-value	p-value	max or minimum
Constant	1.807	$0.160*10^{-1}$	113.11	0.000	
Stand age	0.198	$0.585*10^{-1}$	3.39	0.001	1870
(Stand age)^2	$-0.531*10^{-4}$	$0.152*10^{-4}$	-3.49	0.000	
SO_x	$0.183*10^{-3}$	$0.353*10^{-4}$	5.20	0.000	
NO_x	$0.111*10^{-2}$	$0.466*10^{-3}$	2.38	0.017	798
$(NO_x)^2$	$-0.695*10^{-6}$	$0.193*10^{-6}$	-3.60	0.000	
NH_x	$0.336*10^{-3}$	$0.709*10^{-4}$	4.75	0.000	4382
$(NH_x)^2$	$-0.384*10^{-4}$	$0.123*10^{-7}$	-3.13	0.002	
N/P ratio	$0.152*10^{-1}$	$0.551*10^{-2}$	2.8	0.006	
Relative transpiration	0.441	0.156	2.83	0.005	
Rel tran previous years	-2.661	0.935	-2.85	0.004	0.65
Rel tran previous years^2	2.061	0.635	3.25	0.001	
Max summer temp	-0.297	$0.431*10^{-1}$	-6.89	0.000	
Soil moisture availability	0.702	$0.219*10^{-1}$	3.21	0.001	
Insect damage	0.176	0.111	7.71	0.000	
$R^2_{adj.}$	22.59				

All air pollution predictors (SO_x, NO_x, NH_x) are selected from the total set of relevant variables, and the relationship is demonstrated to be quite significant (Table 2). For all the three air pollution components a positive relationship is found with defoliation, indicating an increasing defoliation with an increasing deposition level. From the estimates of NO_x, NO_x^2, NH_x and NH_x^2 a maximum level is calculated above which an increase in deposition level has no further effect on the defoliation. For SO_x the square term was not significant, thus no maximum could be calculated. For NO_x the maximum amounts about 800 mol ha^{-1} a^{-1}. This maximum is quite low when considering the average deposition level on oak stands over the period 1984-1994 which is about 1200 mol ha^{-1} a^{-1}. For NH_x the maximum effect level is calculated on about 4400 mol ha^{-1} a^{-1}, which is higher than the maximum deposition level over the period considered.

The N/P ratio is positively correlated with the defoliation class, meaning that defoliation increases with an increasing N/P ratio. The N/P ratio increases with an increasing N status of the soil, which, in its turn, is strongly affected by the level of N deposition (Leeters et al. 1997).

For transpiration also a significant relationship is found with defoliation. The relative transpiration in the year of the recording of the defoliation as well as the relative transpiration in the three previous years of the recording are found to be significantly correlated with the defoliation class. The relative transpiration in the year of recording is positively correlated with the defoliation class, while a negative correlation was expected. The relative transpiration of previous years is, as expected, negatively correlated. This means that defoliation increases with a decreasing relative transpiration. The relative transpiration is low when precipitation is low and transpiration (viz. temperature) is high. For the relative transpiration of the previous years, a minimum level is calculated on 0.65. Below this level (viz. in the range 0.65-1.0) no further effect of relative transpiration is expected.

The maximum temperature in the summer period is negatively correlated with the defoliation class. The defoliation class decreases (i.e. more foliage) with an increasing temperature during the summer period. This is in accordance with results from earlier studies on the defoliation of oak (Hendriks et al. 1997).

The soil moisture availability class is positively correlated with the defoliation class, which was also expected. A high class of soil moisture availability means a low amount of available soil moisture (e.g class 1 equals > 200 mm, class 5 equals < 50 mm). Hence the defoliation increases with decreasing soil moisture availability.

The insect damage class is, as expected, positively correlated with the defoliation class. A low insect damage class means little insect damage (mainly damage by caterpillars). Thus defoliation is low when insect damage is also low and the other way round.

3.5.2 Scots pine

The detailed split-plot analysis of the Scots pine data resulted in an explaining model that contains 25 predictors excluding the constant (Table 3). Possibly more than 25 predictors are significant, but this could not be tested because 25 is the maximum number of predictors that can be included in a model within the REML procedure. The set of 25 different predictors consists of 14 different variables. Hence for eleven predictors a linear as well as a square term are included in the model, expressing non-linearity of the relationship of the variable and the defoliation class. For the predictors that are included with only a linear term, the square term was not significant or could not be included because of the maximum number of predictors in the REML procedure. Thus, when predictors are included in the model with only a linear term, the relationship, based on the present data, described with a linear function gave a better result than with the tested non-linear function.

The percentage variance accounted for ($R^2_{adj.}$) for Scots pine calculated with this model is 33.73%.

For Scots pine it resulted, from the variance component analysis, that the variance in defoliation is much larger between years than between plots. The variance component for plots of Scots pine was 0.0381 and for plot*year it was 0.2559. This means that variance in defoliation of plots in time is larger than variation in space. Hence the temporal variation must be closely related to predictors that also show large variation in time, such as meteorological predictors.

Table 3 Relevant predictors explaining defoliation of Scots pine with their values for estimates, standard error, t-value, p-value and maximum or minimum of the non-linear function

Predictor	Estimate	Standard error	t-value	p-value	max / minimum
Constant	1.633	$0.907*10^{-2}$	180.05	0.000	
Stand age	0.268	$0.489*10^{-1}$	5.48	0.000	1898
(Stand age)^2	$-0.705*10^{-4}$	$0.127*10^{-4}$	-5.56	0.000	
SO_x	$0.350*10^{-3}$	$0.401*10^{-4}$	8.71	0.000	3023
$(SO_x)^2$	$-0.554*10^{-7}$	$0.661*10^{-8}$	-8.38	0.000	
NO_x	$0.185*10^{-3}$	$0.248*10^{-3}$	7.44	0.000	1863
$(NO_x)^2$	$-0.516*10^{-6}$	$0.906*10^{-7}$	-5.69	0.000	
NH_x	$-0.162*10^{-3}$	$0.450*10^{-4}$	-3.60	0.000	4466
$(NH_x)^2$	$0.181*10^{-7}$	$0.653*10^{-8}$	2.78	0.005	
N/P ratio	$0.654*10^{-1}$	$0.133*10^{-1}$	4.91	0.000	
C/N ratio	$-0.751*10^{-1}$	$0.132*10^{-1}$	-5.69	0.000	
Basic cations	$-1.491*10^{+1}$	2.596	-5.74	0.000	0.27
Basic cations^2	$2.882*10^{+1}$	5.864	4.92	0.000	
Prec sum grow season	$0.156*10^{-1}$	$0.394*10^{-2}$	3.97	0.000	279
Prec sum grow season^2	$-0.287*10^{-4}$	$0.756*10^{-5}$	-3.80	0.000	
Avg. winter temp.	2.705	1.382	1.96	0.050	3.65
Avg. winter temp.^{2}	-0.370	0.183	-2.03	0.043	
Relative transpiration	2.369	0.939	2.52	0.012	0.61
Relative transpiration^2	-1.956	0.53	-3.36	0.001	
Rel tran previous years	-2.395	0.102	-23.5	0.000	
Soil moisture availability	0.285	$0.723*10^{-1}$	3.94	0.000	2.07
Soil moist availability^2	$-0.802*10^{-1}$	$0.101*10^{-1}$	-7.91	0.000	
Insect damage	0.915	0.231	3.96	0.000	2.28
Insect damage^2	-0.201	$0.659*10^{-1}$	-3.04	0.002	
Fungal damage	-0.783	0.115	-6.82	0.000	2.06
Fungal damage^2	0.191	$0.344*10^{-1}$	5.53	0.000	
$R^2_{adj.}$	33.73				

From the split plot analysis, stand age resulted as a significant factor. With increasing stand age defoliation also increases, which was as expected. The calculated maximum value, above which defoliation does not further increases, is 1898 years. This probably is an indication of the potential physiological age of Scots pine under optimal growing conditions.

All tested air pollution components were found to be very significant. For all three components (SO_x, NO_x, and NH_x) the square term was significant and thus a non-linear relationship represents a better fit on the data than a linear fit. The maximum deposition level above which no further effect of the deposition may be expected is about 3000 mol ha^{-1} a^{-1}, 1900 mol ha^{-1} a^{-1} and 4500 mol ha^{-1} a^{-1} for SO_x, NO_x, and NH_x respectively. The maximum level for NO_x is more than 1000 mol ha^{-1} a^{-1} higher than the maximum calculated for oak (Table 2). The average SO_x deposition level over the period 1984-1994 equals about 1750 mol ha^{-1}. The maximum for the NO_x deposition level amounts about 1800-1900 mol ha^{-1} a^{-1}. The average deposition level on Scots pine stands over the period 1984-1994 amounts 1250 mol ha^{-1}. For NH_x the maximum and average over the period concerned equals about 4500 mol ha^{-1} a^{-1} and about 2500-3000 mol ha^{-1}.

The element ratios of N/P and C/N and the fraction basic cations all show expected relationships with the defoliation class. For the C/N and N/P ratio the defoliation increases with an increasing amounts of nitrogen. Defoliation decreases with an increasing fraction of basic cations in the soil solution. The minimum for the basic cations suggest that defoliation increases below a basic cation fraction of about 0.3.

From the set of tested meteorological parameters, the precipitation in the growing season, the average winter temperature, and the relative transpiration showed to be significant. All predictors, except relative transpiration of the year of recording, are non-linear correlated with the defoliation class. Defoliation decreases with an increasing amount of precipitation during the growing season until the maximum of 270-280 mm, above which no further effect of precipitation is expected. The average winter temperature is also positively correlated with the defoliation class, meaning a decreasing defoliation with an increasing average winter temperature until the maximum of about 3.5 ^{o}C above which no further decrease of defoliation is expected. The relative transpiration in the year of recording is found to be positively correlated with the defoliation class. This is not exactly as expected, but it in line with the results for oak. The maximum above which defoliation will not further increase is calculated on about 0.6, which is comparable with the minimum found for the relative transpiration of previous years for oak (Table 2).

The soil moisture availability class was also found to be significantly and positive correlated to the defoliation class, meaning that the defoliation will decrease with an increasing soil moisture availability, which was expected. The maximum is calculated on 2.06. When considering the class width of the soil moisture availability, it can be interpreted as about 200 to 195 mm.

Finally, also insect and fungal damage significantly contributed to the explanation of the defoliation class. Insect damage is positively correlated with the defoliation class, which was also expected. However, fungal damage is negatively correlated with defoliation class, which is the other way round as expected. A similar negative effect between defoliation and fungal damage was found before by Hendriks et al. (1997).

3.5.3 Douglas-fir

The detailed split-plot analysis of the Douglas-fir data resulted in an explaining model that contains 9 predictors excluding the constant (Table 3)**.** The set of 9 different predictors consists of 7 different variables. Hence for only two predictors a linear as well as a square term are included in the model, expressing non-linearity of the relationship of the variable and the defoliation class. For the predictors that are included with only a linear term, the square term was not significant or could not be included because of the maximum number of predictors in the REML procedure. Thus, when predictors are included in the model with only a linear term, the relationship, based on the present data, described with a linear function gave a better result than with the tested non-linear function.

The percentage variance accounted for ($R^2_{adj.}$) for Douglas-fir calculated with this model is 23.85 %.

For Douglas-fir it was also found , from the variance component analysis, that the variance in defoliation is much larger between years than between plots. The variance component for plots of Douglas-fir was 0.0686 and for plot*year it was 0.2344. This means that variance in defoliation of plots in time is larger than variation in space. Hence the temporal variation must be closely related to predictors that also show large variation in time, such as meteorological predictors.

Table 4 Relevant predictors explaining defoliation of Douglas-fir with their values of estimates, standard error, t-value and p-value

Predictor	Estimate	Standard error	t-value	p-value	Max / minimum
Constant	2.546	$0.294*10^{-1}$	86.69	0.000	
SO_x	$-0.718*10^{-3}$	$0.122*10^{-3}$	-5.88	0.000	5167
$(SO_x)^2$	$0.695*10^{-7}$	$0.242*10^{-7}$	2.87	0.004	
NO_x	$0.940*10^{-3}$	$0.142*10^{-3}$	6.60	0.000	
NH_x	$-0.526*10^{-3}$	$0.181*10^{-3}$	-2.91	0.004	3199
$(NH_x)^2$	$0.822*10^{-7}$	$0.289*10^{-7}$	2.85	0.004	
Min temp grow season	-0.368	0.134	-2.74	0.006	
Average winter temp	0.346	0.177	1.95	0.051	
Precipitation grow seas	$-0.187*10^{-2}$	$0.902*10^{-3}$	-2.07	0.039	
Relative transpiration	0.453	0.178	2.55	0.011	
$R^2_{adj.}$	23.85				

It is striking that, contrary to the other tree species, no significant relationship between stand age and defoliation could be demonstrated. With the backward and forward selection stand age also did not turn out to be significant.

For all three air pollution components a significant contribution is demonstrated to the defoliation class. For SO_x and NH_x a non-linear relationship is found, while for NO_x only the linear term showed to be significant. It is remarkable that SO_x and NH_x are negatively correlated to the defoliation class, while a positive correlation was expected. In the backward and forward selection also a negative correlation was found for SO_x, while for NH_x no significant relationship was demonstrated. The minimum for SO_x and NH_x is calculated in between 5100 and 5200 mol ha^{-1} a^{-1} and 3200 mol ha^{-1} a^{-1} respectively. The minima suggest that defoliation decreases with increasing deposition levels, which was not expected on the forehand. The average SO_x and NH_x deposition level on Douglas-fir stands over the period 1984-1994 amounts about 1700 to 1800 mol ha^{-1} and about 2400 to 2500 mol ha^{-1} respectively.

The minimum temperature of the growing season showed to be negatively correlated with the defoliation class, indicating an increase in defoliation with a decreasing minimum temperature. The average winter temperature is positively correlated to the defoliation class, meaning more defoliation with increasing winter temperatures. The precipitation sum in the growing season is negatively correlated to the defoliation class. This is as expected: the more precipitation the less defoliation. The relative precipitation was found to be positively correlated to the defoliation class, while, on the forehand, a negative correlation was expected.

3.6 Conclusions of the detailed assessment

In general it can be said that the split-plot analysis resulted in plausible models for oak and Scots pine. The model for Douglas-fir is less plausible because of unexpected effects of air pollution components. Although the models are quite satisfactory, the percentages variance accounted for are rather low.

Although the percentages variance accounted for are low, it is quite encouraging that the hypothesis that air pollution and meteorological stress are important factors affecting defoliation is underlined by the results of this study. Apart from air pollution and meteorological variables also stand characteristics (stand age), site characteristics (element ratios such as N/P ratio) and biotic characteristics (insect and fungal damage) are important factors influencing defoliation.

On the forehand it was supposed that through the detailed analysis the relationship between defoliation and its determining factors could be established in more detail than with other statistical techniques that had been used in previous studies on this subject. This supposition has found only partly truth. The chance that relevant predictors found with the split-plot analysis are justly included in the model, is larger than for backward or forward selection or for models generated with the RSELECT procedure of GENSTAT. Also the significany of the included predictors and the estimation of the standard error is better for the split-plot analysis. Hence the models found with the split-plot analysis can be considered as more reliable than the models found with the backward and forward selection.

The reason that the split-plot analysis resulted in low percentages variance accounted for can be found partly in the data. For split-plot analysis it is important that as many as possible time series are available, without missing values. The data set on the defoliation class of the tree species for the period 1984-1994 however, contains many gaps. Analysis of the data set showed that for none of the tree species considered, even one single complete record was available, containing the defoliation class for one plot for the whole period. The major part of the records contains four or even more missing values for the relevant period. These missing values are quite certain the major reason for the disappointing percentages variance accounted for.

4 Discussion and conclusions

This study convincingly demonstrates that air pollution and meteorological conditions are related to defoliation of oak, Scots pine and Douglas-fir. Besides these time related factors also stand age, site characteristics and biotic damage affect defoliation. Despite very significant effects of most of these factors, the percentage variation accounted for was low for all tree species. The results also show that variation of defoliation on a plot in time (between years within plots) is larger than the variation of the defoliation in space (between locations).

For the first time in a Dutch study on relationships between defoliation and explaining factors a time series approach was performed. Missing data in the records of defoliation over the period 1984-1994, seriously hampered the possibilities of modelling the data in time. A first-order autoregressive model, inducing a decreasing correlation in time, could not be fitted. The practical solution adopted was a split plot analysis, in which the autocorrelation of defoliation in time is considered to be constant.

The predictor variables period of afforestation and former land use, which were not included in earlier studies, did not significantly contributed to the explanation of defoliation. The hypothesis that these factors are of large importance to crown condition could therefore not be convincingly demonstrated.

The results found in this study are generally in line with results of other studies (e.g. Hendriks et al. 1997b, Klap et al. 1997, Landmann and Bonneau 1995, Mather et al. 1995). However a time series analysis has not been carried out before. Effects of air pollution are demonstrated frequently (Ulrich and Matzer 1983, Innes 1993). Also from other studies abroad, field effects on defoliation were reported (Innes and Boswell 1988, Mather et al, 1995, Landmann and Bonneau 1995, Hendriks et al 1997b). But in the Netherlands no such strong combined effect, based on field data, was demonstrated before. This and the fact that for the first time a time series analysis was performed can be considered as a large step forward.

The low percentages variation accounted for are partially caused by using modelled and interpolated data instead of of measured data. There is considerable room for improvement there. The deposition data has been calculated by means of the deposition model DEADM (Erisman and Draaijers 1995). This model uses stand and tree species characteristics to calculate site specific deposition levels and it has shown to give a good performance (Erisman et al 1994). An omission is the absence of data on air concentration levels of NH_X, NO_X, SO_X, and O_3. The missing of data on the concentration levels of NH_X, NO_X, SO_X can be considered as only a minor problem because deposition levels and air concentration levels are closely related. In previous studies (e.g. Hendriks et al. 1997) it was demonstrated that air concentration levels are exchangeable with deposition levels. A larger omission is the absence of site specific measured meteorological data, especially precipitation, and ozone. For ozone no data was available for the time period of this study because nation wide measurements were carried out only since the beginning of the nineties. The importance of ozone is demonstrated in various studies (e.g. Hendriks et al. 1997, Innes and Boswell 1988, Mather et al. 1995) which show effects of ozone on tree growth and defoliation. It has been shown that meteorological data can be obtained quite reliable through interpolation (van der Voet et al. 1994). This, however, does not hold for precipitation, which, is the most important meteorological factor. Although the uncertainty in the calculated precipitation data is quite large, no better data could be obtained. Further the soil characteristics were derived from the soil map by means of linear regression, which also generates uncertainty in the data.

In addition to uncertainty about the predictor variables, the defoliation itself is a source of uncertainty. The defoliation is recorded in non-equidistant classes, presenting a quite rough subdivision of the defoliation. The influence of factors that cause only little variation in defoliation will not be expressed in the defoliation classes. Because this study is focussed on major effects, this is not considered as a major problem.

For oak and Scots pine, as expected, a positive correlation is found between defoliation class and deposition levels of NH_X, NO_X and SO_X. This implies an increase in defoliation with increasing deposition levels. For Douglas-fir, however, a negative correlation is found between defoliation class and deposition levels of NH_X, and SO_X. For NO_X a positive correlation was found. This unexpected effect is also found in other studies (e.g. Innes and Boswell 1988), who mentioned a possible fertilisation effect as a possible explanation. It is surprising that this effect only occurs with Douglas-fir, which is the only tree species in this study having a strong descending trend in crown condition (Reuver 1998). Over the period concerned, the deposition level of SO_x also strongly decreases. This might, by chance, agree with the decreasing crown condition, while one or more other relevant factors, possibly not included in this study, are the real correlated factors. Olsthoorn and Maas (1994) found that especially the P nutrition and presence of the fungi *Hetrobasidium annosum* are very important factor for crown condition of Douglas-fir. In current study nor the N/P ratio nor the fungal damage did contributed significantly to the explanation of defoliation. Another possibility is that through omission of a relevant factor a negative correlation is found, while a positive correlation will be found when the missing, confounded, factor is added (Oude Voshaar 1994).

Based on the results of this study it is recommended to record only near complete time series of crown condition. Although modelled data can be used in correlative studies, measured data is preferable because of the uncertainty in the results. Further it is recommended to investigate which alternative or additional parameters can be used to express forest condition.

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Annex 1 Backward and forward selection of variables

Backward selection of variables

Oak

For 1773 (84%) of the total number of observations for oak (2106) all data is available on the relevant variables (Annex 2). Compared to most other species, the number of significant predictors contributing to the explanation of the defoliation is relatively small, but still amounts to 36. The percentage variance accounted for is 38.1%. Ten variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic. It makes sense that there is a positive relation between SO_x and defoliation class. This means that more SO_x leads to more foliage loss, and therefore a higher defoliation class. The same seems true for the highly significant positive relation with insect damage and soil type. There is a significant influence of soil type. It is not clear why the temperature in June would have this highly significant relation, while the other summer months do not have a significant relation at all. A cold winter (winter index) has a negative effect on defoliation for this data set. The effects of other weather variables make a less clear impression, with ETS 5 showing a positive relation, while ETS 10 has a negative relation. Higher temperatures during the year and during the summer months (T avg and Heat index) are related to a lower defoliation class, meaning better foliage retention. The mechanism for this behaviour (different response to related variables) is not always clear.

A number of variables are also significant with $t \geq 4$. A higher age is related to less foliage (higher defoliation class), as is more NH_x deposition. More difficult to understand is the relation between defoliation class and potassium (K), and the period of forestation. Again the weather variables show a somewhat confusing pattern. Partly this might be due to interaction between the variables. This has not been tested, as the models would become even more complicated than they are.

Beech

For 415 (74%) of the total number of observations for beech (558) all data is available on the relevant variables (Annex 2). The number of significant predictors contributing to the explanation of the defoliation is the largest for all tree species: 57. The percentage variance accounted for is the largest for all tree species (44.3%), but this is unquestionable due to the large number of predictors. The most significant variables ($t \geq 6$) are the concentration of exchangeable basic cations (BC ex.), the annual temperature sum above 5°C (ETS5), the annual temperature sum above 10°C (ETS10), and the monthly precipitation of June, July and of December of the previous year (Monthly precipitation [6], [7], [12]).

Strikingly, the concentration of basic cations and the monthly precipitation of June and July are positive correlated to the defoliation class, which can be interpreted as an increase in defoliation at an increase of these variables, which was expected the other way round. The negative correlation of the December precipitation can well be explained by the supplementation of the soil moisture storage. In that case, however, it is remarkable that the precipitation of Januari, Februari and March are positively correlated.

As said, it is difficult to interpretate the meaning of the variables ETS5 and ETS10, especially because the sign of the correlation is contrarily (resp. positive and negative). Interpretation would indicate that defoliation increases at an increasing temperature sum above 5 ^{o}C but would decrease with an increasing temperature sum above 10 ^{0}C. The meaning of this is hard to understand, but might indicate a physiological response to temperature.

A small but significant effect was demonstrated for insect damage of leaf eating insects.

In general, it is remarkable that most of the monthly meteorological variables significantly contribute to the explanation of the defoliation class. But, it is also very remarkable that the monthly values are alternately positive and negative without any clear pattern.

If any conclusion is possible, it must be that, except stand (age), all parameters (e.g. site, deposition, meteorology, soil chemistry and biotic stress) are important for the state of defoliation, however the percentage variance accounted for is only moderate.

Douglas-fir

For 678 (85%) of the total number of observations for beech (795) all data is available on the relevant variables (Annex 2). The number of explaining variables is nearly the smallest of all analysed tree species, but still high (32), while the variation explained becomes very small (29.3%). Six variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic. More phosphorus (Pox) is related to more defoliation, but the mechanism is unclear. In the weather variables, relations in some months are highly positive while others are highly negative. This also holds true for the weather variables that are a little less significant ($t \geq 4$). There is an understandable relation between defoliation and deposition of NO_x. When the temperature sum over 5° C (ETS5) is higher, than the defoliation class appears larger.

No effect of insect or fungal damage could be demonstrated in this informal analysis.

In this data set, no relation was found for Douglas-fir with recorded insect damage, and only a hardly significant relation with soil type ($t \geq 2$). The defoliation is more pronounced when the basic cations (BC) in the soil are lower (also $t \geq 2$).

Table A1.1 Significance of predictor variables as a result of a backward selection of predictor variables explaining defoliation class

Predictor variable	Tree species						
	Oak	Beech	Douglas-fir	Norway spruce	Scots pine	Corsican pine	Japanese larch
Age	++			++	+++	-	+++
x-co-ordinate				- -	- - -	-	
y-co-ordinate						+	
Log(SO_x)	+++	+	-	- -	+		++
Log(NO_x)		- -	++	+	+++	+++	-
Log(NH_x)	++	+		-	-		+
PHKCl	- - -	-			-	- -	-
C/N ratio		+				-	- -
$(C/N)^2$ ratio	-	- -		- -		+	+
N/P ratio		++			-		
$(N/P)^2$ ratio		- -	+		+	-	
Log(Pox.)			+++		-	- -	
K ex.	++	- -	+	++	+	+	
Mg ex.						- -	
Ca ex.			+			++	
BC ex.	-	+++	-				-
Winter index	- - -		-			- -	-
Late frost				-	- - -	-	
ETS 5	+++	+++	++		- - -	+++	++
ETS 10	- - -	- - -		+	+	-	-
Heat index	- - -	-			++		++
T avg.	- - -		-	-	+++	- - -	- -
P sum	+	++	+	+	- -		-
T winter							
T min. winter							
Monthly avg.temp. 1)	[3] - - [4] + [5] - - [7] - - [8] ++ [10] - - -	[1] - - [3] ++ [4] - - [5] ++ [6] - - [7] ++ [8] - - [9] ++ [11]++ [12] - -	[1] + [3] +++ [12] - -	[2] - - - [5] - - [6] +++ [7] ++ [8] – [9] - - [10] ++	[4] +++ [6] - [7] - [12] - -	[1] + [6] ++ [8] + [9] - - [10] + [11] - - [12] +	[5] - - [7] ++ [9] -
Monthly min.temp 1)	[3] ++ [4] - - [8] + [10] + [11] +	[1] ++ [2] + [3] ++ [5] - - [6] + [8] + [10] - - [12] ++	[4] + [5] - - - [7] – [8] +++	[3] ++ [5] +++ [7] - - - [10] -	[2] - - - [3] - - - [4] - [6] ++ [8] ++ [11] +	[1] - - [2] ++ [5] - - [8] – [10] – [11] ++	[6] ++ [7] - [12] -
Monthly max.temp 1)	[6] +++ [9] - [11] ++	[1] + [2] + [3] - - [5] - - [6] ++ [7] - - - [8] ++ [9] ++ [10] - [11] ++ [12] ++	[1] - - [5] ++ [7] - - - [8] ++ [11] - -	[3] - - - [4] + [5] – [7] + [8] + [9] – [11] + [12] ++	[2] + [3] + [4] + [11] - - -	[2] + [3] - - [4] ++ [6] – [8] – [9] +++ [10] - - -	[1] + [4] - [5] + [7] - - [8] ++
Monthly precipitation 1)	[1] + [8] + [10] -	[1] ++ [2] ++ [3] ++ [5] - - - [6] +++ [7] +++ [9] ++ [10] + [11] - - [12] - - -	[1] - - - [3] +++ [6] – [8] + [9] ++ [12] +++	[1] ++ [2] + [4] - - [5] - - [6] – [12] - -	[2] +++ [3] + [6] – [8] ++ [11] + [12] ++	[4] – [5] – [7] – [11] +	[8] ++
Relative transpiration 2)							
Rel. transpiration previous years 2)	[3] -			[2] -	[1] - - - [2] - - -	[3] -	[1] - -
Soiltype	xxx	xx	x	xxx	x		
Soilmoisture supply		xx	x	xx	x		x
MHG	-				-		
MLG	+				+	+	
Period of forestation	xx	xx	x			x	
Former land use				x			
Fungi					-		
Insect	+++	+		+	++	+	+
n (observations)	1773	415	678	618	5394	829	1040
Number of significant predictors	36	57	32	41	44	45	29
$R^2_{adj.}$	38.1	44.3	29.3	43.2	39.5	41.9	25.0

+++ / - - - = $t \geq 6$ positive, respectively negative correlation
++ / - - = $6 \geq t \geq 4$ positive, respectively negative correlation
+ / - = $4 \geq t \geq 2$ positive, respectively negative correlation

1) the index refers to the number of the month (e.g. [1]=January etc.)
2) the index refers to the year previous to the year of recording (e.g. [0]= year of recording, [1] 1 year before recording year etc.)

Norway spruce

For 618 (87%) of the total number of observations for Norway spruce (712) all data is available on the relevant variables (Annex 2). The number of explaining variables is high: 41, the percentage of explained variance (43.2%) is the one but highest. The most significant variables are soil type and the meteorological monthly variables average temperature of February and June, minimum temperature of May and July, and the maximum temperature of March.

When considering soil type, the defoliation class on clay soils, sandy clay soils, nutrient rich sandy soils, and calcareous sandy soils is significantly better than on nutrient poor sandy soils and loess soils. On peat soils, the defoliation class was found to be poorer than on nutrient poor sandy soils. This result confirms the expectation of the influence of soil type.

Not much can be said about the influence of the average, minimum and maximum monthly temperature because the correlations found are alternately positive and negative without a clear pattern.

Further it is remarkable that the x-coordinate of the plot is negatively correlated to the defoliation class. This might indicate several causes, for instance salt spray (sea influence) and wind speed.

A small but significant effect was found of leaf eating insects. The insect damage recorded for Norway spruce recorded mainly fitted in the class little damage, but showed to represent enough variation to be significant.

In general it can be concluded that all parameters included in the model (stand, site, deposition, soil chemistry, meteorology and biotic stress) contributed significantly to the explanation of defoliation of beech, however the explained variance is moderate.

Scots pine

For 5394 (95%) of the total number of observations for Scots pine (5654) all data is available on the relevant variables (Annex 2). The number of explaining variables is high (44), while the variation explained is only 39.5%. Thirteen variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic. It makes sense that older trees show more defoliation and that more NO_x deposition causes more defoliation. A higher annual temperature (T avg) is related to more defoliation. Then it also makes sense that dry years prior to the year of the survey, are related to more defoliation, even up to two years prior to the survey. Other temperature variables show a less clear pattern of sometimes high or medium significance. Insect damage is significantly related to defoliation ($t \geq 4$). Soil type and soil moisture supply is slightly related to defoliation ($t \geq 2$).

Corsican pine

For 829 (90%) of the total number of plots for Corsican pine (920) all data is available on the relevant variables (Annex 2). The most significant variables are NO_x

deposition, annual temperature sum above 5^oC, average annual temperature, and the maximum temperature of the months September and October.

Strikingly is the demonstrated effect of NO_x deposition. From literature (e.g. Van de Burg and Kiewit 1989) it is known that Corsican pine is sensitive to N deposition. The effect of the variables ETS5 and the average annual temperature support the preference of the species to a warmer climate. This is also supported by the effect of the x- and y co-ordinates, however they have only a moderate significance. The maximum September and October temperature is correlated contrary to defoliation, without being clear why.

The effect of insect damage is, however significant, only small.

In general it can be said that the defoliation class of Corsican pine is correlated to all the different parameters included in the model (stand, site, deposition, soil chemistry, meteorology, and biotic stress. The percentage variation accounted for, however, is only moderate.

Japanese Larch

For 1040 (95%) of the total number of plots for Japanese Larch (1097) all data is available on the relevant variables (Annex 2). The number of explaining variables is also high (29), while the variation explained is only 25.0%. Only one variable is highly significant ($t \geq 6$): at older age the defoliation is higher. The temperature and nutrition variables show a contradictory behaviour ($t \geq 4$ or $t \geq 2$), and further analysis would be needed. A small effect of insect damage was demonstrated as expected.

Forward selection of variables

Oak

The number of explaining variables has been reduced to 9, and the variation explained is 29.9%. This is a large simplification compared to the backward selection analysis. Six variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic. The relations with the temperature variables (ETS5, ETS10 and heat index) are contradictory, and further analysis is needed. The relation with deposition of NO_x and NH_x makes sense, more defoliation with higher deposition rates. Also with insect damage, the relation makes sense. A positive relationship with N/P ratio and age is also significant ($t \geq 4$). The statistical model is more acceptabel than the model from the backward selction analysis.

Beech

The two most significant variables ($t \geq 6$) are the annual temperature sum above 5^oC and 10^oC (ETS5 and ETS10). As said in section 4.1.1, these variables are difficult to interpretate and possibly point out some physiological temperature effect.

Compared to the backward selection, the number of predictors is reduced dramatically from 57 to 6. This is mainly due to the elimination of significant monthly meteorological variables, but also other variables are no longer found to be significant in the forward selection.

For all the significant variables, the sign of the correlation is as expected positive or negative. In this respect, it is remarkable that in the forward selection the concentration of basic cations is, as expected, negatively correlated to the defoliation class, while in the backward selection it was found to be positively correlated.

The model as a whole seems quite plausible, with this remark that the effects of ETS5 and ETS10 have to be explained.

With 27.8%, the percentage accounted for is the lowest but two. In the backward selection, the explained percentage variance for beech (44.3%) was the highest of all tree species (table A1.1). This large difference is due to the large reduction in significant predictors.

Douglas-fir

The number of explaining variables is surprisingly low (5), but with a low variation explained (15.5%). Two variables are highly significant ($t \geq 6$), and the sign of the relation with deposition of SO_x is not logic. The positive relation with deposition of NO_x makes sense. The temperature variables are somewhat contradictory ($t \geq 4$). Therefore, the statistical model is unsatisfactory, and further analysis would be needed.

Norway spruce

For Norway spruce the maximum temperature of January was found to be the only very significant variable ($t \geq 6$). The maximum January temperature is positively correlated to the defoliation class, which might indicate an effect of uncompensated transpiration. Remarkable is the negative correlation for the SO_x deposition and the late frost index. For both variables a positive correlation was expected.

The model as a whole contains predictors of which indeed an effect on defoliation is expected. Through detailed further analysis the unexpected correlation of SO_x deposition and late frost must be clarified.

The percentage variance accounted for (31.8%) is one of the highest found in this forward selection, but still is low.

Table A1.2 Significance of predictor variables as a result of a forward selection of predictor variables explaining defoliation class

Predictor variable	Tree species						
	Oak	Beech	Douglas-fir	Norway spruce	Scots pine	Corsican pine	Japanese larch
Age	+ +			+ +	+ + +		+ + +
x-co-ordinate							
y-co-ordinate							
Log(SO_x)		+ +	- - -	- -			
Log(NO_x)	+ + +		+ + +	+	+ + +	+ + +	
Log(NH_x)	+ + +					+ + +	+
PHKCl							
C/N ratio							
$(C/N)^2$ ratio							
N/P ratio	+ +			+ +			
$(N/P)^2$ ratio							
Log(Pox.)							
K ex.							+ +
Mg ex.							
Ca ex.					- - -		
BC ex.		- -					
Winter index							
Late frost				- -	- - -	-	
ETS 5	+ + +	+ + +			+ + +	+ + +	+ +
ETS 10	- - -	- - -			- - -	- - -	
Heat index	- - -	- -					
T avg.					+ + +		- -
P sum				+			-
T winter							
T min. winter							
Monthly avg.temp. 1)				[3] -- [6] +	[3] - - -	[7] +	[7] +
Monthly min.temp 1)	[5] - -					[2] + [5] -	
Monthly max.temp 1)			[4] + +	[1] + + +	[11] + + +	[2] -	[6] - - - [8] + + +
Monthly precipitation 1)			[6] + + [11] - -		[9] - - - [12] + +	[9] + [12] - -	[8] + +
Relative transpiration 2)					[0] - -		
Rel. transpiration previous years 2)					[1] - - - [2] - - - [3] -	[3] - -	[1] - - [2] +
Soiltype					+ +		
Soilmoisture supply					- - -		
MHG							-
MLG							
Period of forestation				x			
Fungi					-		
Insect	+ + +	+ +		+	+ + +		+
n (observations)	1773	415	678	618	5394	829	1040
Number of significant predictors	9	6	5	11	19	12	14
$R^2_{adj.}$	29.9	27.8	15.5	31.8	37.4	32.9	20.9

+++ / - - - = $t \geq 6$ positive, respectively negative correlation

++ / - - = $6 \geq t \geq 4$ positive, respectively negative correlation

+ / - = $4 \geq t \geq 2$ positive, respectively negative correlation

1) the index refers to the number of the month (e.g. [1]=January etc.)

2) the index refers to the year previous to the year of recording (e.g. [0]= year of recording, [1] 1 year before recording year etc.)

Scots pine

The number of explaining variables is the highest of all tree species in the forward selection (19), but far less than in the backward selection model, while the variation explained is still nearly as high (37.4%). Fourteen variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic, especially in the weather variables. A number of understandable relations are found. Older tree age, more insect damage and more NO_x deposition are related to more defoliation. A better calcium nutrition and more moisture are related to better vitality. Higher annual temperatures (T avg.) are related to defoliation, but the weather picture as a whole, needs further analysis. It is difficult to understand why a lower relative transpiration in the previous years would lead to more defoliation in the year of observation. Soil type also has a significant influence ($t \geq 4$).

Corsican pine

In the relationship with defoliation class, a very significant correlation was found for the deposition of NO_x and NH_x, and the annual temperature sum above 5°C and 10°C (ETS5 and ETS10). From literature the effect of N deposition on the defoliation class is known (Van den Burg and Kiewit 1989). This effect is confirmed by the result found. The meaning of the variables ETS5 and ETS10 are difficult to interpretate, but Corsican pine is known to be sensitive for temperature (xxx lit ref).

As a whole the model explaining defoliation class seems plausible, however, the effects of some variables must be clarified through further study.

The percentage variance accounted for is relatively high (32.9%), but in absolute way, it still is low (table A1.2).

Japanese larch

The number of explaining variables has been reduced to 14, and the variation explained is 20.9%. This is a large simplification compared to the backward selection analysis. Three variables are highly significant ($t \geq 6$), but the sign of the relation does not always seem logic, again for the weather variables. The relation with age is that older trees have more defoliation. Most variables have a less significant contribution ($t \geq 4$ or $t \geq 2$), e.g. insect damage and groundwaterlevel. The relation with potassium content in the foliage is difficult to understand. Again, interactions between the variables could play a role, and further analysis would be needed.

Annex 2 List of all variables with their definitions as used in the statistical analysis.

Terms marked with * in the column REML are used in the detailed REML-analysis. Where ** is used, the variables have been combined to a new varibal in the REML-analysis.

Abbreviated name of the variable / term	Explanation / Definition	Unit	REML
Plot identification			
plotnr.	number of the plot	number	
X	x-coordinate	Km	
Y	y-coordinate	Km	
bm	treespecies	Code	
kmjr	year of germination	Year	
Vitality data			
naald1	defoliation class 1	Treecount in class 1	**
naald2	defoliation class 2	Treecount in class 2	**
naald3	defoliation class 3	Treecount in class 3	**
naald4	defoliation class 4	Treecount in class 4	**
kleur1	decoloration class 1	Treecount in class 1	
kleur2	decoloration class 2	Treecount in class 2	
kleur3	decoloration class 3	Treecount in class 3	
kleur4	decoloration class 4	Treecount in class 4	
vital1	vitality class 1	Treecount in class 1	
vital2	vitality class 2	Treecount in class 2	
vital3	vitality class 3	Treecount in class 3	
vital4	vitality class 4	Treecount in class 4	
mort	mortality rate	Count of dead trees per plot	
Deposition variables			
sox	SOx deposition	Meq ha^{-1} $jaar^{-1}$	*
noy	NOy deposition	Meq ha^{-1} $jaar^{-1}$	*
Nhz	NHz deposition	Meq ha^{-1} $jaar^{-1}$	*
Soil variables			
Os	organic matter	%	
$CaCO_3$	percentage of $CaCO_3$	%	
PHKCl	acidity		*
C/N	C/N ratio		*
N/P	N/P ratio		*
Pox	Phosphate oxalate	meq kg^{-1}	
FKuit	?? term in English	fraction	
FMguit	?? term in English	fraction	
FCauit	?? term in English	fraction	
FBCuit	?? term in English	fraction	*
Annual meteorological variables			
Winx	winter index	degreedays under 0^o C	*
Lvorst	frost in spring	degreedays under 0^oC April 1-June 30	*
Ets5	summer index5	degree days above 5^o C	
Ets10	summerindex 10	degree days under 10^o C	

Abbreviated name of the variable / term	**Explanation / Definition**	**Unit**	**REML**
Hitte	high temperature index	degree days under 30° C	*
Tavg	average year temp.	degrees celsius	*
Psum	yearly precipitationsum	millimeters	*
Monthly meteorological variables			
Tavg1	average temp. Jan.	degrees celsius	
Tavg2	average temp. Febr.	degrees celsius	
Tavg3	average temp. March	degrees celsius	
Tavg4	average temp. April	degrees celsius	
Tavg5	average temp. May	degrees celsius	**
Tavg6	average temp. June	degrees celsius	**
Tavg7	average temp. July	degrees celsius	**
Tavg8	average temp. August	degrees celsius	
tavg9	average temp. Sept.	degrees celsius	
tavg10	average temp. Oct.	degrees celsius	
tavg11	average temp. Nov.	degrees celsius	
tavg12	average temp. Dec.	degrees celsius	
tmin1	minimum temp Jan.	degrees celsius	
tmin2	minimum temp Febr.	degrees celsius	
tmin3	minimum temp March	degrees celsius	
tmin4	minimum temp April	degrees celsius	**
tmin5	minimum temp May	degrees celsius	**
tmin6	minimum temp June	degrees celsius	**
tmin7	minimum temp July	degrees celsius	
tmin8	minimum temp Aug.	degrees celsius	
tmin9	minimum temp Sept.	degrees celsius	
tmin10	minimum temp Oct.	degrees celsius	
tmin11	minimum temp Nov.	degrees celsius	
tmin12	minimum temp Dec.	degrees celsius	
tmax1	maximum temp Jan.	degrees celsius	
tmax2	maximum temp Feb.	degrees celsius	
tmax3	maximum temp March	degrees celsius	
tmax4	maximum temp April	degrees celsius	
tmax5	maximum temp May	degrees celsius	**
tmax6	maximum temp June	degrees celsius	**
tmax7	maximum temp Jul	degrees celsius	**
tmax8	maximum temp Aug.	degrees celsius	
tmax9	maximum temp Sept	degrees celsius	
tmax10	maximum temp Oct.	degrees celsius	
tmax11	maximum temp Nov.	degrees celsius	
tmax12	maximum temp Dec.	degrees celsius	
psum1	sum precipitation Jan.	millimeters	
psum2	sum precipitation Feb.	millimeters	
psum3	sum precipitation Mar	millimeters	
psum4	sum precipitation April	millimeters	**
psum5	sum precipitation May	millimeters	**
psum6	sum precipitation June	millimeters	**
psum7	sum precipitation Jul	millimeters	**
psum8	sum precipitation Aug.	millimeters	
psum9	sum precipitation Sept.	millimeters	
psum10	sum precipitation Oct.	millimeters	

Abbreviated name of the variable / term	Explanation / Definition	Unit	REML
psum11	sum precipitation Nov.	millimeters	
psum12	sum precipitation Dec.	millimeters	
Relative transpiration variable			
reltrans	relative transpiration	fraction	*
p-excess	excess precipitation	millimeters	
Additional site variables			
bodemtyp	soiltype (1:50.000 map)	code	*
gt	groundwater level	code (I, II, II*, III, III*, IV, V, VI, VII, VII*, VIII	
albos	type of forest according to albos	A,B,C,D,E,F,G, Kees H classes of…..?????	
smart	smart soil code	clay, loess, peat, poor in sand, rich in sand	*
vochtlv	moisture supplying capacity	class (50, 50-100, 100-150, 150-200, >200, unknown, <1800, 1800-1850, 1850-1900) 1900-1950, >1950	*
ontstaan	history	unknown, old forest, agricultural land, wasteland	
Insect Variables			
schimsrt	Fungi species	code 84: 0=unknown	*
		85: 1=dieback or sphaeropsis canker, 2=brunchorstia (Gremmeniella abietina Morelet, 3=Watermarkdisease (Erwinia salicis Chester), 4=essensterfte ??????? 5=Bacterial canker or bacterial wilt ????? (Pseudomonas ?????	
		86-94: 1=sphaeropsis canker shoot???, 2=spaeropsis canker branch??? 3=brunchorstia ????, 19=unknown, 11=no affection	
insectsrt	insect species	code 84: 0=unknown	*
		85: 0 = no affection 1=common pine shoot beetle (Tomicus piniperda L.), 2=??, Aradus cinnamomeus Panz., 3=Pine woolly aphid (Pineus pini Macq), 4=green spruce aphid (Elatobium abietinum Wlk.), 5=larch case-bearer (Coleophora laricella Hb), 6=Douglas-fir chermes (Adelges cooleyi Gill.), 7=Nun-moth (Lymantria monacha L.), 9=unknown	
		86-94: 1=Spruce bark beetle (Ips typographus L.), 2=Gregarious spruce sawfly (Pristiphora abietina Christ), 3=Spruce beetle (???), 4=Douglas-fir , chermes (Adelges cooleyi Gill), 5=Felted beech coccus (Cryptococcus fagisuga , Lind.), 6=Woolly beech aphid (Phyllaphis fagi L.), 7=Pine shoot moth (Rhyacionia buoliana Den. et Schiff), 8=Common pine shoort beetle (Tomicus piniperda L.), 9=Gypsy moth (Lymantria dispar L.), 19=unknown, 11=no affection	
gemschim	average affection by fungi class 1 – 4	1= no affection, 2= < 40 %, 3= 40-60 %, , 4= > 60 %	*
gembast	average affection by bark beetles class 1 – 4	1= no affection, 2= < 40 %, 3= 40-60 %, 4= > 60 %	*
gembast	average insect affection class 1 – 4	1= no affection , 2= < 40 %, 3= 40-60 %, 4= > 60 %	*

Annex 3 Description of the basic data used for the informal assessment

Crown condition

To test the database after selection graphs were plotted with the crown condition index for each tree species, and compared with the graphs in the National reports (Reuver, 1997 and 1998). If the graphs would differ to a great extent, the selection procedure for the data might have had systematic consequences for the database, and the causes for the differences would have to be analysed. However, the selected database shows the same patterns and values for the crown condition index in the different years (Fig. 1). The only exception was a lower crown condition index for Beech in 1988 in our database of around 10 %. The other differences were smaller (1 or 2 % or less). This has no consequences for our statistical approach.

The vitality indicators are described in the section below. The median of the number of trees in each of the four classes is discussed. Only one graph is shown as an example. The total number of trees per plot is 25, therefore the median is between zero and 25 trees.

Defoliation index

Oak: The median of the defoliation class 4 is always zero (zero trees out of 25 sampled trees in each plot). The median of defoliation class 3 varies between 1 and 9 trees (out of 25). Yearly differences in this class in fact account for the pattern in the yearly reports. The pattern of class 1 and class 2 and 3 is usually diametrically opposing. Defoliation index 1 reaches a minimum in 1988 and 1992, with a maximum in 1984, 1990 and 1994.

Beech: The median of defoliation class 4 is always zero. In most years, the median of defoliation class 3 is zero. In the period 1987 to 1989 and 1991 and 1993 the median of defoliation class 3 is 4 trees at the maximum. Most beech trees belong to defoliation class 1 in all years, except between1987 and 1989, when class 2 is at the maximum of the whole period (up to 12 trees out of 25). Class 2 mostly varies between 4 and 10 trees. Defoliation index 1 reaches a maximum in 1984, 1990 and 1994.

Douglas-fir: The median of defoliation class 4 is zero in the beginning of the sample period, and is 1 or 2 from 1989 onwards. The long-term decrease in vitality, as described by Reuver (1998), is mainly caused by the continuous increase in the number of trees in defoliation class 3, from 7 trees in 1984 to 19 trees in 1994. Defoliation class 1 is nearly absent in all years, defoliation class 2 shows a decreasing pattern, from 5 trees in 1984 to 3 trees in 1994, with a maximum of 10 trees in 1987.

Norway spruce: The median of defoliation class 4 is always zero trees in the sample period. The defoliation class 3 shows a strong increase from 1990 onwards, with a maximum of 13 trees in 1994. Defoliation class 2 is fairly constant, mostly varying between 6 and 8 trees per plot. Defoliation class 1 shows a diametrically opposing pattern with class 3, meaning that trees move from class 1 to class 2 in the following year, while other trees move from class 2 to class 3. It is possible that a small number of trees move directly from class 1 to class 3. This cannot be analysed separately. The decrease in number of trees in defoliation class 1 is fairly steep between 1991 and 1993.

Foliage discoloration index

Oak: The median of discoloration class 3 and 4 is always zero in the whole period. The discoloration class 1 is around 20 trees in nearly all years, with a maximum of 23 and 24 trees in respectively 1985 and 1993, and a dip of 12 trees in 1989, and decreasing to 18 in 1994. The patterns in class 1 and 2 are diametrically opposing.

Beech: The median of discoloration class 3 and 4 is nearly always zero in the whole period. Only in 1984, 1987 up to 1990, the discoloration classes 3 and/or 4 reach values of 1 to 2 trees. The median in the defoliation class 2 reaches a maximum of 14 trees in 1988, but is usually less than 4 trees. The median of the discoloration class 1 is mostly above 16 trees, but reaches a minimum of zero in 1988.

Douglas-fir: The median of discoloration class 3 and 4 is always zero in the whole period. The median of the discoloration class 1 is mostly above 20 trees, but reaches a minimum of 10 trees in 1986 and 13 in 1989, when discoloration class 2 reaches a maximum of respectively 15 and 11 trees. Discoloration class 2 is usually around zero or one tree per plot with a diametrically opposing pattern with class 1.

Norway spruce: The median of discoloration class 3 and 4 is always zero in the whole period. The median of discoloration class 1 is nearly always above 22, and shows a diametrically opposing pattern with class 2, which is nearly always below 5 trees per plot. Discoloration class 1 reaches a minimum of 20 trees in 1989.

Crown condition index

The crown condition index is a combination of the defoliation index and the discoloration index. As the discoloration classes 3 and 4 were nearly always absent in the four tree species, the fluctuations are in fact the same as the fluctuations in the defoliation index. According of the definition table to calculate the crown condition index, a discoloration index of 1 or 2 means that the crown condition index is the same as the defoliation index. A correction compared to the defoliation index is only made when the discoloration index is 3 and 4, leading to a minimum value for the crown condition index of 2 and 3 when the defoliation index is 1. The biggest exception is in 1987, when two beech trees in the plot are in the discoloration class 3, leading to a small difference in the pattern in the crown condition index for these two trees. The general pattern is exactly the same in the graphs of the defoliation index and the crown condition index (not shown). Therefore, the data do not need to be described separately for each tree species. For the values and patterns in the crown condition index see the paragraph Defoliation index (above).

Stand conditions

The available stand characteristics are year of germination, period of afforestation, and former land use.

Year of germination

It is known that Dutch forests are relatively young when considering the site, but also when considering the age of the stands. This is reflected in the age of the stands of the monitoring network of forest condition. For all tree species the mean year of germination is 1939. Stands of oak and beech are somewhat older than the mean year of germination, the mean year of germination is 1935 and 1914 respectively. Douglas-fir and Norway spruce are younger on the average, the mean year of germination is 1953 and 1947 respectively. The deciduous species plots contain stands from the 19th century. For beech the oldest stand even dates from 1780, which is a more than 200 years old stand. The oldest coniferous stand is a stand of Douglas-fir, which dates from 1885. The oldest stand of Norway spruce dates from 1907.

Based on this age distribution, an age effect may be expected in the regression analysis.

Period of afforestation

Most Dutch forest areas dates from the end of the 19th century and the beginning of the 20th century. This is very well reflected in the data set of the forest condition survey. Current oak and beech stands grow more often in older forest areas than Douglas-fir and Norway Spruce. 25% of the oak stands and 30% of the beech stands are afforested before the year 1800. For Douglas-fir and Norway spruce this percentage is 10% and 13% respectively. The percentage young forest areas is for all tree species about 10%.

Former land use

For all tree species, but especially for Douglas-fir and Norway spruce, the dominant former land use is wasteland, which includes heather, drift-sand and marshes. Oak and Beech stands relatively often are growing on old forestland.

Site conditions

The soil type and ground water table are assessed using a map overlay procedure. For this co-ordinates of longitude and latitude were combined with the soil map of The Netherlands, scale 1 : 50 000.

Soil type

For all tree species the forest stands grow on a large number of different soil types. In total 365 different soil types or combination of soil types were found. In goes in to much detail to describe them all. Therefore some general conclusions are presented on the appearance of the most dominant soil types.

For all tree species the most frequent soil types are podzolized soils. Dominant podzol types are gleyic podzols (Dutch: veldpodzol, mapping unit Hn21), humic podzols (Dutch: haarpodzol, mapping units Hd21 en Hd30) and leptic podzols (Dutch: holtpodzol, mapping units Y30). Gleyic podzols are usually developed in cover sand, i.e. a type of aeolian sand. Originally these soils have high ground water tables, but at present days, the soil water tables have been lowered considerably. The nutrient status and soil moisture supply are relatively low. Both humic and leptic podzols mostly are developed in sandy push moraines. The parent material is mostly various, differing from aeolian sand to fluviatile sand. These soils often are slightly gravally. The soil nutrient status differs considerably from good to poor, which also holds for the soil moisture supply.

Another frequent soil type for all tree species is the albic arenosol (Dutch: duinvaaggrond, mapping unit Zd21). The soils are developed in stabalized land dunes wich have a hummocky relief. The parent material is recent aeolian sand, overlying pleistocene aeolian sand. These are quite nutrient poor sites with a low soil moisture supply.

Soil cluster

Also a map overlay procedure was applied with a clustered soil map. For the clustering the concept of Kros et al. 1995 was used, distinguishing the clusters clay, calcareous clay, loess, peat, nutrient poor sand, nutrient rich sand, and calcareous sand. As expected, for all tree species most stands grow on nutrient poor sand. For oak 71% of the stands grow on such soil cluster, for beech, Douglas-fir and Norway spruce this percentage is 78%, 75% and 73%. 13% of the oak stands grow on nutrient rich stands, for beech, Douglas-fir and Norway spruce this percentage is 7%, 10% and 13% respectively. On the other soil clusters only a few percent of the stands grow, but all clusters are represented.

Soil moisture supply

For about half of the stands the soil moisture supply is calculated to be less then 50 mm. For oak the percentage in the class less then 50 mm is 47%, for beech 57%, for Douglas-fir 51% and for Norway spruce 44%. The classes 50-100 mm and 150-200 mm are represented by about 10% for all tree species. About 20% of the stands fit in the class 100-150 mm. 13% of the stands fit in the class more then 200 mm, except for beech for which species the percentage of stands in this class is 7%. From this it may be concluded that in cases of little rain during the growing season serious drought stress is expected. Only for about 13% of the stands no drought stress is expected on the base of the soil moisture supply capacity of more then 200 mm.

Groundwater table

For 427 of the total number of oak stands (454) a groundwater table was found through the map overlay procedure with the Soil Map of The Netherlands, scale 1 : 50 000. 46 oak stands (11%) grow on soils with a groundwater table I, II, II*, III, or III*, and 260 (61%) stands grow on soil with the groundwater tables VII or VII*. Latter two groundwater tables, and especially groundwater table VII*, have deep lowest groundwater levels, which means that it are dry soils.

For 96 beech stands a groundwater table was found of the total of 102. Only 4 stands (4%) grow on wet soils (groundwater table I, II, II*, III, or III*) and 82 stands (85%) grow on dry soils (groundwater table VII or VII*).

140 of the 145 Douglas-fir stands could be labelled with a groundwater table. Of these 140 stands 10 stands (7%) grow on wet soils (groundwater table I, II, II*, III, or III*) and 88 stands (63%) on dry (groundwater table VII or VII*) soils.

116 of the 121 Norway spruce stands were labelled with a groundwater table. 18 stands (16%) grow on wet soils (groundwater table I, II, II*, III, or III*) and (79%) grow on dry soils (groundwater table VII or VII*).

Nutritional conditions

Soil acidity
Mean soil pH-KCl for all tree species is 3.6. The mean pH-KCl for the deciduous stands is somewhat higher than for the coniferous stands. Mean soil pH-KCl for oak and beech is about 3.7 and for Douglas-fir and Norway spruce 3.5. The p05 differs little for the deciduous and the coniferous species, pH-KCl is about 3.2 for the deciduous and about 3.3 for the coniferous species. The p95, however, differs significantly with 6.4 for oak, 4.3 for beech, 3.6 for Douglas-fir and 3.8 for Norway spruce.

Based on these figures, soil acidity for the deciduous stands shows enough variation for a significant contribution in the regression analysis. The range in soil acidity of the coniferous stands is small by which no significant effect is expected on the forehand.

C/N ratio
The mean C/N ratio amounts 21.1 for all tree species. For Norway spruce it is 21.7, for beech 21.0, for Douglas-fir 20.9 and for oak 18.4. This indicates a relative better site quality of the oak stands compared to the other species and a reltive poorer site quality of the site of Norway spruce. This is also represented in the p05, which is 11.1 for oak, 13.0 for beech, 15.9 for Norway spruce and 17.8 for Douglas-fir. The range in C/N ratio is larger for the deciduous species than for the coniferous species. On the basis of the range, the C/N ratio can be a significant factor in the regression analysis.

N/P ratio
The mean N/P ratio for all tree species is 7.2. For Douglas-fir and Norway spruce, the mean N/P ratio is somewhat higher (resp. 7.5 and 8.8) than for oak and beech (resp. 6.7 and 5.4), which represents a poorer site quality due to a lower P content. The variation in the range of the N/P ratio varies significantly per tree species. The p05 to p95 range for oak is 3.5 to 8.2, for beech 2.8 to 6.7, for Douglas-fir 6.1 to 8.8 and for Norway spruce 4.4 to 10.0. based on these ranges, the N/P ratio can be a significant factor in the regression analysis.

$CaCO_3$

The $CaCO_3$ content is for all tree species almost zero, and therefore no effect is expected in the regression analysis.

Pox

The mean Pox content for all tree species is 1.9 meq kg^{-1}. The mean Pox for the deciduous tree species is higher (3.72 and 2.86 for oak and beech respectively) than for the coniferous species (2.2 and 1.8 for Douglas-fir and Norway spruce respectively). The ranges are relatively large, especially for oak and beech. It is however not clear whether any effect can be expected in the regression analysis.

Exchangeable cations

For all exchangeable cations (K, Mg, Ca) it holds that the mean contents are higher for oak and beech tahn for the coniferous species Douglas-fir and Norway spruce, which probably is caused by a better site quality of the soil types on which the deciduous stands grow. Also the ranges are broader for the deciduous species. If any effect is expected, than this especially holds for the deciduous species.

Meteorological conditions

Mean annual temperature

The plot specific average mean temperature for the period 1984 to 1994 was 9.7 ^{o}C. In comparison, the average temperature over the same period for weather station De Bilt amounts 9.8 ^{o}C, while the long year average for De Bilt amounts 9.4 ^{o}C. The years 1985, 1986 and 1987 were colder years compared to the long year average. The years 1988 to 1994, with exception of 1993, all were extreme warm years, with mean temperatures more than 1 ^{o}C above the long year average. The years 1989, 1990 and 1994 are the three warmest years of this century (KNMI 1994). No large differences exist between the temperature for the plots of the different tree species.

Mean annual precipitation

The plot specific average mean precipitation for the period 1984 to 1994 was 791 mm. In comparison, the average precipitation over the same period for weather station De Bilt amounts 788 mm, while the long year average of De Bilt amounts 803 mm. The years 1989, 1990 and 1991 were dry years, in which the precipitation was more than 100 mm less than the average for the examined period. All other years can be classified as wet years. The year 1994 can even be classified as extreme wet. It was one of the four wettest years of this century (KNMI 1994). No large differences exist between the annual precipitation for the plots of the different tree species.

Winter index

The average winter index for the period 1984-1994 amounts 61.9 degree.days. The mean winter index for the yeas 1985, 1986 and 1987 are 2 to 3 times the eleven years average, while for the years 1988, 1989 and 1990 it amounts only 5-10 degree.days. It is strikingly that cold winters (1985-1987) are directly followed up by warm winters

(1988-1990). Since there is a large variation in the winter index, it may have effect in the regression analysis.

Late frost

The eleven years average late frost index amounts 1.4 °C. In 1987, 1992, and 1993 no or hardly no late frost occured. In 1986 however serious late frost occured, the index amounts 4.2 °C. However some variation in the late frost index occurs, the variation is not very large. This may result in no or little effect in the regression analysis.

Growing season index

Effective Temperature sum above 5 °C (ETS*5*)

The average mean ETS*5* for the period considered is 3430 degree.days. The ETS*5* for the years 1989, 1990, 1992 and 1994 are significantly higher than the eleven years average. In 1984 and 1985 the index was much lower. The ETS*5* is a difficult to interpret index, but the variation in the index makes an effect in the regression analysis possible.

Effective Temperature sum above 10 °C (ETS*10*)

The average mean ETS*10* for 1984-1994 is 2699 degree.days. The ETS*10* for the years 1989, 1990 and 1994 are significantly higher than the eleven years average, while for the years 1986 and 1987 the index was significantly lower. As considered the expectation of possible effects of the ETS*10* the same holds as for the ETS*5*.

Summer index

The eleven years average mean summer index is 2.0 °C. For most years the summer index is not higher than 1.0 °C. In 1990 and 1994 however, the mean summer index amounts 6.8 °C and 9.1 °C respectively. It is not clear if any effect in the regression analysis may be expected.

Atmospheric deposition

SO_x deposition

A general decreasing trend in the SO_x deposition is shown from a mean deposition level of 2307 mol SO_4^{2-} ha^{-1} a^{-1} in 1984 to 1046 mol SO_x ha^{-1} a^{-1} in 1994. The highest mean deposition flux was calculated for the year 1986, in which on the average 3357 mol SO_x ha^{-1} a^{-1} was calculated. This is 122% more than the national deposition of SO_x in the open field as calculated by Erisman and Bleeker (1996). The lowest mean deposition flux is found for the year 1994, in which a flux was calculated of 1046 mol SO_x ha^{-1} a^{-1}, about 220% lower than the highest deposition of 1986 in this ten years period. On the average the mean deposition calculated for the forest stands is about 45% higher as calculated for the open field (Erisman and Bleeker 1996).

The ranges within one year vary significantly for all tree species. In the mid eighties the range in the deposition level varies a factor 7 to 8 for the same tree species. In the early nineties the variation in the range is decreased to a factor 4 to 5. The range in the SO_x deposition level is large enough to expect effects from in the regression analysis.

For most years in this ten years period, the calculated SO_x deposition is increasing from oak, beech, Norway spruce to Douglas-fir. This is as expected when taking into account the biomass of the crown

NO_y deposition

The NO_y deposition shows a fluctuating trend for the period 1984 to 1994. The NO_y deposition increased from 1400 mol ha^{-1} a^{-1} in 1984 to 2307 mol ha^{-1} a^{-1} in 1986. Then it decreased to a level of 1057 mol ha^{-1} a^{-1} in 1991, whereafter it increased to a 1298 mol ha^{-1} a^{-1} in 1994. The highest deposition level 1991 is 54% higher than the lowest level in 1986. The average depostion on forest stands in 1986 is about 104% higher than the open field deposition of NO_y as calculated by Erisman and Bleeker (1996). On the average the mean NO_y deposition calculated for forest stands is about 52% higher than the open field deposition (Erisman and Bleeker 1996).

The ranges of the NO_y deposition within one year vary significantly. In the mid eighties the range in the deposition level varies a factor 3 to 4 for the same tree species. In the period 1987 to 1994 the range between minimum and maximum depostion level per plot is a factor 2 to 3.

From the variation between the years (temporal variation) as well as from the variation within one-year (spatial variation) the range in deposition level is large enough to expect effects from in the regression analysis.

In general the calculated mean NO_y deposition flux is the highest in the stands of Douglas-fir, followed by Beech, then by Norway spruce and is the lowest in oak stands. De average deposition level in stands of Norway spruce and beech is about equal.

NH_x deposition

The NHx deposition level gradually increases from an average of 2617 mol ha^{-1} a^{-1} in 1984 to 3032 mol ha^{-1} a^{-1} in 1987 after which the level gradually decreases to a level of 2013 mol ha^{-1} a^{-1} in 1994. The highest level in 1984 is about 35% higher than the level for 1994. This fluctuation is not as high as for the SO_x and NO_y deposition. The average deposition on forest stands is about 20% higher than the deposition flux in the open field as calculated by Erisman and Bleeker (1996). This holds for all years.

The ranges of the NH_x deposition within one year vary significantly. In 1984 the maximum NH_x deposition was a factor 20 higher than the minimum level. On the average, this within year variation is about a factor 11. For the years 1992 to 1994 it is a factor 6 to 8.

The within year (spatial) variation of the NH_x deposition is much larger than the between years (temporal) variation. It is not clear whether the temporal variation is large enough to expect effects in the regression analysis. The spatial variation, sure is large enough to expect within year effects.

In general the average NH_x deposition flux is the highest in the stands of Norway spruce, followed by Douglas-fir, then by oak and it is the lowest in stands of beech.

Biotic conditions

From the recordings in the field information was available on insect and fungi species with their measure of appearance. Over the period concerning this study, i.e. 1984-1994, biotic stress was not recorded uniformly. In the early years of the recordings, damage classes and differentiation of species differed from the later years. From about 1988, the classification and recording remained about the same until 1994. Therefor the data of the early years were transformed in such a way they could be compared to the data from the years 1988 to 1994.

Because of the inconsistency of the data throughout the years and also because of doubt about the quality of the data on biotic stress, it was decided that a rough classification of both species and damage would give the best results when using this data in a statistical analysis. Therefor, the original data were rewritten into some major classes depending on the type of damage. Insects were classified into two groups, a group of bark beetles, and a group of leaf eating insects, mainly caterpillars. Fungi were not subdivided but only the appearance was taken into account. Damage classes were reduced to 4 classes indicating no (0%), little (1-40% damage), moderate (41-60%) and severe damage (61-100%).

Insect damage

The insect damage shows a very different measure of affection depending on the type of insect and tree species. Hardly any affection by bark beetles was found for any of the tree species, except for Scots pine. For about 15% of the observations on Scots pine a little to moderate affection was recorded, mainly due to the bark beetle *Tomicus piniperda* L.

The picture with regard to leaf eating insects is quite different than that of the bark beetles. Corsican pine was the only species for which small percentage (less than 5%) observations with any affected was recorded. For both Scots pine and Douglas-fir about 20% of the observations was classified to be affected. Within this 20% the severeness of the damage was recorded mostly as little. For the deciduous species oak and beech and for Norway spruce and Japanese larch a significant damage was recorded being about 95%, 80%, 55% and 45% respectively. For Norway spruce most damage was recorded as little. For beech most of the damage about equally distributed over the damage classes little and moderate. For oak about two third of the damage was classified in damage class moderate. Important insects causing damage on oak are caterpillars like *Tortrix viridana* L., *Operophtera brumata* L. and *Erannis defoliaria* Cl.

With regard to these results, no effect of bark beetles is expected in the statistical analysis. A significant effect is expected for the leaf-eating insects, especially for oak beech and Norway spruce.

Fungal damage

The picture of the fungal damage is quite different per tree species. For beech, Norway spruce, Douglas-fir and Japanese larch only a small percentage of the observations (2-10%) was classified having any fungal damage. Oak, Scots pine and Corsican pine all show about 50% of the observations having any fungal infection. For all three species most of the damage was classified in the class little damage.

If any effect in the statistical analysis is expected, it will be for oak, Scots pine and Corsican pine. However, most damage war classified as little, making any effect uncertain. The highest chance of any effect is expected for Scots pine because the 50% of the observations with fungal damage represent by far the highest number of observations (3650).

Annex 4 General values of relevant data used in the detailed analysis on the relationship between stress factors and the defoliation of douglas fir, oak and scots pine.

Table A4.1 Mean, minimum p05, p95 and maxima of the values of relevant data used in the detailed analysis on the relationship between stress factors and the defoliation of douglas fir

Douglas fir	GEM	%SD	MIN	pO5	MED	p95	MAX	N
Germ.yr	1949	1	1885	1925	1951	1975	1982	687
SOx depos.	1646	50	528.4	837.2	1330	3499	5333	687
NOxdepos	1305	21	606.7	929.0	1268	1813	2296	687
NHxdepos	2460	33	1225	1507	2239	4021	5821	687
Soil pH	3.443	3	3.180	3.219	3.460	3.610	3.850	687
Soil c_n ratio	20.84	7	15.57	17.94	21.11	22.74	27.29	687
Soil n_p ratio	7.419	26	4.000	6.118	6.840	8.820	25.44	687
Soil basic cations	0.08719	40	0.06000	0.06000	0.07700	0.1260	0.3250	687
Tavg-sum	16.10	2	15.50	15.61	16.11	16.67	16.75	687
Tmax-sum	21.08	2	20.36	20.46	21.12	21.59	21.71	687
Tavg-ann	10.39	3	9.817	9.861	10.44	10.78	10.83	687
Tmin-grw	4.694	8	3.660	4.220	4.710	5.260	5.380	687
Psum-ann	1051	6	906.8	934.4	1069	1183	1233	687
Psum-grw	264.8	14	191.6	192.4	270.4	324.6	331.2	687
Reltranp	0.8634	15	0.4954	0.6225	0.8857	1.000	1.000	687
Smart	1.292	70	1.000	1.000	1.000	2.000	7.000	679
Vochtlev	3.872	33	1.000	1.000	4.000	5.000	5.000	679
Ontstaanv	3.514	85	1.000	1.000	2.000	9.000	9.000	687
Gemschim	1.030	14	1.000	1.000	1.000	1.120	2.120	687
Gemvraat	1.088	27	1.000	1.000	1.000	1.920	4.000	687

Table A4.2 Mean, minimum p05, p95 and maxima of the values of relevant data used in the detailed analysis on the relationship between stress factors and the defoliation of oak.

Oak	**GEM**	**%SD**	**MIN**	**pO5**	**MED**	**p95**	**MAX**	**N**
Germ yr.	1935	1	1817	1889	1938	1975	1986	1902
SOx depos.	1422	49	492.0	709.6	1164	2911	5433	1902
Noxdepos	1165	21	567.5	749.2	1148	1616	1941	1902
Nhxdepos	2367	40	570.2	984.0	2183	4140	6486	1902
Soil pH	3.778	20	3.190	3.320	3.580	6.340	7.140	1902
Soil c_n ratio	18.35	20	6.850	11.15	18.78	22.41	32.50	1902
Soil n_p ratio	6.630	47	2.170	3.530	6.060	8.190	23.96	1902
Soil basic cations	0.2537	84	0.1060	0.1100	0.1720	0.8750	0.9950	1902
Tavg-sum	16.06	2	15.32	15.50	16.10	16.82	17.12	1902
Tmax-sum	21.00	2	20.01	20.35	21.11	21.77	22.12	1902
Tavg-ann	10.38	3	9.772	9.824	10.44	10.88	11.24	1902
Tmin-grw	4.766	10	3.660	3.940	4.770	5.450	6.550	1902
Psum-ann	1058	7	901.0	935.0	1069	1230	1233	1902
Psum-grw	259.2	15	190.8	192.0	266.2	319.2	331.2	1902
Reltranp	0.8958	15	0	0.6003	0.9641	1.000	1.000	1902
Smart	2.039	77	1.000	1.000	1.000	6.000	7.000	1838
Vochtlev	2.980	48	1.000	1.000	3.000	5.000	5.000	1824
Ontstaanv	3.892	80	1.000	1.000	2.000	9.000	9.000	1902
Gemschim	1.229	32	0	1.000	1.000	2.000	3.960	1902
Gemvraat	1.680	34	0	1.000	1.938	2.620	4.000	1902

Table A4.3 Mean, minimum p05, p95 and maxima of the values of relevant data used in the detailed analysis on the relationship between stress factors and the defoliation of Scots pine

Scots pine	GEM	%SD	MIN	pO5	MED	p95	MAX	N
Germ. Year	1936	1	1830	1894	1938	1974	1985	5483
SOx depos.	1652	51	487.5	833.7	1343	3428	7211	5483
Noxdepos	1222	20	544.5	859.0	1191	1704	2355	5483
Nhxdepos	2692	34	744.7	1552	2518	4389	7870	5483
Soil pH (pH KCL)	3.581	2	3.210	3.450	3.580	3.720	4.060	5483
Soil c_n ratio	22.48	7	13.62	19.89	22.42	24.96	36.52	5483
Soil n_p ratio	7.408	21	3.720	6.800	6.930	8.990	27.92	5483
Soil basic cations	0.07495	34	0.05800	0.05800	0.06800	0.1120	0.3800	5483
Tavg-sum	16.24	2	15.48	15.70	16.19	16.72	17.09	5483
Tmax-sum	21.23	1	20.29	20.56	21.23	21.66	22.09	5483
Tavg-ann	10.51	2	9.782	9.960	10.48	10.83	10.98	5483
Tmin-grw	4.730	7	3.660	4.220	4.770	5.250	5.450	5483
Psum-ann	1041	7	906.8	931.2	1054	1191	1233	5483
Psum-grw	252.4	15	187.8	202.4	243.6	308.6	331.2	5483
Reltranp	0.8592	14	0.4120	0.6412	0.8767	1.000	1.000	5483
Smart	1.119	51	1.000	1.000	1.000	2.000	7.000	5449
Vochtlev	4.375	23	1.000	2.000	5.000	5.000	5.000	5421
Ontstaanv	3.340	84	1.000	1.000	2.000	9.000	9.000	5483
Gemschim	1.196	29	0	1.000	1.000	2.000	3.000	5483
Gemvraat	1.033	17	0	1.000	1.000	1.160	3.000	5483

Annex 5 Number of remaining plots and forest stands after the selection procedure and length of the time series included (period 1984-1998)

Species Code	English name	Obser-Vations	Stands	Plots	Number of annual observations per stand 3	4	5	6	7	8-10	11-14	15
00	None/unknown	0	0	0	0	0	0	0	0	0	0	0
GD	Scots Pine	5654	1180	1124	342	274	205	181	119	34	25	0
CD	Corsican Black Pine	920	168	166	40	32	33	22	18	9	14	0
OD	Austrian Black Pine	27	8	8	7	0	0	1	0	0	0	0
ZD	Maritime Pine	13	4	4	3	1	0	0	0	0	0	0
WD	Eastern White Pine	3	1	1	1	0	0	0	0	0	0	0
PC	Lodgepole Pine	0	0	0	0	0	0	0	0	0	0	0
DG	Douglas-Fir	795	145	137	39	28	20	20	14	13	11	0
FS	Norway Spruce	712	121	121	33	16	18	20	10	9	15	0
SS	Sitka Spruce	31	7	7	3	2	0	0	2	0	0	0
JL	Japanese Larch	1096	202	199	50	29	31	36	29	19	8	0
EL	European Larch	0	0	0	0	0	0	0	0	0	0	0
AA	European Fir	0	0	0	0	0	0	0	0	0	0	0
AG	Grand Fir	3	1	1	1	0	0	0	0	0	0	0
TS	Hemlock-Fir	0	0	0	0	0	0	0	0	0	0	0
DO	Other Pines	0	0	0	0	0	0	0	0	0	0	0
OS	Other Spruce	6	1	1	0	0	0	1	0	0	0	0
ON	Other Conifers	85	23	23	10	10	3	0	0	0	0	0
EI	Oak (Pedunc. & Sess.)	2106	454	420	188	101	52	39	30	29	15	0
BU	Beech	558	102	96	31	19	17	9	5	12	9	0
BE	Birch	63	21	21	21	0	0	0	0	0	0	0
ES	Ash	51	17	17	17	0	0	0	0	0	0	0
PO	Poplar	598	138	135	47	37	28	15	9	2	0	0
ZE	Black Alder	33	11	11	11	0	0	0	0	0	0	0
WI	Willow	24	8	8	8	0	0	0	0	0	0	0
AE	Red Oak	53	17	17	16	0	1	0	0	0	0	0
ED	Maple	0	0	0	0	0	0	0	0	0	0	0
OP	Other Poplar	0	0	0	0	0	0	0	0	0	0	0
OL	Other Broadleaves	934	244	244	94	105	40	4	0	1	0	0
Total		13765	2873	2639	962	654	448	348	236	128	97	0