Relationships Between Recent Changes of Growth and Nutrition of Norway Spruce, Scots Pine, and European Beech Forests in Europe

– R E C O G N I T I O N –

EFI Working Paper 19

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FOREWORD

Growth of forests in Europe appears to have increased over recent decades. The rigorous studies on which this conclusion was based are nevertheless a kind of "accessibility" sample of the forest population – selected because data was available. It is imperative that the conclusion is tested on a wider range of sites. The cause of the growth increment must also be investigated. There is a wide range of environmental variables that could conceivably be responsible – anthropogenic N deposition; CO2 increase, temperature increase etc. It is important that we try to understand which and in what combination could be responsible. The long term consequences and the ameliorative measures required (if any) will vary with the differing causes. This problem cannot be tackled by representatives of one narrow scientific discipline. Nor can it be tackled by one means alone. More field observations are required. Interpretation will need the input of ecophysiological modelling skills.

When workmen meet in the cold light of dawn before beginning the day's work it is normal for them to check their tools. If the task they face is unknown or the members of the team have different ways of working, it would be normal for that checking to be more rigorous. This is in some ways an unusual scientific publication because it is analagous to that process. Professor Spiecker has reviewed the very strict limitations that must be placed on field data acceptability and acquisition. Professors Prietzel and Rehfuess review the soil and plant nutritional data that are available and its limitations. Dr Cannell and Dr Kahle document the air chemistry and climatic data available. Professor Ågren and co-workers review the adequacy of current ecophysiological models to test integrated hypotheses and Dr Cannell and co-workers describe early results from use of one such model to see if the overall aims of the project are within the realms of possibility. Having checked our tools we remain convinced that an investigation into the causes of increased tree growth in Europe remains both necessary and possible. We hope to attract support to carry it out.

Ian Hunter
Director
European Forest Institute

1 INTRODUCTION

J. Prietzel and K.E. Rehfuess

During the last decades, researchers in many European countries (e.g. Pretzsch 1985; Andersson et al. 1988; Becker et al. 1990; Makkonen-Spiecker 1991; Kenk et al. 1991; Keller 1992; Kenk 1993; Eriksson and Johansson 1993; Spelsberg 1994; Tomter 1994; Röhle 1995; Elfving and Tegnhammar 1996; Untheim 1996) noticed a considerable (up to 60%) growth increase of forest stands compared to the past. Results of recent studies from 12 countries were presented in the EFI Research Report “Growth Trends in European Forests” (Spiecker et al. 1996). A reduction of growth was reported only a minority of monitored stands (Kenk et al. 1983; Schöpfer and Hradetzky 1986; Röhle 1987; Pretzsch 1996).

The reasons for the *recent growth increases* are not yet elucidated. Generally, tree growth is regulated by the availability of light, water, nutrients (macro nutrients N, P, K, Ca, Mg, S, Fe, micro nutrients, CO_2), by the duration of the vegetation period, and by the presence or absence of noxious chemical agents and biotic as well as abiotic factors including disturbances. For different sites, tree species, and years, different factors may be growth-limiting. Thus, the increment changes reported above may be due to changes of different or varying growth-limiting factors. Various causes discussed as being responsible for the observed increases in growth are reviewed briefly.

Increased site fertility

In many forest regions of Central Europe, nutrient export by harvesting decreased remarkably during recent decades. Whereas in the past centuries, small wood, branches, and bark were used as fuel wood, in modern forestry only the trunks are removed from the forest ecosystems (Kreutzer 1993). Moreover, in many regions litter-raking and forest pastory were stopped. This might be the most important reason for the fact that site fertility in general and particularly the supply of nitrogen increased significantly during the last decades (Kreutzer 1993). This should affect growth, since N was and still is – as shown by many fertilisation experiments (cf. Kenk and Fischer 1988; Nilsson and Wiklund 1992, 1995) – the most prominent growth-limiting nutrient in many European forest ecosystems. Additionally, site fertility might have increased due to (i.) enhanced atmospheric inputs (N and S in acid deposition), (ii) increased liberation of nutrients from soil organic matter by climate warming, or changes in litterfall composition), and (iii) forest fertilisation with limiting elements and liming.

On the other hand, also negative changes in site fertility (e.g. reduction in base cation pools) have been reported regionally (see Chapter 4), which should result in decreased nutrient availability and thus reduced forest growth. The pH, which is of major importance for the regulation of the biotic activity, for the release of nutrients via mineralisation and mineral weathering, and for the mobilisation of ecologically undesirable Al in forest soils, decreased significantly in topsoil horizons of many European forest sites (e.g. Butzke 1981, 1988; Lochman 1981; Hallbäcken and Tamm 1986; Buberl et al. 1994; Prietzel et al. 1997). Yet, it must be noted that rapid soil acidification often seems to be associated with a temporarily enhanced supply of base cation nutrients due to intensive mobilisation of the latter by (i.) increased mineral weathering and (ii) desorption of base cations from exchange sites as a consequence of increased Al concentrations in the soil solution. Thus, the recent growth increase in many European forests might be partly the effect of a simultaneous increase in the supply of N and an increase in plant-available base cations driven by atmospheric deposition.

However, increased N deposition to forest stands with very low pools of base cations has the potential to induce or aggravate nutritional imbalances (Nihlgård 1985) by two mechanisms: (i.) In N-limited forest ecosystems, the increased growth of trees due to improved N supply is associated with an increased demand for other nutrients as P, K, Ca, and Mg. (ii) With decreasing N limitation of forest ecosystems, nitrification and NO_3^- leaching increase in well-aerated, permeable soils. This process is associated with soil acidification, increased export of nutrient cations from the ecosystem and/or enhanced mobilisation of inorganic monomeric Al, which impedes Ca and Mg uptake by forest trees. At non-nitrifying sites, elevated NH_4^+ concentrations in the soil solution may slow down root uptake of Ca, Mg, and K. Thus, particularly for sites on base-poor bedrock, tree growth in the longer run could be restricted by insufficient K, Mg, and Ca supply (cf. Likens et al. 1996).

At present, however, base cation (or P) deficiencies probably limit forest growth only in a small portion of the European forests (sites or regions with extraordinarily high atmospheric acid deposition as e.g. the Ore Mountains or stands in the vicinity of stock farming and fertiliser plants (v. Breemen and v. Dijk 1988; Hofmann et al. 1990; Heinsdorf and Krauss 1991; Ferm et al. 1990; Binkley and Högberg 1997). Yet, the recent significant changes in tree growth may indicate a current instability or "ecological drift" of many European forest sites and ecosystems, which should be observed with attention, since it might finally result in a future decrease in forest growth and ecosystem stability on larger areas in Europe. A drastic growth decrease was reported recently for the Hubbard Brook Experimental Forest (Likens et al. 1996), which is suggested to be caused by an insufficient Ca supply of the stand after long-termed Ca losses of the ecosystem by seepage water export. These losses obviously were driven by high atmospheric acid deposition. An over-optimal N supply of trees also may be associated with a reduction of growth (e.g. Kennel and Wehrmann 1967) and ecosystem stability (Bolsinger and Flückiger 1989; Laatsch et al. 1968; Fangmeier et al. 1994).

Vice versa, increased forest growth may also affect site fertility. It results in an enhanced rate of biological acidification and nutrient depletion of the rooted soil in the course of a rotation period. The extent to which the absorbed nutrients will remain in the ecosystem in the long-term (>1 rotation period), largely depends on the harvesting technique (cf. Glatzel 1991). Under optimal climatic growth conditions, base cation export due to timber harvesting for many forest ecosystems, particularly for those on base-poor bedrock and acidic soils, might exceed the nutrient input by atmospheric deposition and release by mineral weathering, if inappropriate harvesting techniques are used. If that process is not compensated for by adequate fertilisation, its long term consequence might be a significant depletion of base cation pools in the rooted soil and a reduction in site fertility. Thus, an accelerated forest growth requires increased attention of foresters and requires efforts to minimise nutrient exports from critical sites by using appropriate techniques of timber harvesting. It requires (i.) a monitoring of nutrient balances (comparison of nutrient exports by timber harvesting and with the seepage water with nutrient inputs by mineral weathering and atmospheric deposition) for managed forests and (ii) the avoidance of nutrient balance disequilibria either by harvest export reduction or by adequate fertilisation.

Climate conditions

Dependent on site, tree species, and stand conditions, the effects of climate fluctuation on forest ecosystems are highly variable. Thus, only some general remarks can be made at this place. Forest growth is obviously affected negatively by warm and dry vegetation periods inducing a shortage of plant-available water (Spiecker 1986, 1991a; 1995; Kahle and Spiecker 1996). A prolongation of the vegetation period due to warmer spring and summer seasons with a contemporaneous increase in water supply (either due to increased soil water replenishment during winter and/or higher precipitation during the growing season) is expected to result in increased increment rates of forest trees. Thus, a possible cause for observed growth increases are – at least for some sites – favourable weather conditions during the 1950s and 1960s, inducing a phase of forest growth recovery after sharp increment decreases in Central Europe between 1940 and 1950, which was a period of dry and unfavourable climate (see Chapter 6). Regarding long-term trends of climate in Central Europe, the available data indicate a significant increase of the annual and especially winter precipitation up to ca. 10% and 30%, respectively, and of the annual average air temperature of +0.5 K, and a general shift towards a more maritime climate during the last 100 years (see Chapter 6). This trend, which may be at least partly due to increased atmospheric concentrations of greenhouse gases, should result in a wide-spread growth increase of forests due to prolonged vegetation periods, mild and rainy winters, and reduced phases of water shortage.

Other causes

Besides the changes in physical climate, also a direct *fertilisation effect of increased tropospheric CO_2 concentration* (see Chapter 5) is probably responsible for recent growth increases of forests, particularly, if the N nutrition is improved simultaneously (see Chapter 8.2).

Changes in silvicultural management practices (e.g. intensive thinning already in young stands, utilisation of improved and site-adequate tree species and provenances for forest regeneration) may also result in an increased forest growth.

On the other hand, *high atmospheric SO_2 immission and acidic deposition* – in most cases combined with climatic stress – have been suggested to account for the recent reduction of forest growth observed on acidic soils at high-elevation sites in Central Europe (Röhle 1987; Elling 1993; Kreutzer 1993; Wienhaus et al., 1994; Zimmermann et al. 1997). On these sites (however not exclusively there, but also on calcareous high-elevation sites with low atmospheric N and S deposition), trees are often characterised by deteriorated crown conditions. Substantial growth decreases of these stands compared to trees without crown defoliation, however, were reported only for Norway spruce and silver fir trees showing needle losses of more than 30-50% (e.g. Kenk and Fischer 1988). But even the latter group of trees grew at least as fast as predicted by yield tables.

It can be summarised that the interrelations between soil fertility, the changing physical and chemical climate, and forest growth are manifold and complex. For sites differing in climate, soil physical and chemical properties, levels of N and acid deposition, and history of forest utilisation, as well as for different tree species, various patterns of interrelationships are likely to occur. Recent changes of forest growth as well as the unexpectedly rapid change of relevant soil chemical properties reported for many European forest ecosystems emphasise the necessity of detailed investigation into that issue. As the changes are a pan-European phenomenon, their investigation should be conducted on the European level.

Therefore, in the end of 1996, a group of forest scientists from various disciplines (forest growth, forest soil science, forest nutrition, forest ecology) and various European countries (Finland, Germany, Great Britain, Sweden) formed in order to establish a joint European research project to investigate the <u>Re</u>lationships between recent <u>C</u>hanges <u>O</u>f <u>G</u>rowth and <u>N</u>utri<u>tion</u> of European Norway spruce, Scots pine, and European beech forests (acronym: RECOGNITION). According to its pan-European character, the research project is aimed to be funded by the European Union. The preparation of the project was financially supported by the European Forest Institute.

2 FOREST GROWTH

H. Spiecker

2.1 MEASUREMENT OF FOREST GROWTH

2.1.1 Forest growth – an indicator of environmental conditions

Growth reactions of trees are indicators of environmental changes in their spatial and temporal extent. Recent investigations in European forests show long-term changes in growth. Many case studies clearly indicate that productivity of many forest sites in Europe has increased already since several decades. Some studies showed no trend and in rare cases a decreasing trend was observed. (see Chapter 2.3). These findings indicate changes in environmental conditions. There are several potential causes of the observed site productivity changes such as land use history, management climate, including nitrogen deposition and increase in CO_2 content in the atmosphere, and natural disturbances. The growth changes may have been caused by one factor, a factor combination or by regionally changing factors which finally had similar effects on growth. Forest growth by itself therefore is not a sufficient tool for the diagnosis of specific causes. Growth studies, however, may provide information about the spatial and temporal growth changes.

Information about the causes of the observed growth changes is needed for predicting future forest development and for estimating risk assessments. The RECOGNITION project emphasises potential effects of changes in nutrient supply and the increased CO_2 content in the atmosphere on forest growth. Other factors affecting forest growth, however, have to be considered as well.

An ecologically sound growth parameter in ecosystem analysis would be biomass production per unit of area. Information about long-term change of biomass production, however, is rather limited. On the other hand, forest wood production has been investigated extensively. Growth parameters such as height, diameter and volume have been measured in Europe on thousands of long-term permanent plots for many decades. Meanwhile a lot of information on forest growth has been accumulated in growth and yield research centres.

The data sources for forest growth are:

1. data from tree analysis
2. periodically repeated measurements

The RECOGNITION project aims at the stimulation of a joint effort to present and interpret results of forest growth and nutrition studies and to present the importance of the main causes on a European scale. The results help to understand past environmental changes and their effect on forest growth. This information is essential for sustainable forest management.

For the joint research approach, standardised methods have to be defined to facilitate the comparison of results on a European scale. This chapter on ‘Measurement of forest growth’ is based on the two publications: EFI Working Paper No. 4 (Spiecker et al. 1994) and in EFI Research Report No. 5 (Spiecker et al. 1996).

2.1.2 Tree analysis data

The measurement of annual rings and shoots allows the reconstruction of tree growth even over long observation periods with yearly time resolution on any site where forests are growing in temperate climatic conditions. As a result height growth, diameter growth, development in stem form and volume growth of individual trees can be described retrospectively. This source of data may be used when no long-term permanent plot data are available and/or a yearly time resolution of growth is needed.

For the reconstruction of height growth trees generally have to be cut. Annual shoot growth can be identified along the stem but has to be checked by counting annual rings. When annual shoots are missing or more than one shoot per year has been identified the interval of ring checking along the stem has to be shortened. Some species do not develop annual shoots that can easily be detected. By cutting discs at short distances along the stem periodic height growth can be reconstructed by determining cambial age differences and height differences between the discs. Annual radial growth can be measured by cutting discs at predefined locations along the stem and by measuring annual growth along several radii in order to be able to analyse irregular and eccentric radial growth. As an alternative increment, cores can be used to measure annual ring width. Here the trees do not need to be cut but will be damaged and possibly infected by fungi.
A main problem of tree analysis data is that stand history may not be known and that it is impossible to find individual trees which represent stand growth over a long-term period by their growth. Even all remaining trees in a stand may not represent past growth of the stand properly (Spiecker 1992). Individual competition dynamics are influenced by the constellation of neighbouring trees which may be modified by thinning operations, natural mortality or on growth. The population representing the stand is changing over time. Thus tree analysis does generally not allow a reliable reconstruction of long-term basal area or volume growth of a stand. An example of management influences on radial growth is shown in Figure 2.1.

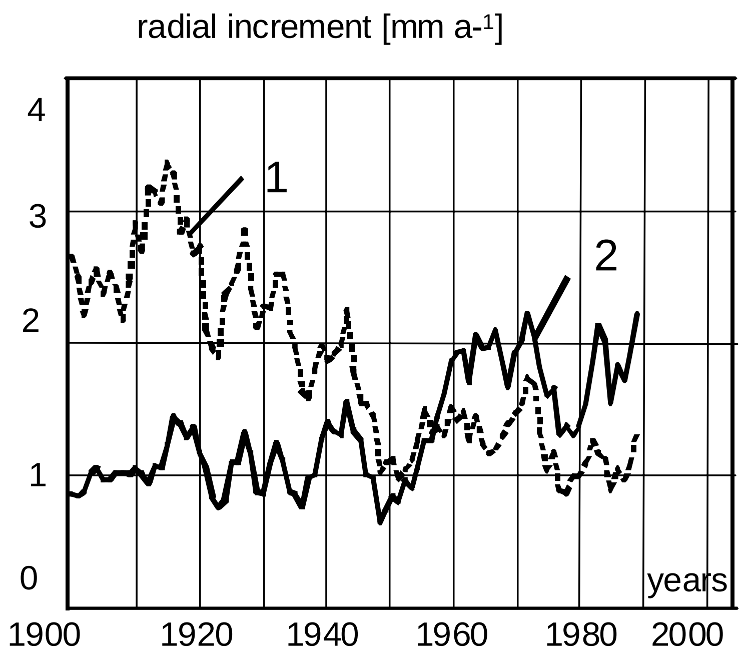

Figure 2.1. Differences in radial growth trends caused by past competition: 1: wide initial spacing, no thinning; 2: heavy release (Spiecker 1992).

Methods of detecting site-related growth trends by radial increment or ring width data of single trees have to include non-site factors, especially stand density and ageing (e.g. Briffa 1992; Leblanc 1993; Van Deusen 1987). For minimising competition effects dominant trees should be selected for tree analysis. Growth reaction of dominant trees may however differ from the reaction of co-dominant and suppressed trees. The potential of tree-ring measurement lies in the precise reconstruction of the annual variability of increment. Events with strong effects on tree growth are rather easy to detect (Schweingruber et al. 1990). Tree-ring analysis has been successfully used especially in short- and medium-term dendroecological studies. Combining measurement of annual ring data of sample trees with periodic diameter measurements of all trees on permanent plots may provide reliable area-related annual growth values (Spiecker 1987, 1991a).

Data from height analysis may be used as indicators in site productivity evaluation. However, the reliability of height growth as indicator for site productivity has to be validated. The combination of tree analysis data with permanent research plot data leads to an improved database for detecting growth trends.

2.1.3 Permanent research plot data

Many forest research organisations installed hundreds of long-term permanent plots in Europe. The earliest have been established in the middle of the 19th century. The trees within the plots have been numbered and diameters of all trees as well as height of selected trees have been remeasured in several years lasting time intervals.

The earliest permanent research plots generally were established to determine long-term volume growth potential of a site for a particular species or forest type. Later new research objectives were added. Provenance trials, spacing and thinning trials, fertiliser trials and others were established. For investigation of changes in nutrition and their effects on forest growth, the non-fertilised control plots of fertiliser trials are of special interest because generally more detailed information on site conditions and on the nutrient status of the stands exists and in most cases only moderate thinning treatments were applied. The great advantage of long-term permanent plot data as compared to tree analysis data is the generally well-known stand history. Disadvantages are non-representativity due to insufficient repetitions, subjective implementation and only periodic time resolution.

Stand growth can be expressed by basal area growth, height growth or volume growth. Basal area growth is easy to measure, but is more influenced by silvicultural measures than height growth. Volume growth combines basal area and height growth, including stem forms and their changes. Volume growth generally is used as an indicator of site productivity. A comparison of volume growth from several decades is only valid if the methods of tree volume calculation are the same. Generally, methods of measurement as well as methods of calculation have to be described in detail. The use of stand growth data on a per ha basis allows the use of simpler methods for describing growth changes than the use of tree analysis data.

Stand history and former land use history must be known as exactly as possible. Plots that have been damaged considerably by storm, fire, snow, insects or fungi must not be included in the analysis. Also fertilised plots must not be included when fertiliser effects have to be eliminated. It is important to pay enough attention to site-specific growth patterns, which in special cases could be taken for growth trends. These often turn out to be typical growth patterns for specific site types, for example when roots penetrate deeper soil layers with changing properties. Climatic and deposition data are also needed.

On long-term permanent plots stem diameters are usually measured at breast height ($d_{1,3}$) periodically every 3 to 10 years. To determine tree growth, every tree should be measured each time at exactly the same position (permanent marking of measuring point is essential). When this requirement is not fulfilled, the reconstruction of past tree diameters could be based on increment cores or stem discs.

A combination of single tree data with permanent plot data allows the correction of periodically measured plot data and can provide measurements of volume increment of permanent plots in an annual time resolution (see 2.1.2). Combining single tree data with temporary plot data helps to overcome some limitations of single tree growth data. It is possible to take increment cores or discs from trees to be removed from permanent plots. Increment cores cause damages and should therefore not be taken from remaining trees in ongoing experiments. By combining tree analysis data with periodically measured stand characteristics, it is possible to study the annual effects of environmental changes on tree diameter and height increment. In addition, it is possible to detect and eliminate ex post systematic errors of periodic diameter measurements (Spiecker 1985).

If stand characteristics are calculated based on models derived from sample tree measurements, the number of sample trees must be large enough. The heights of trees are usually measured from 20-40 sample trees. The previous selection of the sample trees can therefore have a high influence on the results (dominant, co-dominant, suppressed trees, the same sample trees every time or not). Trees in different social classes may show different growth trends. These trends, arising from natural stand dynamics, must not be misinterpreted.

Analysing growth trends in mixed stands is problematic due to differences in the growth rhythms of tree species and the continuously changing competition between them. So different species can show positive and negative growth trends in the same stand depending on tree age, species composition, type of mixture and site influences. Investigations in pure stands are recommended in order to exclude such influences. It is useful to have research plots on clearly different site classes because effects of environmental changes on growth can be different on fertile and poor sites.

2.2 Existing growth data

Within the frame of the RECOGNITION project the most limiting data are those describing long-term changes in deposition rates, changes in air chemistry and nutrient uptake. Whenever there exist such data series growth data should be provided either by using existing data from long-term permanent plot measurements or from tree analysis. When no adequate growth data are available data should be provided by tree analysis for the sites where reliable environmental data series exist.

Data from control plots of long-term fertiliser plots are of special interest since generally detailed descriptions of site conditions and nutrient content in the needles/leaves are available. In Europe, fertiliser trials have been established since the beginning of this century. Data from the control plots are of special interest in the context of the RECOGNITION project. More than twenty researchers from various European countries indicated that they would like to co-operate within the RECOGNITION project. In some cases data are already available in digital form, in other cases old data still have to be transformed and checked. By comparing the individual results in a standardised way a better understanding of environmental changes and their effects on growth is expected.

2.3 DETECTING CHANGES IN FOREST GROWTH

2.3.1 General remarks

Deviations of actual growth from expected growth indicate site productivity changes. As a reference of expected growth past growth of stands with similar characteristics on the same location or on sites with similar history and actual site characteristics may be used. Yield tables generally do not fulfil these requirements and therefore do not describe expected growth adequately. Growth trend estimation methods are discussed by several authors (Cook et al. 1990; Dupouey et al. 1992; Van Deusen 1991; Spiecker et al. 1996; Zahner 1988; cf. these for further literature). Further methodological hints are given in many publications relating to growth effects caused by forest damages for example by Deutscher Verband Forstlicher Forschungsanstalten, Sektion Ertragskunde (1988); Lorenz (1987), and McLaughlin and Bräker (1985).

2.3.2 Detecting changes in forest growth by comparing the growth of trees and stands with different germination dates

The majority of permanent growth plots in Europe have not existed for longer than one generation. Therefore, the comparison must in most cases be done by comparing former growth of older and younger stands situated in some distance from each other.

This method includes the comparison of time-series of different parameters (e.g. height and diameter) of trees germinated at different points in time. The following conditions must be fulfilled:

- Management (regeneration, tending of young stands, thinning intensity, way of thinning etc.) influences at a given age must be constant over time, especially if tree-ring data are analysed.
- Genetics and competition of the compared trees should be the same.
- Sites under consideration must be the same at one given point in time. Only in this case site-related growth changes can be detected.
- Fluctuations in growth conditions influence reference values. For example several years lasting unfavourable weather conditions during the reference period may have an effect if the fluctuation is not properly corrected.

If individual tree data are compared on a regional basis, equal competitive regimes and site distributions in time must be represented by the data. Examples for this method are described by Becker (1989) using tree ring data and by Untheim (1996) using height growth data (Fig. 2.2). Site classification at one point in time is a problem in growth trend studies, because possible growth trends may be caused by site changes such as soil succession. If this is not taken into account, the possible trend cannot be found in the analysis. The problem exists when site classification is based on height development as well as when plant communities in the stand are used as reference.

Comparisons between several site types may give a better insight into possible causes. For example, regional comparisons of site types with good and poor nutritional status could be helpful. Additional information could also be drawn from analysing tree response to fertilisation.

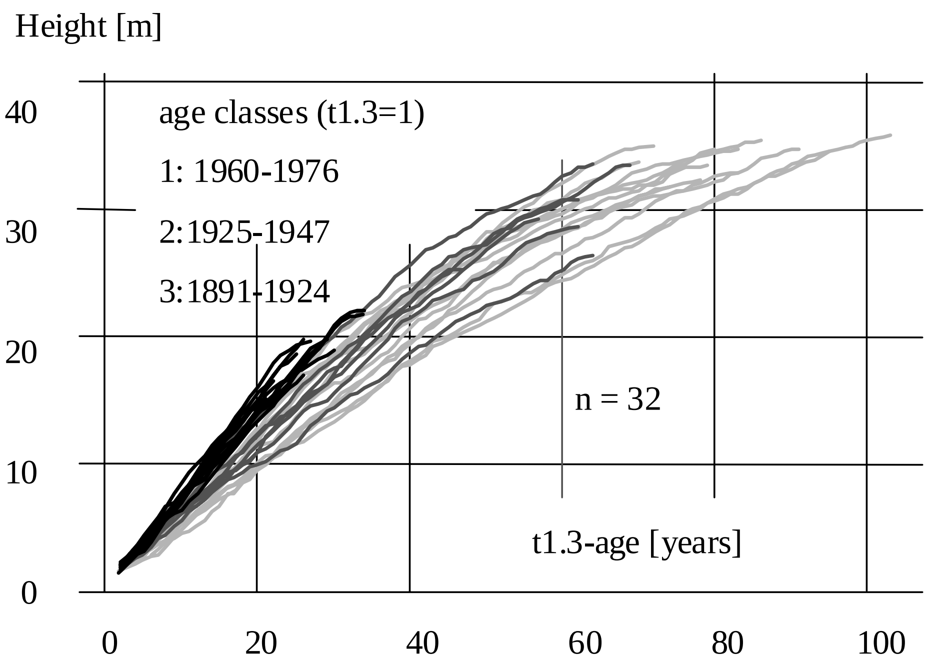

Figure 2.2. Height growth of Norway spruce with different germination dates (Untheim 1996). 32 Norway spruces grown on comparable sites in the northern Swabian Alb show changes in height growth with time. 't1.3' is the cambial age at breast height at the time of the analysis.

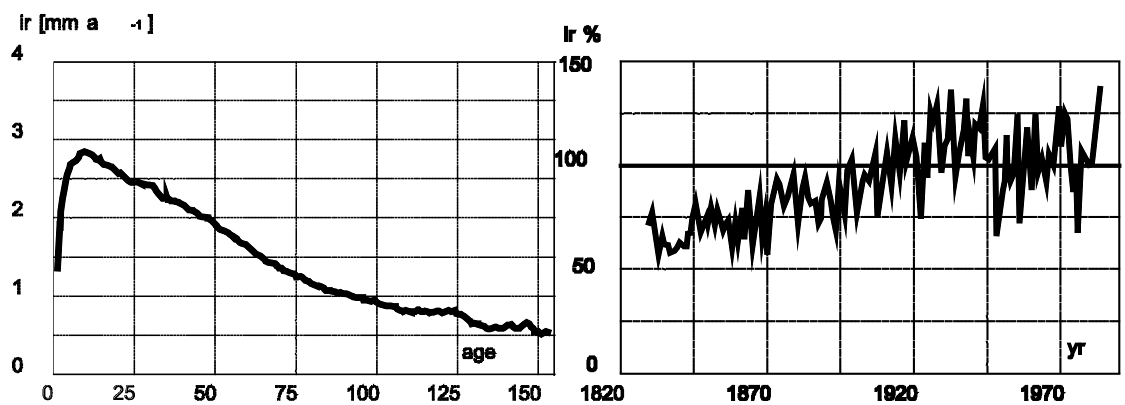

Figure 2.3. Radial growth trend (left graph: average radial growth over age; right graph: average radial growth deviation from the growth trend shown in the upper curve, Becker 1989).

2.3.3 Detecting changes in forest growth by comparing the growth of successive generations

Growth patterns of successive generations on an identical geographical location have been compared by several authors (e.g. Eriksson and Johansson 1993; Keller 1992; Kenk et al. 1991). This is a suitable method for detecting site productivity changes. In cases where the second generation stand has not been measured, single tree height development data might be compared with research plot data of previous generations (c.f. Figure 2.4). By using this method interpretation is limited by the following restrictions:

- Genetic structure and stand management of the consecutive generations must be comparable.
- Several consecutive generations of the same species might, depending on the site, lead to site productivity changes.

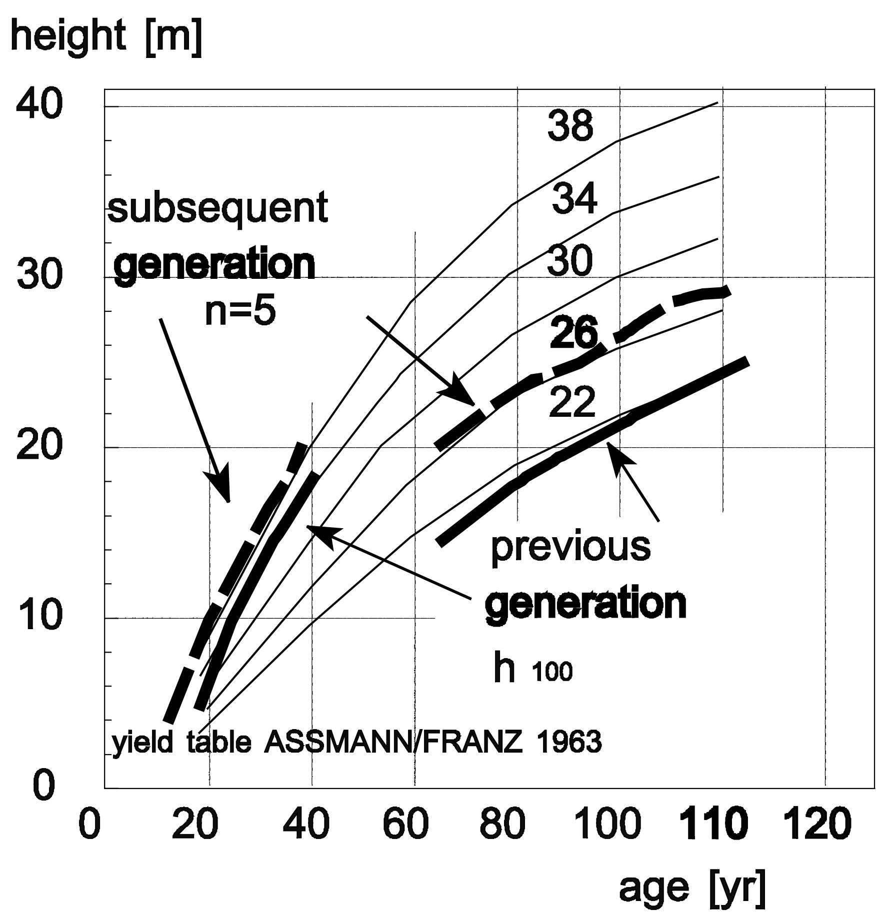

Figure 2.4. Height growth of two successive spruce generations on the same plot (source: Kenk et al. 1991).

This method will be used in the context of RECOGNITION only in exceptional cases since information on the nutrient status of the former generation rarely exists.

If there are enough height data available from successive tree generations in a region, some kind of correction could be made by modelling the site index change as a function of time. In this way it is possible to correct the site index of a stand established in the 1960s to correspond with the initial site index of the same stand in the 1920s. By doing so, a certain comparison between the productivity of stands from different decades can be made. If this correction of the site index is not carried out, the possible trend will not be visible.

2.3.4 Detecting changes in forest growth by comparing growth with yield tables or other growth models

Yield tables and other growth models often are used as growth reference. For the interpretation of deviations from the reference the date base of these references must be known. The database must be comparable with respect to site conditions, management regime etc.

For using yield tables or other growth models as reference certain conditions must be fulfilled as in the case of 2.3.2:

- Management practices in the reference stands influence reference values.
- Genetics and stand structure should be similar.
- Site conditions at a given point in time should be the same.
- Fluctuations in growth conditions have to be taken into account.
- References may be biased due to uneven distribution of site classes in different age classes. If e.g. the oldest stands used in yield tables grew on relative poor sites, a comparison with these tables leads to an overestimation of actual productivity in older stands (Assmann 1970).

Growth models other than yield tables can either be based on the whole study material or can be calculated on the basis of other representative material. The latter method needs to know when the trees were measured. The model must first be calibrated to give unbiased estimates of tree or stand growth at the time of its data measurements. The residuals along calendar years reveal growth deviations from expected growth.

Modelling single tree growth by using long-term constant (especially topographic and edaphic characteristics) and varying site factors (especially weather conditions) as predictor variables allows for the comparison of former growth response to site factors with the response today. Assuming that tree competition, genetic and ageing influences are removed from the time-series under consideration, an altered response must be due to changing site factors. This method thereby allows a separation of expected reactions from unknown reactions.

The greatest problem with this method is the question of detrending. There is no superior method of removing age-related and competition trends. Analysis must be carried out very carefully to avoid eliminating parts of the searched for long-term trend signal. Unlike most statistical estimators of population parameters, no statistical theory tells us how well the observed signal in tree rings estimates the expected signal. In most cases, we must rely on statistical measures of signal strength, frequency domain definitions of signal and noise, and knowledge about sites, stand histories, and tree biology to guide us (Cook and Briffa 1990).

Height growth, especially top height growth, is often used as an indicator of site productivity. Nevertheless, total volume growth is a better indicator.

height growth = f (age)	(1)
total volume growth = f (height)	(2) (yield class)
$\rightarrow$ total volume growth = f (age)	(3) (site productivity)

Function (1) and (2) may change in opposite directions so that an increase in height growth does not necessarily reveal a change in site productivity. Yield level cannot be estimated with single tree data.

For height growth data the referred definition of stand height, the measurement method, and the method used for relating height to age has to be described. The calculation of volume growth on the base of height and basal area growth must be well defined, as volume functions can be very sensitive to changes in the independent variables.

Studying the trend of dominant height development on the basis of site index curves is not possible, if the site index curves are based on long-term observations within the time to be analysed. The possible growth trend is included in the site index curves as well and possible changes will not be discovered.

2.4 RECENT CHANGES IN FOREST GROWTH

Even without human influences, forests have been exposed to environmental changes. Consequently, growth rates have always been changing over time. In addition, human activities are increasingly influencing the environment. Changes in historical management, litter raking, pasturing, fertilisation and liming, climate (including air chemistry), atmospheric deposition, occurrence of pests and diseases, disturbances caused by fire, storm and snow, as well as browsing have influenced site conditions considerably. The global increase of atmospheric CO_2 and atmospheric deposition of nitrogen have an impact on forests. The above mentioned environmental changes vary in space and time.

The main interest in growth changes on a European level refers to changes in site productivity such as changes in water and nutrient supply (Spiecker et al. 1996). It is difficult to separate these growth trends which reflect long-term changes in site productivity from episodic changes caused by extreme events such as frost, drought, snow and storm damage, fire, by insect or fungal diseases or by a combination of several events which will be followed by a reverse change. Growth trends were defined as long-term deviation of actual growth from expected growth. Three data sources were available: research plot data, inventory data and tree analysis data. Since existing data had to be used, the quantity and quality of available data varied. In some countries, no long-term growth data were available in an appropriate form. Some data reported in the EFI publication refers to case studies on rather small areas, others – as for example some inventory data – refer to larger regions or nations. Also, the time span of available data varies from few decades to several centuries. Since the data analysed were usually not collected for analysis of long-term growth trends, a certain variation in the applied standards has been unavoidable.

Because of these shortcomings, the EFI Research Report does not present growth development of forests in Europe in a uniform and statistically representative way. However, the results may still allow some conclusions on the European level. The EFI Research Report No. 5 consists of 22 papers written by 45 scientists from 12 countries are presented in this report. Most studies were conducted in Northern and Central Europe. Only two studies refer to Southern Europe. To ensure scientific standard an editorial board was founded. In total 61 scientists independently reviewed the individual contributions and gave valuable comments.

Growth of European forests has changed considerably in recent decades. Although the methods applied in the 22 studies varied according to the data available, most studies showed the same general trend: site productivity has increased on many sites. An increasing growth trend has been observed in the southern regions of Northern Europe, in most regions of Central Europe and in some parts of Southern Europe. The results derived from long-term observations on permanent plots and from tree analysis are supported by inventory results which are representative for large areas, but cover generally shorter observation periods. Site productivity in terms of wood volume increased on various sites within the last decades by up to 50 %, in some cases even more. No clear trend was found in the most northern part of Europe, in rare cases in Central Europe and in some observations in Southern Europe. A decreasing trend was found in exceptional cases where extreme growth conditions such as intense exposure to pollutants or exceptional climatic conditions occurred. Several other publications on changes in forest growth support the findings described (Elfving and Tegnhammar 1996; Kauppi et al. 1992; Keller 1992; Kenk et al. 1991; Kuusela 1994; Pretzsch 1987; Röhle 1995, Spelsberg 1994; Spiecker 1986).

Besides effects of changes in site productivity data on wood production rates on regional or national levels are influenced by

- inconsistencies in inventory methods
- changes in forest area
- changes in species composition
- changes in age class distribution
- changes in forest management

The researchers involved in the EFI project considered these factors when they discussed the increase in site induced growth trends.

The general increasing growth trend may have been caused by one factor, a factor combination or by regionally changing factors which finally had similar effects on growth. As potential causes land use history, forest management, natural disturbances, climate, including nitrogen deposition and increased CO_2 content of the atmosphere, and other factors, including a combination of several factors are in discussion. The significance of each factor possibly varies in space and time. Growth responses to the influencing factors are modified by site and stand conditions.

The amount and complexity of the scientific problems evolving from the observed forest growth trends show that solutions can only be developed by the co-operation of scientists covering various disciplines on a European or world wide level. Co-operation will lead to a more comprehensive understanding and will provide a more realistic and reliable basis.

3 CHEMICAL SOIL PROPERTIES AND STAND NUTRITION

J. Prietzel and K.E. Rehfuess

3.1 MEASUREMENT OF CHEMICAL SOIL PROPERTIES AND STAND NUTRITION

The nutritional status of forest stands is intimately related to chemical properties and nutrient contents in the rooted soil zone (e.g. Miller et al. 1977; Ke and Skelly 1990/91; Liu and Trüby 1989; Nohrsted and Jakobson 1994; Braekke 1996). Thus, changes in soil chemical properties can – besides other factors as climate, water supply, fungal infestations – considerably affect the nutritional status of trees and forest stands. Therefore, soil chemistry should be considered when time-trends of stand nutrition and growth are discussed or prognosed.

3.1.1 Measurement of chemical soil properties

The most important chemical soil properties governing the nutritional status of forest stands include:

(1) The total nutrient content/pool as maximum supply of potentially plant-available nutrient elements. This variable is usually analysed by wet oxidation/digestion of the dried and ground soil sample in a mixture of concentrated HF or HNO_3 with $HClO_4$ and a subsequent determination of interesting elements in the extract using various spectrophotometrical instruments (flame spectrophotometry, AES, AAS, ICP-OES). C, N, and S are usually quantified by wet oxidation techniques using $H_2SO_4/K_2Cr_2O_7$, Kjeldahl-mixture, NaBrO, or most recently by instrumental analysis.

(2) The soil pH value as key factor controlling the mobility and plant-availability of various nutrient and noxious elements and ions by governing:

- (i) their solubility equilibrium (Fe, Mn, PO_4, SO_4, trace elements, Al, heavy metals)
- (ii) ion exchange equilibrium
- (iii) the variable charge of adsorbents
- (iv) the intensity of mineral weathering
- (v) the abundance and vitality of soil micro-organisms involved in the element turnover of forest ecosystems
- (vi) the mobility of dissolved organic matter (DOM) in the soil

This parameter is usually measured with a glass electrode after equilibration of a dried and sieved soil sample in various liquid matrices (deionised H_2O; 0.01 M $CaCl_2$; 1 M KCl) and at various soil : solution ratios. For forest soils, 0.01 M $CaCl_2$ is suggested to provide the most realistic values that are only very little biased by seasonal concentration/dilution effects.

(3) the concentrations/pools of exchangeable, i.e. plant-available base cations (K^+, Na^+, Mg^{2+}, Ca^{2+}) as well as the base saturation (BS), which is the percentage of these concentrations to the total cation exchange capacity (CEC). These variables are commonly measured by treating the sample with an excess amount of NH_4^+, Ba^{2+}, or Ag^+, which displace all adsorbed cations from the cation-exchanging surfaces. The concentrations of the mobilised cations in the extract are measured spectrophotometrically (ICP-OES, AES, AAS, FES) and by potentiometric titration (H^+).

(4) the C/N ratio in the humic topsoil describing the N supply of the forest ecosystem as well as the plant-availability of nitrogen and other nutrients by humus mineralisation. This variable is usually analysed by wet oxidation/digestion of the sample using $H_2SO_4/K_2Cr_2O_7$, (C_{org}) or a Kjeldahl-mixture (N_{tot}), or most recently using instrumental elemental analysers (C,N).

All these criteria are comparably simple to determine and only to a small degree affected by short-termed fluctuations. Therefore, it is commonly suggested that primarily these parameters should be assessed when interrelations between soil chemistry and forest nutrition are aimed to be studied. In addition, it is helpful to investigate the availability of soil-adsorbed S and P to plants as well as the amounts of easily-mineralisable elements in the humic topsoil.

3.1.2 Assessment of stand nutrition

The nutritional status of forest stands can be assessed most properly and reliably by chemical analysis of the concentrations of the interesting nutrients in the needles or leaves of the trees (diagnostic foliar analysis; cf. Lundegårdh 1951; Wehrmann 1959, 1963; Tamm 1964; Fiedler et al. 1973; Evers 1986; Brække 1996). Since foliar photosynthesis provides the energetic and material (biosynthesis of organics) basis of existence of higher plants, needles and leaves are generally supplied best as possible with the plant-available nutrients. However, for a reliable data assessment providing comparable results of different studies, several rules must be regarded (cf. Wehrmann, 1959, 1963; Tamm 1964; Evers 1972, 1986, 1988; Hüttl, 1985, 1991):

(i) As the youngest needles/leaves of the upper, intensely-lighted part of the canopy are the place of most intensive photosynthesis, they – perhaps in addition also older needles on the same branch – should be sampled to get an unbiased view of the nutritional status of a tree (Wehrmann 1959; Hüttl 1985; Evers 1988).

(ii) At least 10 dominant or co-dominant trees should be sampled at various expositions of the canopy for an accurate assessment of the nutritional status of a forest stand (Wehrmann 1959; Hüttl 1991).

(iii) The sampling should take place in the late season of a year, (august for deciduous species, October or November for conifers), since foliar nutrient concentrations are significantly influenced by various translocation processes immediately before and during the vegetation period (Wehrmann 1959).

(iv) The sampling period should include more than one year to reduce possible biases induced by exceptional climate conditions, infestation, or high fruit production in single years (c.f. Evers 1972). For conifers and nutrients like N, Mg, and K, the concentration of which are decreasing normally with age, due to translocation from older to younger needles, the analysis of older needles in addition to the youngest ones may help to identify nutrient deficiencies.

After drying the samples, followed by determination of the 100- or 1000-needle/leaf mass of randomly chosen individuals, the samples are finely ground and their nutrient concentrations determined by instrumental elemental analysis (N, S), Kjeldahl digestion (N), or acid digestion with subsequent spectrophotometrical analysis (ICP-OES, AES, AES, flame photometry (P, S, B, metals).

For evaluating the nutritional status of the sampled trees and its dynamics, several approaches exist: They include:

(i) the comparison of the determined concentration values with established and commonly-accepted threshold values (e.g. Wehrmann 1963; Zöttl 1973; Ingestad 1979; Heinsdorf and Krauss 1988; v.d. Burg 1988; Brække 1994)

(ii) the comparison of ratios between different nutrients with optimum ratios (e.g. Ingestad 1979; Montanes et al. 1993).

(iii) the application of graphical vector analysis (Krauss 1965; Timmer and Stone 1978; Valentine and Allen 1990; Prietzel and Kölling 1998).

(iv) the application of the DRIS system (Beaufils 1973).

3.2 Existing data on chemical soil properties and stand nutrition

Intensive forest ecosystem research in various European countries during the past two decades as induced by the great public interest concerning the phenomena of "forest dieback" resulted in the establishment of numerous ecosystem monitoring sites (e.g. level I and level II network sites) and ecosystem manipulation studies (each containing control plots). Thus, countless data are available today describing the present chemical status of European forest soils under various site conditions. They are partly based on standardised sampling and analytical procedures (e.g. level II sites). However, this is often not the case for the vast part of the available data. Here, a comparison of results of different studies must be carried out with utmost caution.

Reliable data concerning the recent temporal development of soil chemistry, however, are less frequent. This is due to the following reasons: (i) Changes in soil chemistry occur rather slowly due to the fact that often large element pools are affected by comparably small changes of element fluxes; moreover, the spatial variability of soil chemical parameters is considerable (Grigal et al. 1991). Thus, it takes many years, if not decades, until effects of changed environmental conditions (e.g. elevated S, N and H^+ input) become visible in a change of chemical properties of the soil solid phase. This is particularly true, if total element contents in the soil matrix instead of smaller pools like exchangeable cations or easily-minerisable N and S are regarded. (ii) Another reason is the fact that repeated area-representative inventories of soil matrix properties are extremely seldom.

The use of diagnostic foliar analysis as tool to describe the nutritional status of trees and forest stands started in the 1930s. It was improved to a powerful scientific tool in the 1950s and 1960s (Lundegårdh 1951; Wehrmann 1963; Tamm 1964). Thus, the longest available time-series of foliar nutrient concentrations cover a period of about 30 to 40 years (e.g. Prietzel et al. 1997). However, these data in most cases are from fertilisation and amelioration experiments, which were often established on particularly poor sites. Thus, these time-series are probably not representative for many other forest stands, and their results can not be generalised.

3.3 RECENT CHANGES OF CHEMICAL SOIL PROPERTIES AND STAND NUTRITION

3.3.1 Changes in chemical soil properties

In most forest ecosystems of humid regions, soil chemical properties always have been and are continuously changing due to climate changes and fluctuations, to the modification and development of the ecosystem's structure and composition, the fluctuations of the rates of element losses and/or gains governed by the concomitant processes of mineral weathering, erosion, root uptake, litterfall, soil solution export, and due to other reasons. In many regions, humans have been influencing and changing the morphology and chemistry of soils for centuries or even millennia by logging, agriculture, pastory, litter raking, manuring, fertilisation, and amelioration. Driven by the increase in the human population and technological advance, the anthropogenic effect on the chemical status of European forest ecosystems including their soils has increased dramatically since the 15th century (start of litter raking and forest pastory, intensive forest exploitation for glass production, firewood, and construction, large scale replacement of primary by secondary forest of different species composition and structure), and particularly in the 20th century (anthropogenic deposition of H^+, N, and S, intensive forest management including prescribed burning, liming, amelioration, and fertilisation). Pre-industrial anthropogenic changes of soil chemical properties can only be assessed and quantified very roughly. The development of forest science, analytical chemistry, meteorology, biology, and – last not least – the establishment of forest soil science as subjects in the 19th and 20th century, included the set-up of monitoring sites and experimental studies and the availability of reliable analytical tools. This permits a better, in many cases nevertheless only semi-quantitative insight in the chemical changes of forest soils during the last decades. The number of available and reliable data concerning the chemical status of forest soils increased during the recent decades from only few sites 50 to 100 years ago (e.g. Ebermayer 1898, Frank 1927; Hesselmann 1937) to numerous forested sites investigated nowadays (e.g. as part of the level II network, European Council 1992; European Commission 1994, 1995, 1996).

A major factor responsible for this increase was the public concern about potential adverse effects of acidifying and eutrophying immissions (S, N, H^+) to European forest ecosystems (see Chapter 5). These immissions are supposed to induce in forest soils:

(i) **acidification** due to increased losses of base cations accompanying mobile SO_4^{2-} and NO_3^- anions with the soil solution (Reuss and Johnson 1986). The acidification can be identified by a pH decrease of the soil (intensity variable), or more precisely, quantified by the change in ANC (Acid Neutralising Capacity) and/or a decrease in the amount of exchangeable base cations (capacity variables) in the soil compartment of interest.

(ii) **S accumulation** as organic S (due to enhanced biosynthesis of C-bonded S and ester sulphates and/or reduced S_{org} mineralisation) or as inorganic S (due to enhanced SO_4^{2-} adsorption, precipitation of Al hydroxy sulphates). Whereas organic S predominantly accumulates in the forest floor and the humic topsoil horizons, the accumulation of inorganic S predominantly is observed in the subsoil.

(iii) **N accumulation** as organic N in litter and humus compounds of the topsoil horizons due to enhanced biosynthesis of proteins in plant and microbial biomass. Organic N almost exclusively accumulates in the forest floor and the humic topsoil horizons. The accumulation of inorganic N as NH_4^+ is generally low and restricted to soil horizons rich in illite-derived clay minerals at sites with low nitrification rates. An accumulation of the highly mobile anion NO_3^- does not play a significant role.

Besides these effects, which theoretically can be identified and quantified in soils rather easily, also many other chemical properties (heavy metal pools, sesquioxide pools, clay mineralogical composition) of forest soils are altered directly or indirectly by elevated atmospheric S and N deposition (v. Zezschwitz 1986; Blum and Rampozzo 1988; Veerhoff and Brümmer 1992). Additionally, the rate of mineral weathering is probably enhanced. However, all these features are rather difficult to deal with and often reclaim sophisticated analytical procedures, which were not been available in earlier times. As noted in Chapter 4.2, the annual changes of soil chemistry are small compared to the spatial variability of the respected variable in soils even for sites subject to high anthropogenic deposition. Thus, recent temporal changes of chemical properties of forest soils can only be identified and quantified for those variables, which have been studied for a time period of at least one or two decades with standardised and reliable analytical methods. It must be emphasised that, even if a change in one ore more of the soil properties can be identified and quantified successfully, the attribution of these changes to distinct driving forces (e.g. atmospheric deposition, natural development or change of the ecosystem's structure, change in silvicultural management) often remains a matter of speculation.

3.3.1.1 Soil acidification

The pH value of forest soils has been measured since more than 50 years. Thus, recent changes in the pH of European forest soils during the last decades are reported frequently. A good review concerning that issue is given in Rehfuess (1990). Obviously, the pH decreased significantly in most forest soils in *Sweden* (e.g. Hallbäcken and Tamm 1986 [Figure 3.1]; Falkengren-Grerup 1987), *Norway* (e.g. Stuanes et al. 1992), *the Netherlands* (e.g. v.d. Burg (1990), *Germany* (e.g. Butzke 1981, 1988; v. Zezschwitz 1982; Hildebrand 1994; Prietzel et al. 1997), *Czechia* (e.g. Klimo and Kulhavy 1984) and *Switzerland* (e.g. Kuhn 1990). Obviously, the pH decreases were particularly high for slightly acidic soils (c.f. Wiklander 1980; Falkengren-Grerup and Ericsson 1990) and in those afforested with coniferous stands (Hallbäcken and Tamm 1986), whereas very acidic soils (pH < 4) obviously did not exhibit a further pH decrease (Riebeling and Schäfer 1984; Fiedler and Hofmann 1986). However, in most studies, the soil-acidifying effects of an increasing stand age (Hallbäcken and Tamm 1986) have not been separated from those of acid deposition. The acidifying and de-acidifying effects of temporal fluctuations in humus turnover also cannot be addressed properly in most cases. However, the results of a recent large-scale forest soil survey indicate a negative correlation between atmospheric acid deposition and pH in the topsoil of European forest soils (Vanmechelen et al. 1997).

A more suitable and powerful tool for identifying and quantifying soil acidification is the investigation of changes in the pool of exchangeable cations. However, that variable has not been measured earlier than in the 1950s. Therefore, compared to pH, there exist fewer studies dealing with recent changes in the composition of the cation exchange complex of European forest soils. Most of them (*Sweden*: e.g. Troedsson 1980; Berden et al. 1986; Falkengren-Grerup and Eriksson 1990; Hallbäcken 1992; *Norway:* e.g. Stuanes et al. (1992); *Germany*: e.g. v. Zezschwitz 1985a; Grimm and Rehfuess 1986; Matzner 1988; Prietzel et al. 1997; *Czechia*: Lochman 1981), but not all (cf. Spiecker et al. 1992) indicate a decrease of the base saturation and the amount in base cations, particularly Ca, in topsoil horizons of conifer ecosystems subject to high atmospheric acid deposition. However, as it was the case for the pH changes, the proper separation of deposition effects from those of other processes (e.g. nutrient uptake by trees; cf. Miller 1990; Hallbäcken 1992; Hüttl and Schaaf 1995) or changes in tree species and humus composition (cf. Binkley and Högberg 1997) is difficult. It should be noted that during the recent years, in many Central European countries large forested areas have been limed (application of up to 10,000 kg ha^{-1} dolomitic limestone) in order to counteract acid deposition.

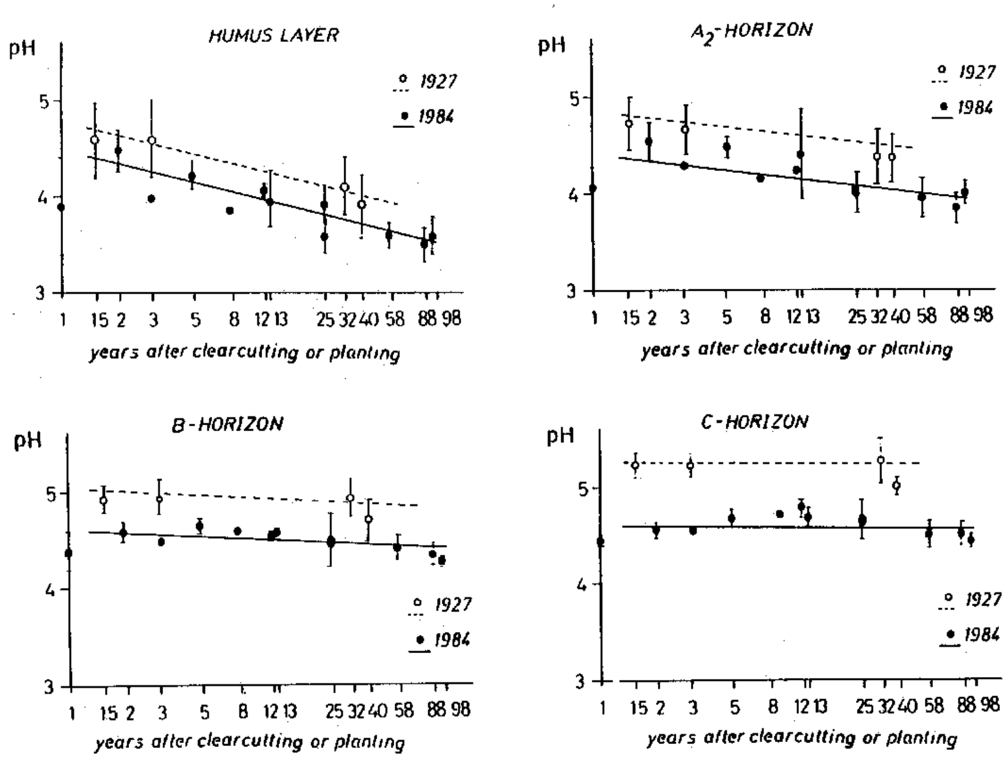

Figure 3.1. Changes in pH in the soil under different spruce stands at the Tönnersjöheden Experimental Forest between 1927 and 1984 (from: Hallbäcken and Tamm 1986).

3.3.1.2 Nitrogen accumulation

The N concentrations and the C/N ratios of forest floor and humic topsoil horizons have been analysed since more than a century (e.g. Ebermayer 1898; v. Zezschwitz 1985b). According to Ulrich (1983), v. Zezschwitz (1985b), and Hildebrand (1994), the C/N ratios of German forest soils have decreased on a large area during the recent decades. On the other hand, Matzner (1988) and Prietzel et al. (1997) did not find any significant changes in the C/N ratio of forest soils in the Solling (Matzner 1988) and Bavarian soils (Prietzel et al. 1997). The latter were subjected to intense litter-raking for centuries, and thus were particularly depleted in N. Probably, at these sites the atmospheric N input was sequestered either in the stand biomass or in the increasing humus amount without lowering of the C/N ratio. It seems that the N eutrophication of forest ecosystems subject to elevated atmospheric N deposition is mirrored first in foliar N levels (Prietzel et al. 1997), later in a decreasing soil C/N ratio (Vanmechelen et al. 1997) and finally in the NO_3^- concentrations of the soil solution (Matzner and Grosholz 1997).

3.3.1.3 Sulphur accumulation

The elevated atmospheric S deposition in many European forest ecosystems was obviously associated with an accumulation of S in forest soils. Studies of Meiwes et al. (1980), Zucker and Zech (1988) and Erkenberg et al. (1996), show that soils subjected to high levels of atmospheric S deposition accumulated S in organic (ester sulphate, C-bonded S) and inorganic forms (adsorbed SO_4^{2-}, water-soluble SO_4^{2-}). More S was accumulated in soils under conifers (Norway spruce) compared to broadleaves (European beech) on the same site (Meiwes et al. 1980; Fischer 1989). Contrarily, Gustafsson and Jacks (1993) could not find any S accumulation in the humus-rich B horizon of a Swedish Podsol between 1951 and 1989 despite high atmospheric S deposition.

3.3.2 Recent changes in stand nutrition

3.3.2.1 Nitrogen nutrition

For numerous European Scots pine and Norway spruce stands, foliar N concentrations were obviously increased considerably during the recent decades (*The Netherlands*: e.g. v.d. Burg 1990; *Germany*: e.g. Hofmann et al. 1990; Sauter 1991; Nebe 1991; Hippeli and Branse 1992; Prietzel et al. 1997 [Fig. 3.2]; Prietzel and Kölling 1998; Uebel and Heinsdorf 1997). However, it should be noticed that most of the investigated sites in Central Europe were substantially devastated and depleted in N due to long-termed litter-raking and forest pastory in the past. In those stands where N probably was the growth-limiting element at the beginning of the measurements – a typical feature for boreal forests subject to frequent wildfires (Kimmins 1996) or prescribed burning (Hallbäcken 1992) and for litter-raked forest ecosystems (Ebermayer 1898; Kreutzer 1972), foliar N increased during the investigation period to sub-optimal or even optimal levels. On the other hand, Spiecker et al. (1992) report insignificant increases in foliar N concentrations between 1971 and 1987 for Norway spruce on a (probably not litter-raked) Black Forest site.

For deciduous forests, also increases in the foliar N concentrations were observed in various European countries. Thus, v.d. Burg (1990) reports a strong increase in foliar N of Dutch pedunculate oak stands during the recent years. Flückiger and Braun (1994) observed a significant improvement in foliar N of a Swiss beech stand between 1984 and 1991. On the other hand, foliar N concentrations of beech underplanted in a NE German Scots pine stand did not change between 1977 and 1988 (Uebel and Heinsdorf 1997).

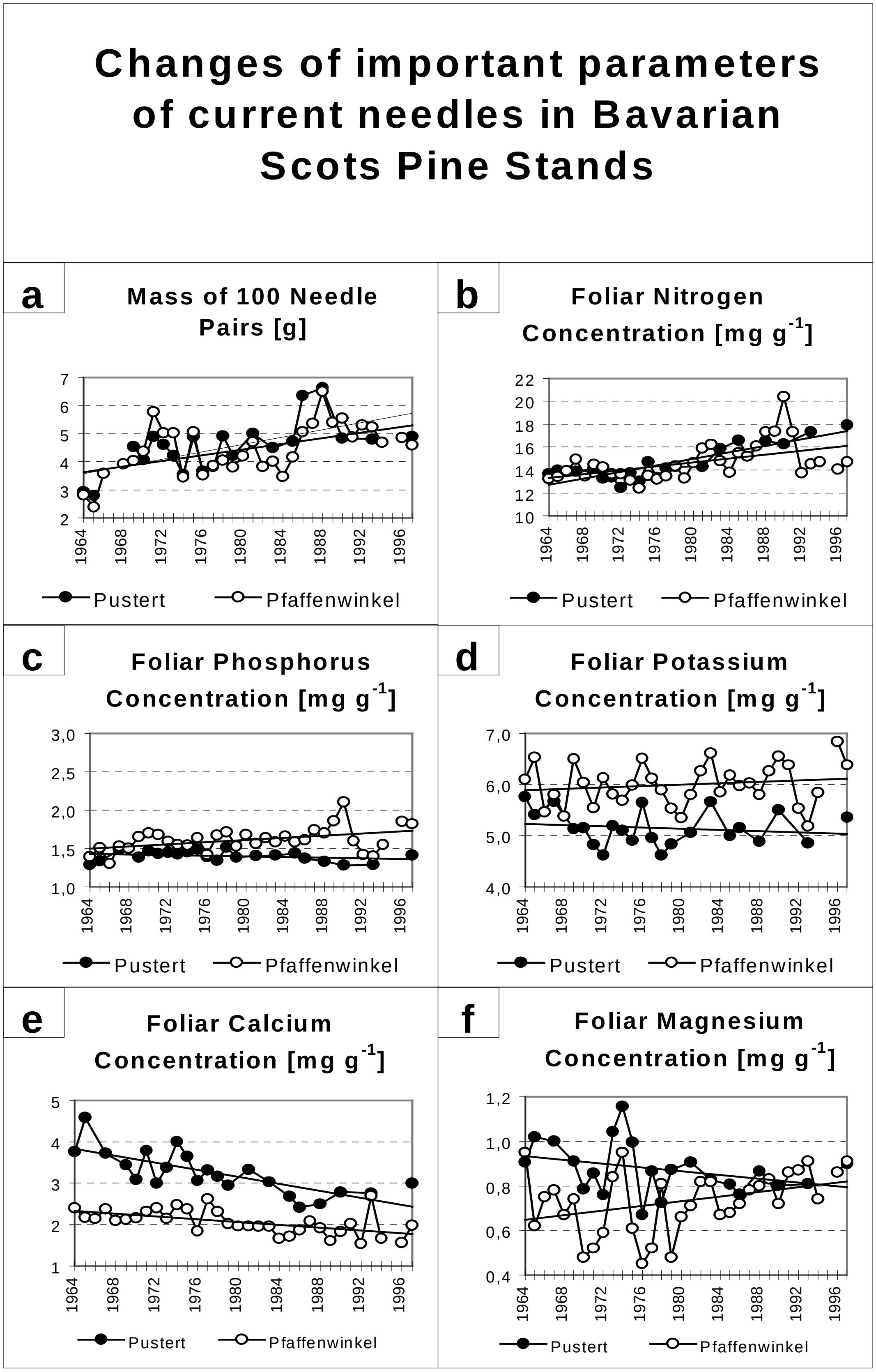

Figure 3.2. Recent changes of important foliar parameters of half-year old needles in two Bavarian Scots Pine stands (modified from: Prietzel et al. 1997).

3.3.2.3 Base cation nutrition

In many European long-term monitoring studies carried out on sites with base-poor parent material and acidic soils, a trend of decreasing Ca concentrations is reported (Hüttl 1986; v.d. Burg 1990; Nebe, 1991; Sauter, 1991; Prietzel et al. 1997). On the other hand, this trend was not observed on other sites with poor (Spiecker et al. 1992) or moderate nutrient supply (Uebel and Heinsdorf 1997).

Also a recent decrease of Mg nutrition was observed for many (cf. Landmann et al. 1997), but not all investigated European forests on soils derived from base-poor bedrock (*Sweden*: Aronsson 1985 [decrease], Tamm and Popovic 1989 [increase]; *The Netherlands:* v.d. Burg 1990 [increase]; *Germany:* Evers 1984 [decrease], Reemtsma 1986 [strong decrease]; Nebe 1991 [decrease]; Sauter 1991 [different trends]; Hippeli and Branse 1992 [strong decrease]; Spiecker et al. 1992 [slight decrease]; Prietzel et al. (1997) [different trends]; Uebel and Heinsdorf 1997 [increase]; *Czech Republic* Materna (1989) [decrease]; *Austria:* Stefan (1989) [decrease]; *Switzerland:* Flückiger and Braun 1994 [decrease]; *France:* Landmann et al. 1995 [decrease]). However, as already noted for Ca, the common feature of most of these studies is a recent widening of the Mg/N ratio.

The K foliar concentrations have not changed significantly and systematically during recent years in most studies; the only exception being the study of Spiecker et al. (1992) where a considerable K decrease in Norway spruce needle was reported to have occurred between 1971 and 1987.

3.4 CONCLUSIONS

Many of the studied stands are characterised by a trend of improved N nutrition, whereas the Ca and Mg nutrition often deteriorated on forest sites with acidic soils on base-poor bedrock. However, there exist only very few case studies, where the temporal changes of the soil chemical status and/or of the nutrition status of forest stands have been monitored with adequate analytical procedures and where the results have been evaluated critically and published. Therefore, a general recognition of recent changes in forest nutrition, as dependent on the highly variable site conditions does not exist yet. Achieving this goal needs a common and integrative effort to assess and to evaluate the bulk of relevant data.

4 AIR CHEMISTRY AND EFFECTS ON TREE GROWTH AS INDICATED BY PRELIMINARY MODELING RESULTS

M.G.R. Cannell, D.C. Mobbs, A.D. Friend and G.I. Ågren

This chapter outlines changes in atmospheric CO_2 concentration and N deposition in Europe and reports some preliminary findings on the effects of these changes on forest growth as indicated by some existing forest growth simulation models.

4.1 AIR CHEMISTRY (WITH SPECIAL REFERENCE TO CO_2 AND N DEPOSITION)

4.1.1 Atmospheric CO_2 concentrations

4.1.1.1 Measurement

Atmospheric CO_2 concentrations (abbreviated as [CO_2]) are measured routinely at 49 land-based and 14 shipboard sites throughout the world (Boden et al. 1994). The most famous record is from Mauna Loa in Hawaii, which started in 1959. In addition, there are several records of [CO_2] dating back many thousands of years, based on gas in bubbles within ice cores, the most famous of which are from Vostok and Siple in Antarctica.

There are 14 [CO_2] measuring sites in Europe which have moderately long time series, nine of which are in Germany, managed as parts of different networks (Table 4.1).

Table 4.1. Atmospheric CO_2 monitoring sites in Europe

Country	Site	Network	Start of record
Ireland	Mace Head	NOAA/CMDL	1991
Norway	Station M	NOAA/CMDL	1981
Germany	Brotjacklriegel	UBA	1972
Germany	Deuselbach	UBA	1972
Germany	Schauinsland	UBA	1972
Germany	Waldorf	UBA	1972
Germany	Westerland	UBA	1972
Germany	Garmisch-Partenkirchen	FI	1978
Germany	Wank Peak	FI	1977
Germany	Zugspitze	FI	1978
Germany	Osnabrück	TUB	1984
Hungary	K-Puszta	IAP	1984
Italy	Lampedusa Island	ENEA	1992
Italy	Mt. Cimone	IMS	1979

CMDL = Climate Monitoring and Diagnostics Lab., Boulder, CO., USA
NOAA = National Oceanic and Atmosphere Admin., Boulder, CO., USA
UBA = Umweltbundesamt, Mainz, Germany
FI = Fraunhofer Institute for Atmospheric Environmental Research, Germany
TUB = Technische Universität, Berlin, Germany
IAP = Institute for Atmospheric Physics, Hungary Met. Services, Budapest
ENEA = ENEA-CRE Casaccia, Rome, Italy
IMS = Italian Met. Service, Sestola, Italy

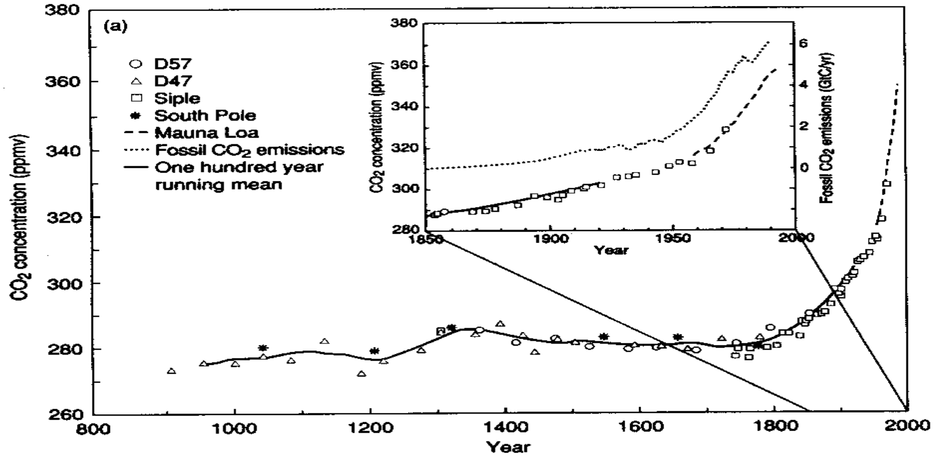

Figure 4.1. CO_2 concentrations over the past 1000 years from ice core records (D47, D57, Siple and South Pole) and, since 1959 from Mauna Loa, Hawaii. The smooth curve is based on 100 year running means. The rapid increase in CO_2 concentration since the onset of industrialisation is evident and has followed closely the increase in CO_2 emissions from fossil fuel combustion. Taken from Houghton et al. (1996).

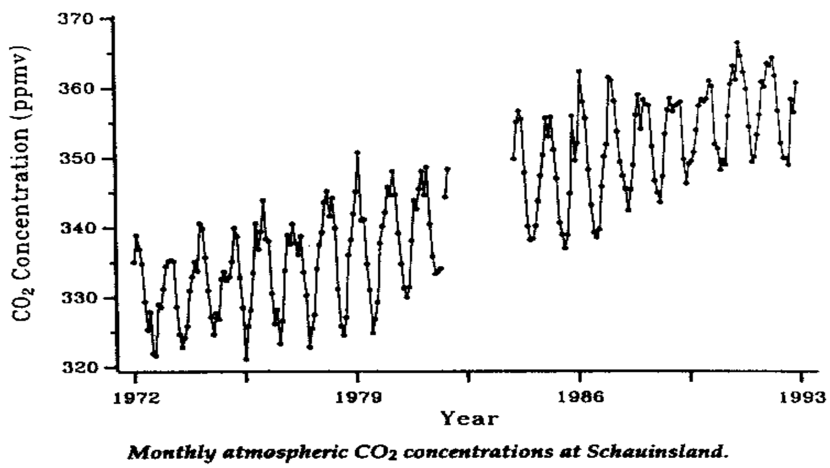

Figure 4.2. Monthly atmospheric CO_2 concentrations at Schauinsland, at 1205 m in the Black Forest, Germany. Taken from Fricke and Wallasch (1994).

4.1.1.2 Trends in concentrations

Atmospheric [CO_2] is well-mixed in the atmosphere, all monitoring stations record similar annual averages and a clear upward trend. Overall, [CO_2] has increased from about 280 ppmv (parts per million by volume) in pre-industrial times to 360 ppmv in 1997 – that is, an increase of 28% (HOUGHTON et al. 1996). At Mauna Loa there was a 12.8% increase in mean annual [CO_2], from 316 ppmv in 1959 to 356 ppmv in 1992. Prior to 1800 [CO_2] fluctuated by little more than ±10 ppmv around 280 ppmv for at least 1000 years (Figure 4.1). The global average increase in atmospheric [CO_2] in the 1980s was about 1.5 ppmv/yr. This slowed to about 0.6 ppmv/yr in the early 1990s, apparently owing to climatic and biospheric variations following the eruption of Mt. Pinatubo in June 1991. But the annual growth rate in [CO_2] has now returned to 1.5 ppmv/yr.

The atmospheric CO_2 records show clear seasonal variation with winter maxima and summer minima, due to seasonal variation in the balance of carbon fixation by photosynthesis and soil and plant respiration. The amplitude of the variation is greatest at northern latitudes, where there is the greatest land mass – e.g. about 25 ppmv at Barrow in Alaska (71°N) – and least in the southern hemisphere and at remote oceanic locations.

European sites show annual trends in line with the global averages, with seasonal variation of 15-20 ppmv, depending on the site. Concentrations tend to be highest at sites close to centres of industrial emissions and seasonal amplitudes are greatest close to forests. Figure 4.2 shows the record from Schauinsland, in the Black Forest at 1205m altitude. Annual [CO_2] rose from 330 ppmv in 1972 to 357 ppmv in 1992 – a growth rate of 1.4 ppmv/yr. This site is considered the least contaminated of the 'Umweltbundesamt' sites, with a seasonal amplitude of 15-18 ppmv.

Projections of future atmospheric CO_2 concentrations were made by the Intergovernmental Panel on Climate Change in 1992 (IPCC Scenarios '92, or IS92). Projections involved assumptions regarding economic, demographic and policy factors, in order to estimate anthropogenic emissions, and assumptions about global carbon cycle, in order to estimate the fraction of CO_2 emissions which remains in the atmosphere. The average business-as-usual scenario (IS92a) assumes that global carbon emissions will rise from their current level of about 6 Gt C/yr to about 20 Gt C/yr in 2100, resulting in [CO_2] rising to over 700 ppmv by 2100 (Houghton et al. 1996).

4.1.2 Air pollutants, with special reference to nitrogen

There are three regional-scale problems concerning air pollutants which affect European forests. They are (i) eutrophication, driven by NO_x and NH_x deposition, (ii) acidification of soils, driven by SO_2, NH_3 and NO_x, and (iii) tropospheric ozone, with background concentrations related to emissions of methane, CO and NO_x and peak episodes determined by hydrocarbon and NO_x emissions. This report concentrates on the eutrophying and acidifying pollutants.

4.1.2.1 Measurement

Data on acidifying and eutrophying air pollutants in Europe is collated by EMEP (Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe) and is synthesised by MSC-W (Meteorological Synthesising Centre-West; Barrett and Berge 1996). EMEP was established to service the technical needs of Governments and subsidiary bodies under the 1979 Geneva Convention on Long Range Transboundary Air Pollution. There are 40 parties to the convention, including 37 European countries, Canada, the United States and the European Community. Data from EMEP underpinned the first sulphur Protocol (signed in Helsinki 1985), the second sulphur Protocol (Oslo 1995), the NO_x Protocol (Sofia 1988) and the Protocol on volatile organic compounds (Geneva 1991).

EMEP manages the European emissions database, which is created by parties reporting emissions to the Secretariat of the UN-ECE (United Nations Economic Commission for Europe). National totals of SO_2 and NO_x have been reported by 65% of the parties for over 10 years. EMEP/MSC-W then estimates pollutant transport and deposition using models – mostly one-layer Lagrangian trajectory ozone and acid deposition models with 150 km resolution but more recently 50 km resolution models (Barrett and Berge 1996).

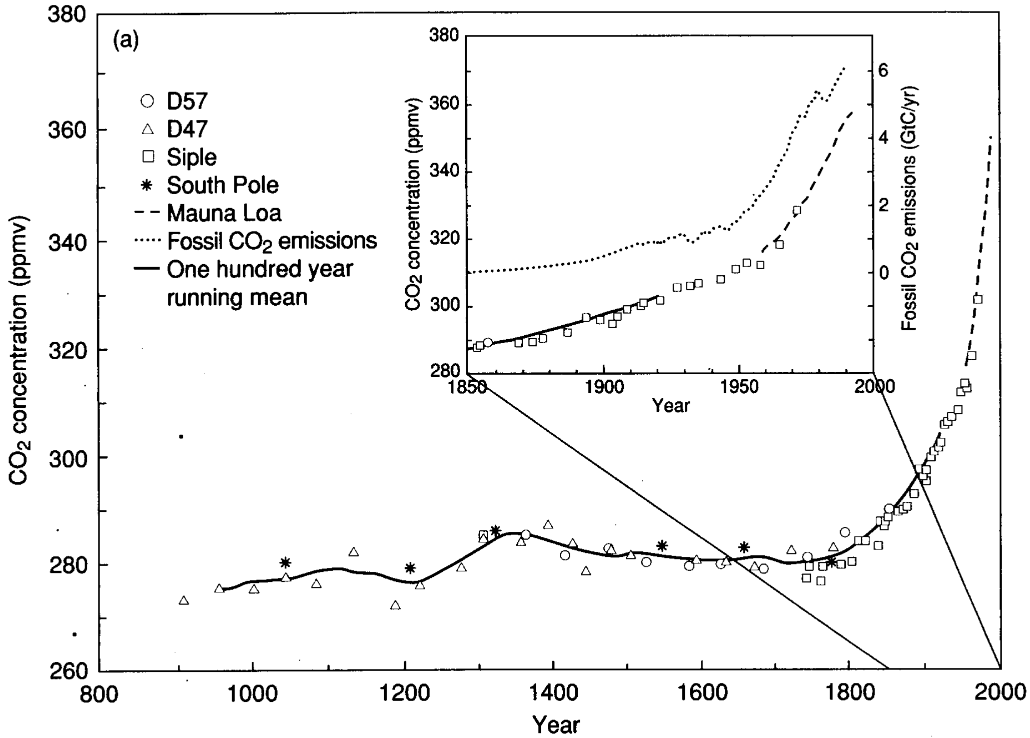

Figure 4.3. Historic trends in the total European emissions of sulphur dioxide (ktonnes S/yr) and nitrogen oxides (ktonnes N/yr) from 1880 to 1993. The solid line refers to sulphur (as SO_2) taken from Mylona (1996). The triangles are sulphur (as SO_2) and the circles nitrogen (as NO_2) taken from Barrett and Berge (1996) and Review Group On Acid Rain (1997).

4.1.2.2 Emissions of S and N

Figure 4.3 shows estimates of the total emissions within the EMEP region (excluding the ex-USSR and Turkey) of SO_2 since 1880 and of NOx since 1979 (Mylona 1996; Barrett and Berge 1996). Emissions were at a relatively low level until about 1950, when they rose 4-fold to reach about 21 Mt S/yr as SO_2 in the 1970s. Since then, SO_2 emissions have fallen to about 13 Mt S/yr as a result of emission reduction Protocols, but NOx emissions have remain relatively constant at 7-8 Mt N/yr. There was an apparent peak in NO_x emissions in the late 1980s, but this may have been due to questionable figures submitted by Romania. Both SO_2 and NO_x emissions are expected to remain at 1994 levels until 2000 and then decline only slightly by 2010 (Barrett and Berge 1996). Ammonia emissions remained constant at about 8 Mt/yr from 1979 to 1989, then fell to about 7 Mt/yr and are expected to remain at that level until at least 2010 (Barrett and Berge 1996).

Largest emissions of sulphur in the 1970s occurred in the south of the former German Democratic Republic. The area of upland forest forming the border of the GDR, former Czechoslovakia and Poland became known as the Black Triangle. Other areas of high emission were the industrial areas of northern England, the Ruhr and eastern Belgium. NO_x emissions, which come largely from motor vehicles, are more geographically dispersed than those of SO_2. The largest emitters are Germany and the UK, and France, the Netherlands and Denmark currently emit more NO_x than SO_2.

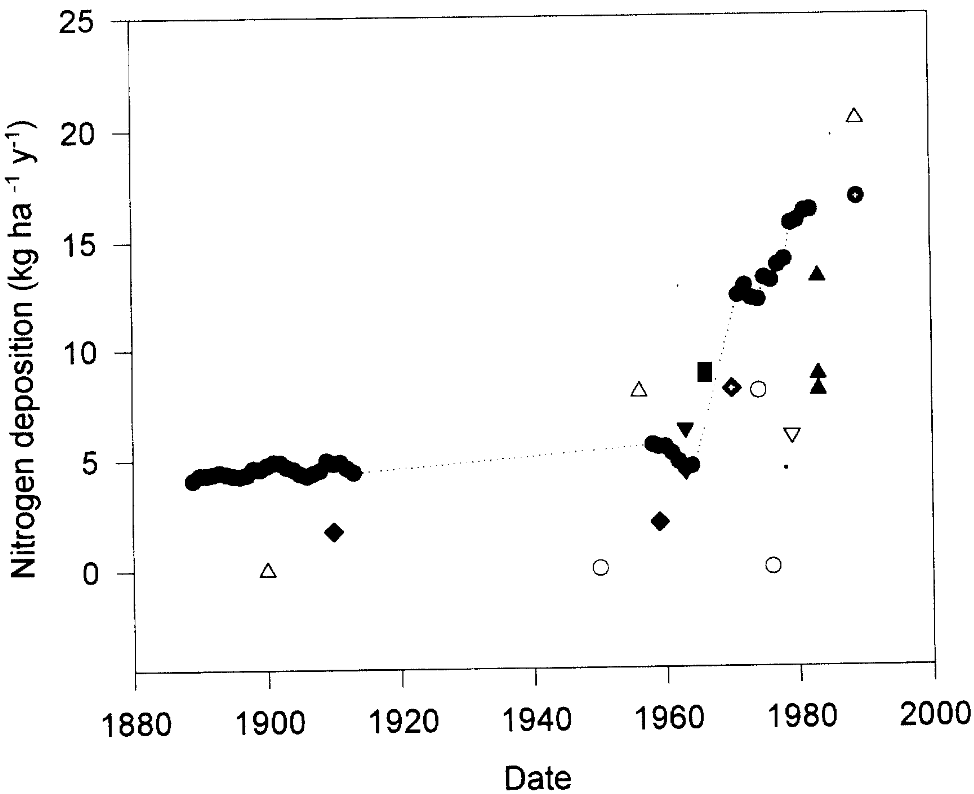

Figure 4.4. Atmospheric deposition of N averaged for the UK from 1880 to 1990. Filled symbols are measured values of deposition of N. Open symbols are total deposition inferred from a relationship between deposition and the tissue N content of mosses. The line connects values from Rothamsted in England. Taken from Pitcairn et al. (1995).

4.1.2.3 Deposition of S and N

There is considerable evidence that the amounts of both S and N deposited on European forests increased dramatically in the period 1940 to 1970, at the time when SO_2 emissions leapt to high levels (Figure 4.3).

Historic trends in the deposition of many air pollutants in Europe have been reconstructed using ice cores from glaciers in the high Alps (Monte Rosa, 4500m and Mount Blanc, 4250m). These corers reveal 3-4-fold increases in both sulphate nitrate deposition between 1940 and 1970 (Wagenbach and Preunkert 1996). Figure 4.4 presents further evidence from the UK, including rare long-term records from Rothamsted, suggesting the total N deposition increased from about 5 to 20 kg N/ha/yr over the period 1940 to 1970.

The current geographic patterns of S and N deposition have been estimated by EMEP (Barrett and Berge 1996). With the exception of Spain and Scandinavia, Europe receives depositions in excess of 5 kg S/ha/yr, most receiving over 10 kg S/ha/yr – approximately 625 equivalents of acidity (H^+) per hectare per year as sulphate. Most of Fennoscandinavia receives over 2 kg S/ha/yr.

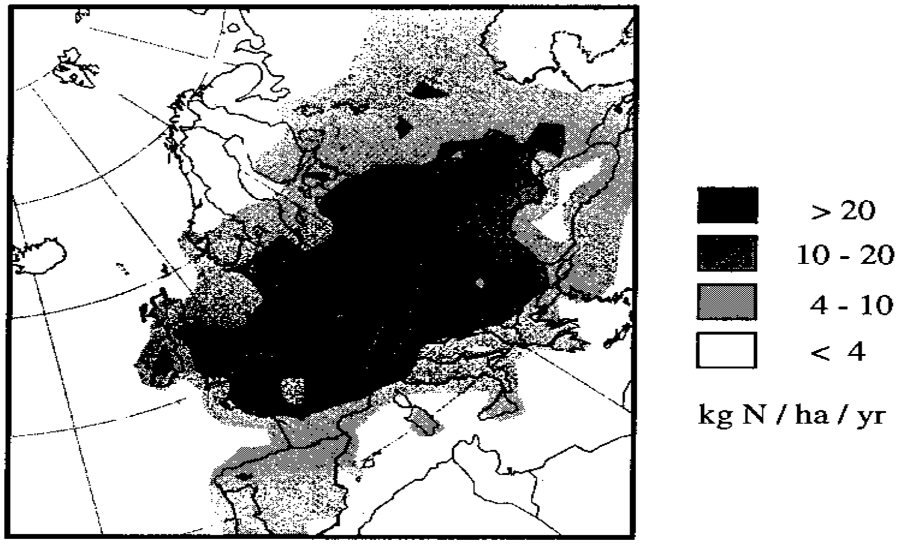

Figure 4.5. Total N deposition in Europe in 1992 (NO_x and NH_x). Taken from Barrett and Berge (1996).

The current geographic pattern of total N deposition (from the EMEP 150 km grid model) is shown in Figure 4.5. Total deposition exceeds 20 kg/ha/yr in most of the BeNeLux countries, Germany and parts of Poland, Austria and the Czech republic. Most of the rest of Europe receives 10-20 kg N/ha/yr, except Spain, most of Fennoscandinavia and Scotland. Finer-scale maps of total deposition for individual countries reveal local variation with hot spots – for example areas receiving over 20 kg N/ha/yr in forested parts of southern Scotland (Review Group On Acid Rain 1997).

Total N is made up from oxidised and reduced N. The pattern of deposition of reduced N in Europe is very variable spatially, because it is readily deposited close to the sources of emission. Largest depositions occur in the BeNeLux countries, southern Germany and Central Europe, all receiving over 10 kg reduced N/ha/yr (over 700 eq./ha/yr as NH_4^+). By contrast, the spatial pattern of oxidised N deposition is much less variable, because NOx is transported some distance before it is transformed into secondary forms (eg nitrate) which are more readily deposited. Deposition levels across a broadly similar region of Europe to that receiving most sulphur are in excess of 5 kg oxidised N/ha/yr (over 360 eq./ha/yr as NO_3^-).

Overall, total N deposition now represents a generally greater contribution to acidity in Europe than oxidised sulphur. Of the two nitrogen components, reduced N (from agriculture) is the greater or equal fraction of total N deposited across much of Europe. However, a decline in reduced N deposition northwards means that oxidised N (from fossil fuels) assumes greater importance in Fennoscandinavia.

4.2 Preliminary modelling results

4.2.1 Assessment of the interaction of CO_2 concentration and N deposition on forest growth

In order to evaluate the effects of increasing CO_2 concentrations and N deposition on forest growth we ran a process-based forest model to equilibrium in 19th century European climates (with 5 kg/ha/yr N deposition and 290 ppmv CO_2) and then followed predicted changes in growth with increasing N deposition and/or atmospheric CO_2 and/or temperature during this century and as predicted throughout the 21st century.

4.2.1.1 Methods

Simulation model
The model used was Hybrid v3.0, which is fully described by Friend et al. (1997). It represents the carbon, nitrogen, and water cycles in a fully integrated manner within a coupled soil-forest-atmosphere system. The model is driven by climate and inputs from the atmosphere such as CO_2 and N. Its behaviour is not predetermined by statistical relationships between ecosystem properties and the current climate. It includes all the major processes regulating forest growth that occur over daily/subdaily, seasonal, yearly and decadal timescales and so is capable of predicting transient (non-equilibrium) responses.

Hybrid is a generic model. It simulates the growth of plots of unmanaged vegetation anywhere on the globe and predicts the relative dominance and properties (NPP, LAI etc.) of different vegetation types, and of the soil, as a function of climate. In this application, the model was constrained to predict the growth of unmanaged conifer forests (spruce or pine) in different regions of Europe. The model combines the strengths of forest gap-type models, which simulate the competition between individual trees as they grow, and process-based models. It has well-tested routines for photosynthesis and transpiration, based on the model PGEN (Friend 1995). It predicts global ecosystem NPP in good agreement with the ‘Miami’ model of Leith (1978) and also accurately simulates the global distribution and properties of forests (Friend and Malard 1998) and CO_2 and water fluxes measured at sites in different biomes (Friend et al. 1997).

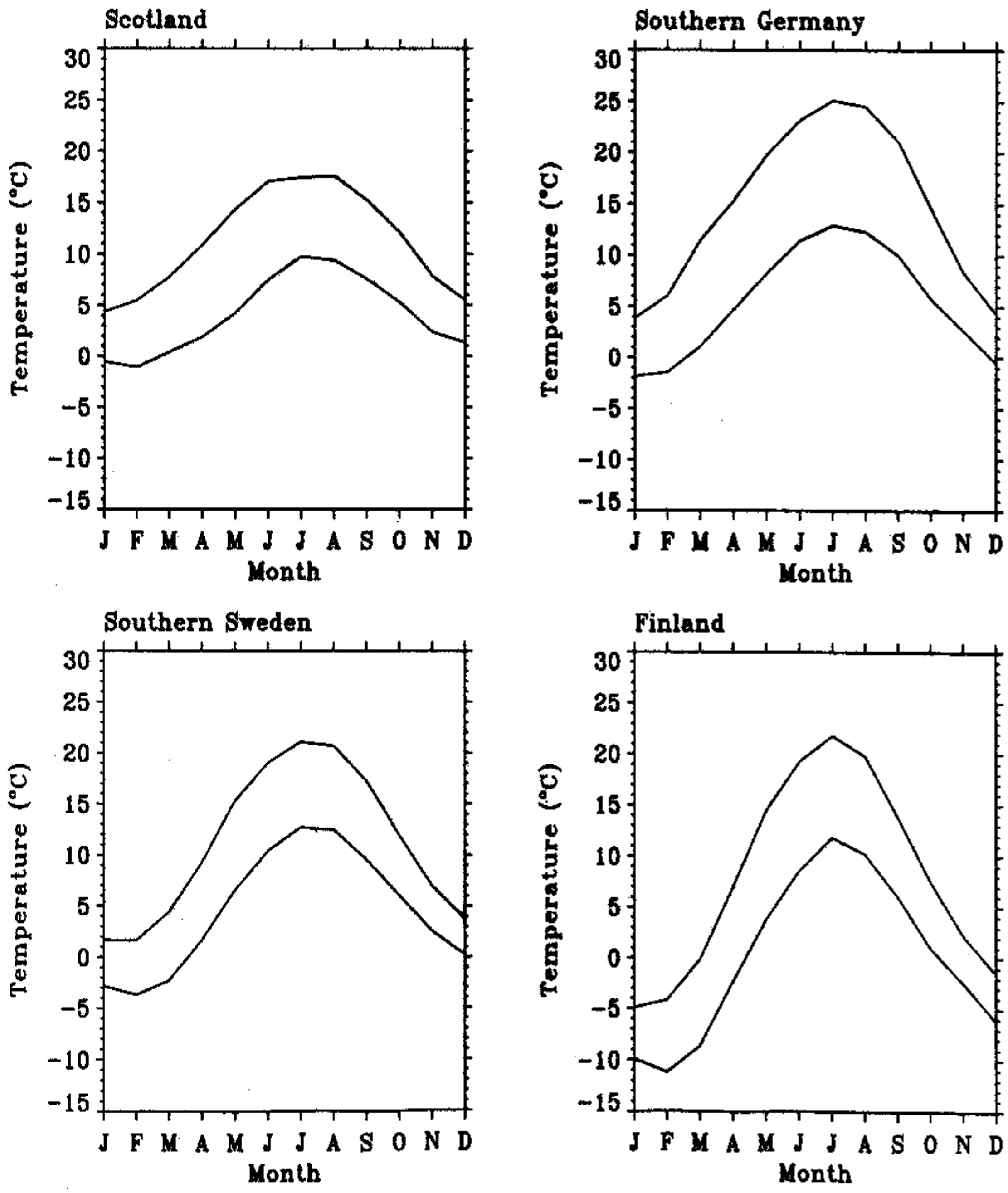

Figure 4.6. Monthly mean maximum and minimum air temperatures for 0.5° grid squares in Scotland (which includes Eskdalemuir), southern Germany (including Freiburg), southern Sweden (including Halmsted), and Finland (including Tampere).

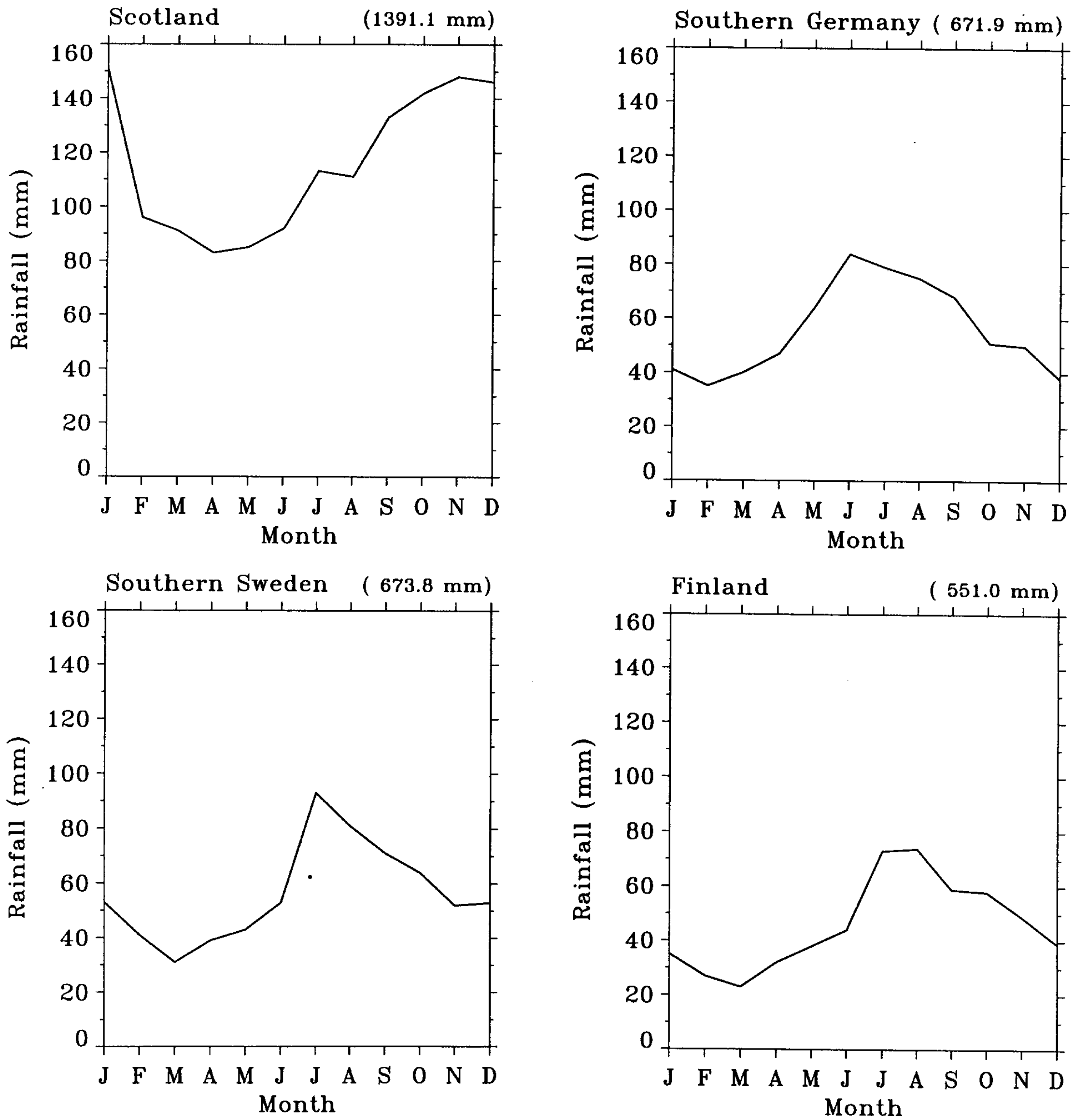

Figure 4.7. Monthly mean rainfall for 0.5° grid squares in Scotland (which includes Eskdalemuir), southern Germany (including Freiburg), southern Sweden (including Halmsted), and Finland (including Tampere).

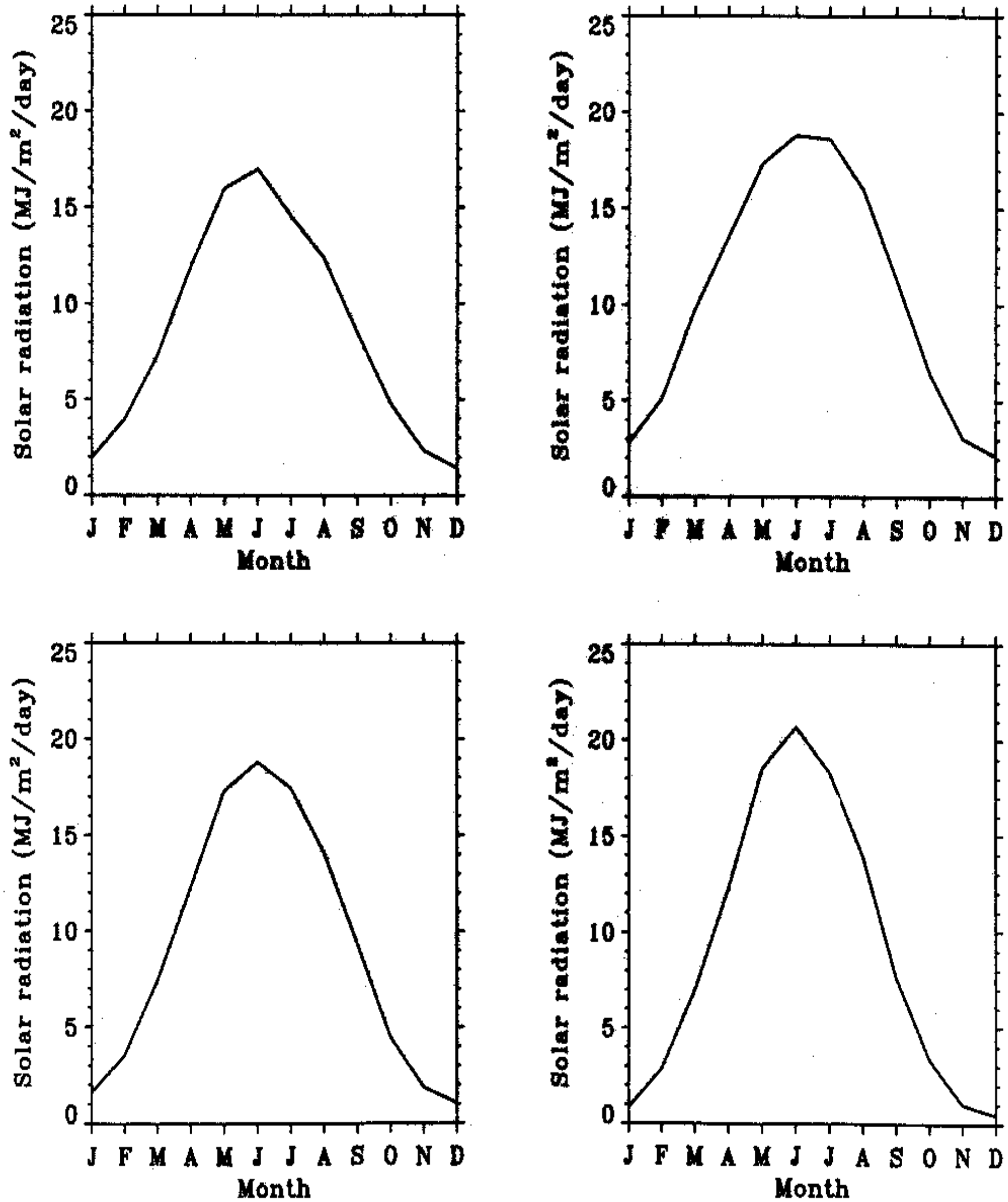

Figure 4.8. Monthly mean solar radiation for 0.5° grid squares in Scotland (which includes Eskdalemuir), southern Germany (including Freiburg), southern Sweden (including Halmsted), and Finland (including Tampere).

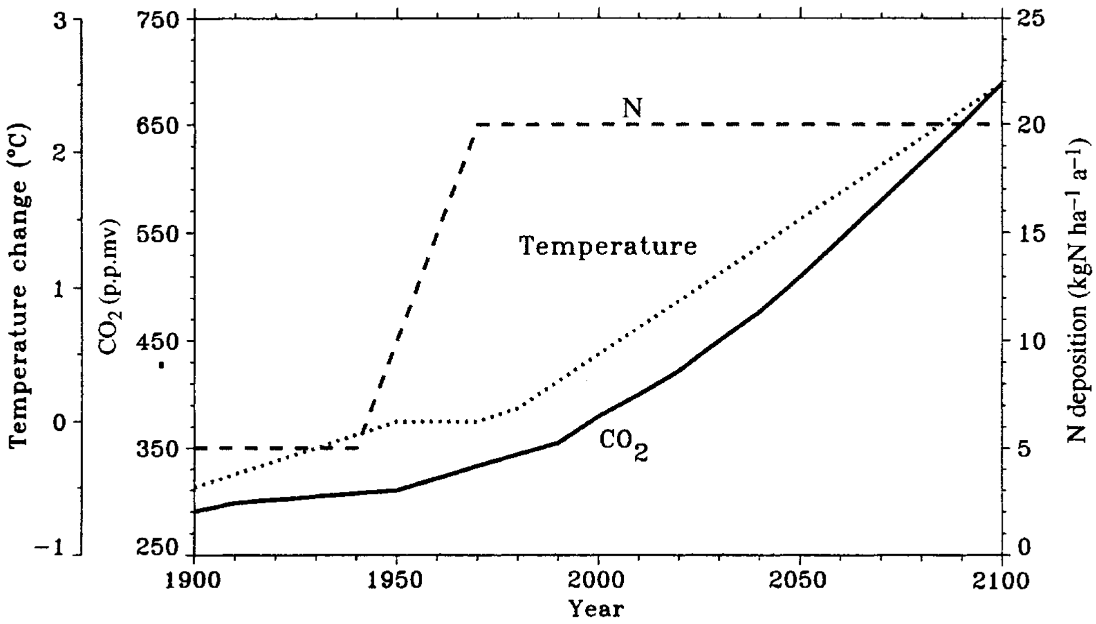

Figure 4.9. The basic scenario of climate change assumed in runs with the model 'Hybrid'.

Climate change scenarios

Hybrid was run using the climate predicted by a weather generator (Friend 1998) for four 0.5° grid squares in Europe representing Scotland (the square which includes Eskdalemuir), southern Germany (including Freiburg), southern Sweden (including Halmsted) and Finland (including Tampere) (Figures 4.6, 4.7, and 4.8). The grid square for Scotland represented a cool, wet region with relatively low summer solar radiation receipt, while the Finnish grid square represented a drier climate with a severe winter and short warm summer. A constant input of 5 kg N/ha/yr was assumed as a result of biological N_2 fixation. It should be noted that the weather generator simulated random year-to-year variation in weather variables and so real changes that have occurred during this century were not simulated. In order to smooth the trends in predicted variables (NPP, LAI, etc.); means were taken of ten model runs and these were further smoothed by taking ten-year running means.

Changes in atmospheric N deposition, CO_2 and temperatures were imposed on each model run as shown in Figure 4.9. Thus, atmospheric N deposition was assumed to be 5 kg N/ha/yr until 1940 (in addition to the 5 kg N/ha/yr from biological fixation) and then increase linearly to 20 kg N/ha/yr by 1970 and remain at that level thereafter (see Chapter 4.1). Mean annual temperatures were assumed to increase by 0.5 °C between 1900 and 1950, as occurred in many parts of western Europe, and to increase again after 1970 according to the Intergovernmental Panel on Climate Change Scenario 1992a. Atmospheric CO_2 concentrations were increased according to known trends until 1990 and then according to the IPCC92a scenario. Runs were done with N deposition, temperature and CO_2 changing singly and in combination.

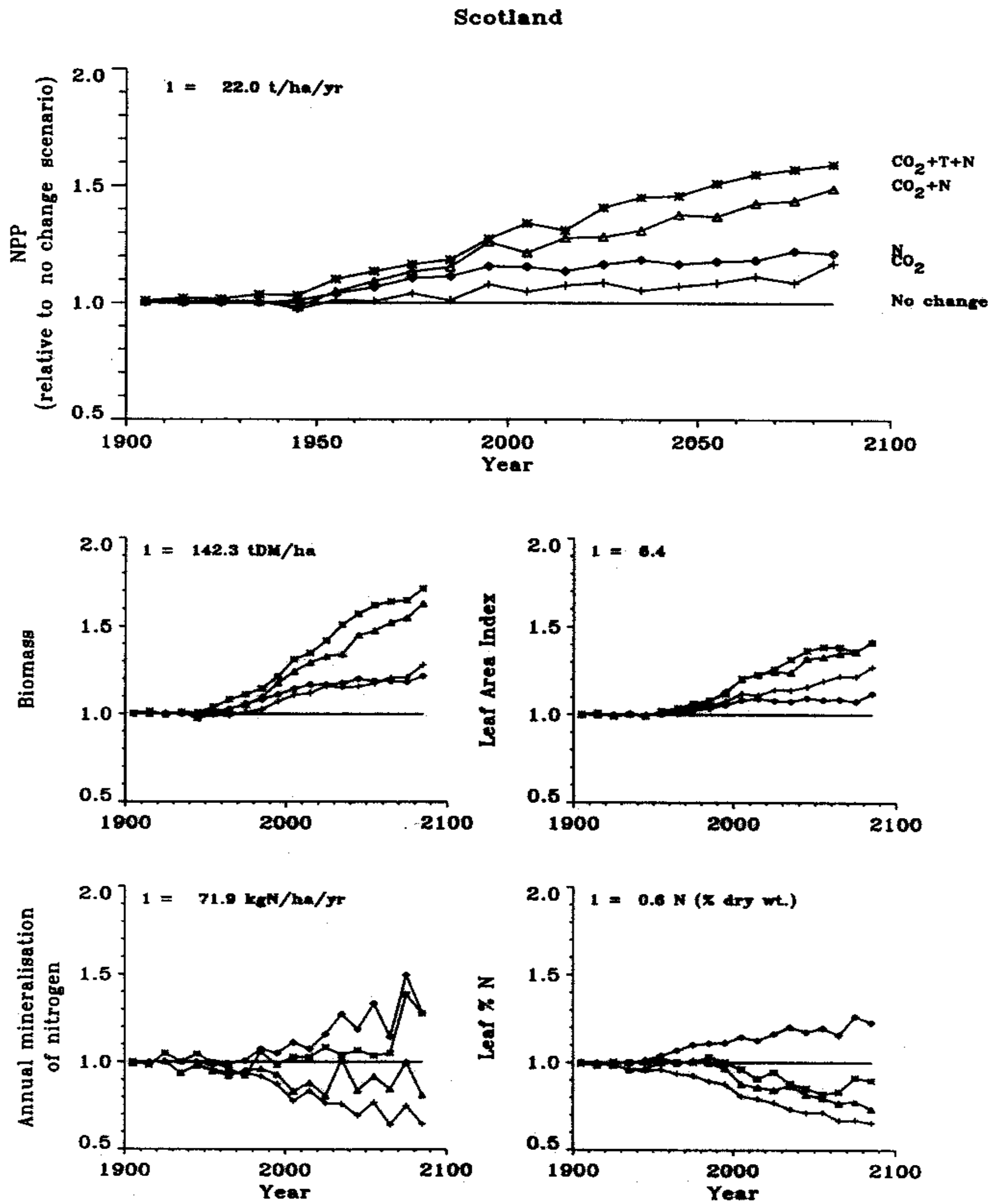

Figure 4.10. Relative changes in net primary productivity and in four ecosystem variables, in unmanaged conifer forests in Scotland predicted by the Hybrid model for the climates shown in Figure 4.6 and climate changes shown in Figure 4.9, with increasing N deposition (5 to 20 kg N/ha/yr from 1940 to 1970), CO_2 and temperature (T). The inter-annual variability is not 'real'; the values given are the results of 10 runs with a random weather generator (parameterized for the location) which were further smoothed by taking 10-year running means.

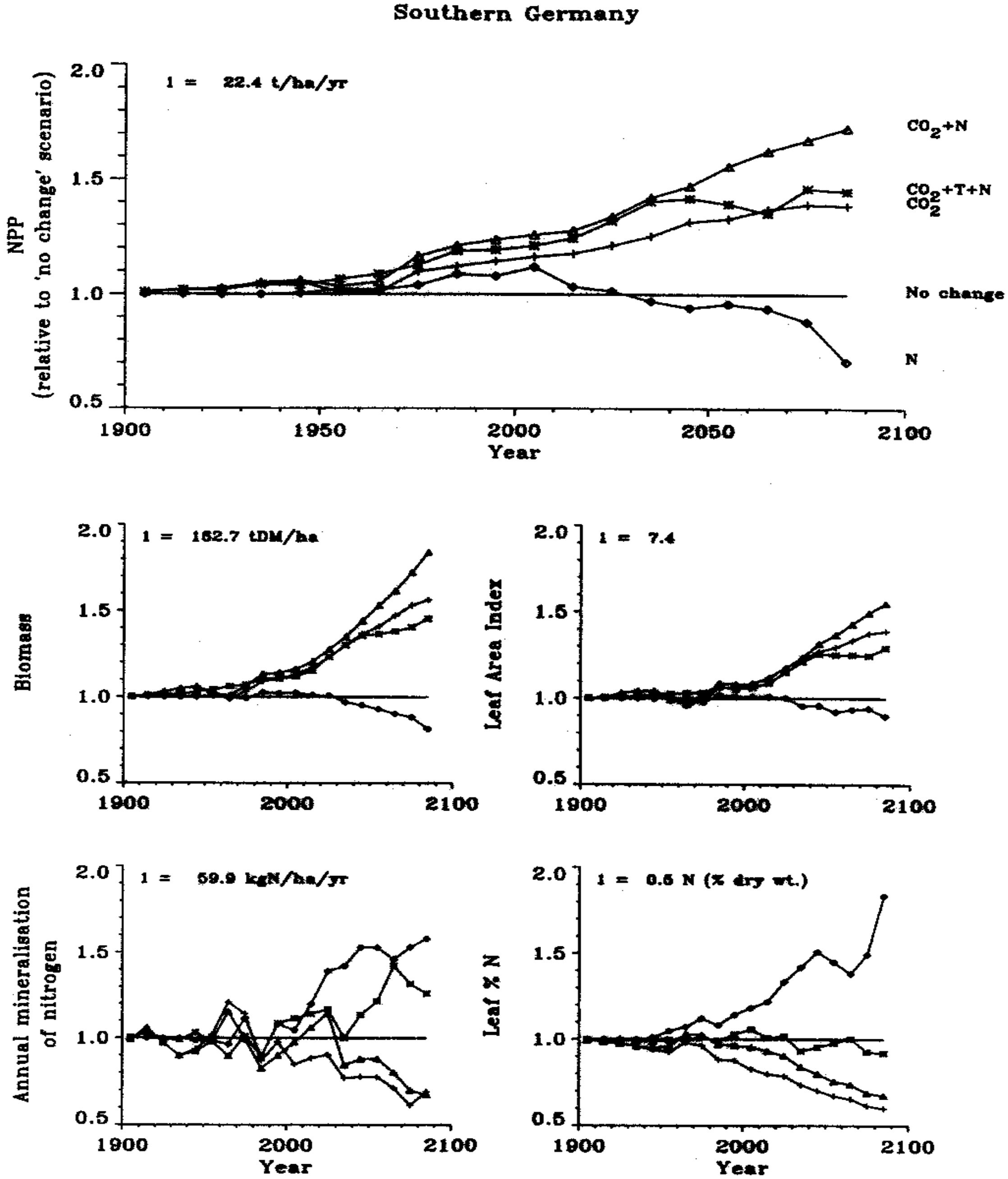

Figure 4.11. Relative changes in net primary productivity and in four ecosystem variables, in unmanaged conifer forests in southern Germany predicted by the Hybrid model for the climates shown in Figure 4.6 and climate changes shown in Figure 4.9, with increasing N deposition (5 to 20 kg N/ha/yr from 1940 to 1970), CO_2 and temperature (T). The inter-annual variability is not 'real'; the values given are the results of 10 runs with a random weather generator (parameterized for the location) which were further smoothed by taking 10-year running means.

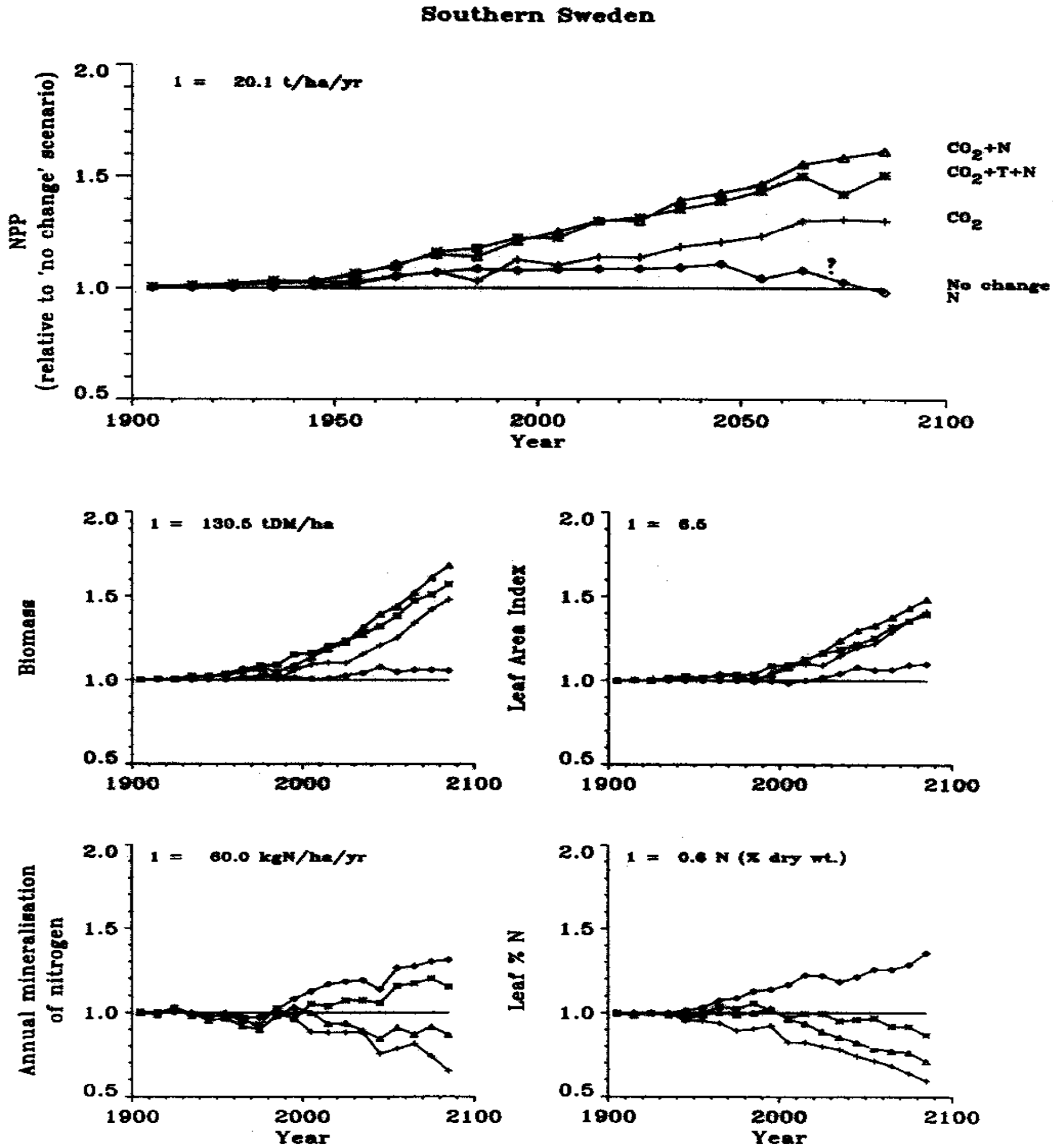

Figure 4.12. Relative changes in net primary productivity and in four ecosystem variables, in unmanaged conifer forests in southern Sweden predicted by the Hybrid model for the climates shown in Figure 4.6 and climate changes shown in Figure 4.10, with increasing N deposition (5 to 20 kg N/ha/yr from 1940 to 1970), CO_2 and temperature (T). The inter-annual variability is not 'real'; the values given are the results of 10 runs with a random weather generator (parameterized for the location) which were further smoothed by taking 10-year running means.

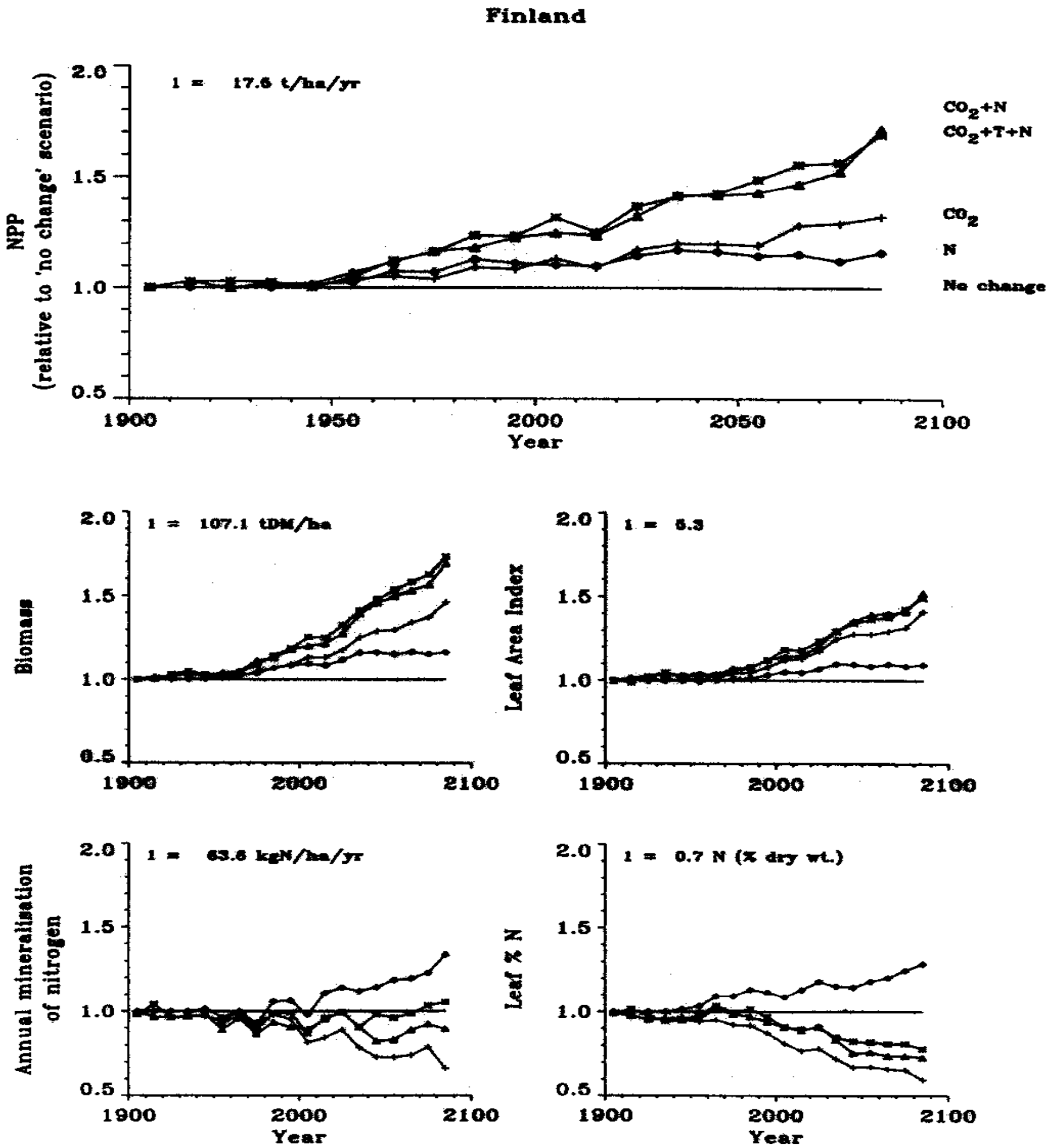

Figure 4.13. Relative changes in net primary productivity and in four ecosystem variables, in unmanaged conifer forests in Finland predicted by the Hybrid model for the climates shown in Figure 4.6 and climate changes shown in Figure 4.9, with increasing N deposition (5 to 20 kg N/ha/yr from 1940 to 1970), CO_2 and temperature (T). The inter-annual variability is not 'real'; the values given are the results of 10 runs with a random weather generator (parameterized for the location) which were further smoothed by taking 10-year running means.

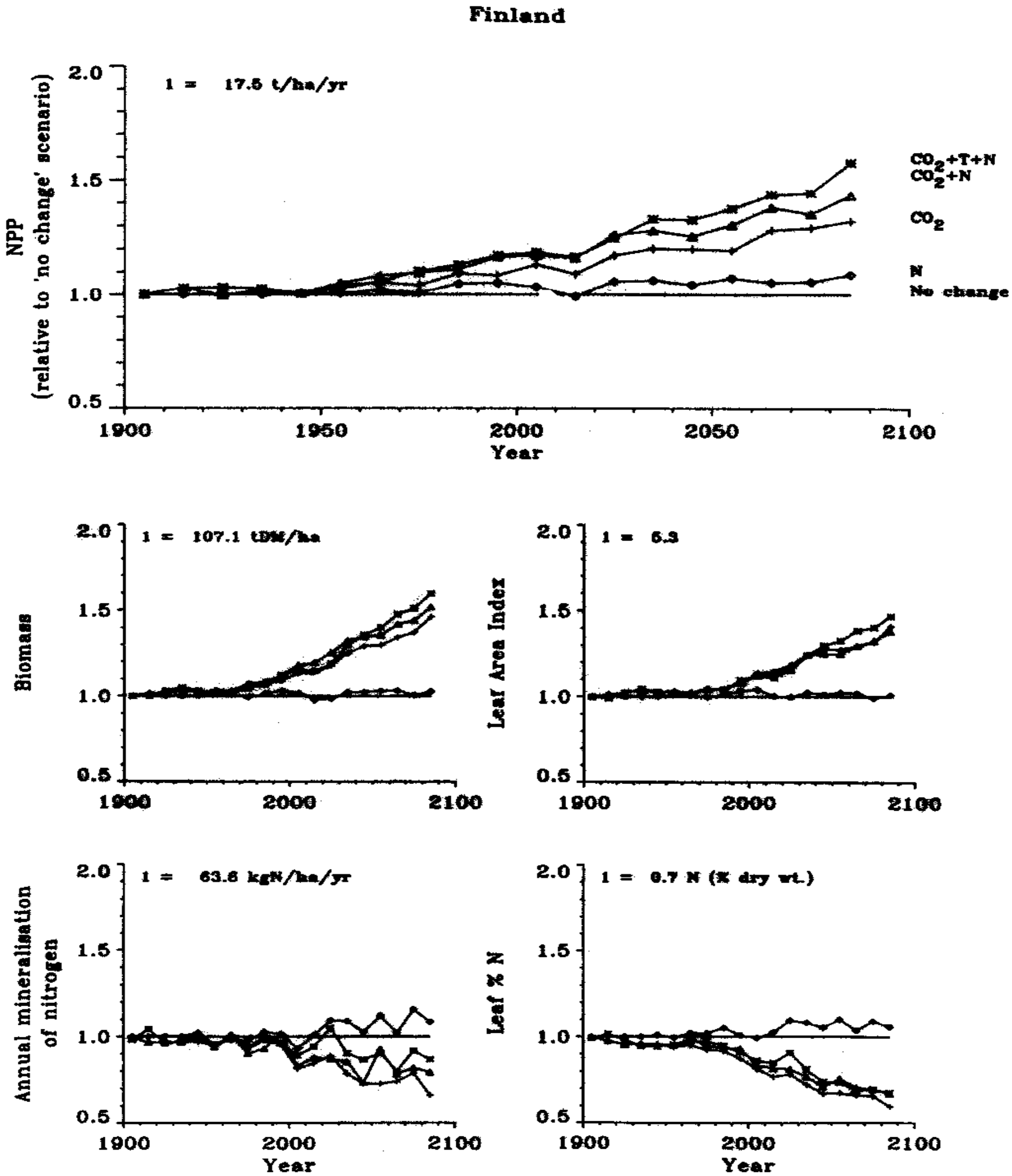

Figure 4.14. Relative changes in net primary productivity and in four ecosystem variables, in unmanaged conifer forests in Finland predicted by the Hybrid model for the climates shown in Figure 4.6 and climate changes shown in Figure 4.9, with increasing N deposition (10 kg N/ha/yr from 1940 to 1970), CO_2 and temperature (T). The inter-annual variability is not 'real'; the values given are the results of 10 runs with a random weather generator (parameterized for the location) which were further smoothed by taking 10-year running means.

4.2.1.2 Model predictions

Figures 4.10 through 4.13 show predicted changes in the productivity and key variables at the 4 European locations, expressed as deviations from the values predicted with no change in climate – where 1.0 indicates no change and 1.5 indicates a 50% increase. Predictions are shown for conditions where CO_2 and N deposition were increased alone, together (CO_2+N), and with increasing temperature (CO_2+N+T). The mean absolute values of the variables are shown for the 'no change' scenario (equivalent to 1.0). It should be noted that Figure 4.14 shows results when the N deposition in Finland was increased from 5 to only 10 kg N/ha/yr (rather than 20 kg N/ha/yr) which is more realistic at this location.

Predicted values of forest productivity and key ecosystem variables

With no climate change, the net primary productivities (NPP) of managed coniferous forests were predicted to be about 22 t/ha/yr of biomass (twice the carbon mass) in Scotland and Germany, decreasing to 20 t/ha/yr in southern Sweden and 17.5 t/ha/yr in mid-southern Finland. The predicted standing biomass varied from 163 t dry matter/ha in Germany to 107 t/ha in Finland and leaf area indices were in the range 5.3 to 7.4. Annual mineralisation rates, which are strong determinants of NPP (Reich et al. 1997) varied from 72 kg N/ha/yr in Scotland to 60 kg N/ha/yr in southern Sweden, while foliage N contents were in the range 0.5 to 0.7% of dry weight.

Predicted changes in net primary productivity

Table 4.2 summarises the approximate increases in NPP predicted to have occurred by 1990 and 2050. The combination of increases in CO_2, temperature, and N deposition to 20 kg N/ha/yr increased NPP by 14-24% by 1990 and 38-50% by 2050.

All three climate drivers were involved, but to different extents at the different locations. Increasing CO_2 concentrations alone was predicted to have increased NPP by 5-11% by 1990 – most at continental locations with warm, high-radiation, dry summers where the benefit of reduced stomatal conductance was greatest. N deposition alone increased NPP by a similar amount (5-12%) by 1990 – with the greatest benefit in Scotland and Finland. The combined effect of elevated CO_2 and N deposition was approximately additive, increasing NPP by 13-20% by 1990. Warming temperatures had only a small additional promotive effect on NPP except in Scotland, where the benefits of higher temperatures were not offset by increases in water stress.

Table 4.2. Approximate percentage increases from 1900 to 1990 (and 1900 to 2050 in brackets) in conifer forest net primary productivity predicted by the Hybrid model in response to increasing CO_2, N deposition, CO_2 + N deposition, CO_2 + N and temperature, at 4 locations in Europe.

	CO_2	N	CO_2 + N	CO_2 + N + T
Scotland (Eskdalemuir)	5 (8)	12 (18)	20 (38)	24 (48)
Germany (Freiburg)	11 (30)	8 (-)**	19 (40)	22 (50)
Sweden (Halmsted)	8 (20)	9 (-)**	16 (40)	18 (45)
Finland (Tampere)	8 (20)	12 (12)	20 (42)	22 (46)
Finland* (Tampere)	8 (20)	5 (8)	13 (28)	14 (38)

**With N deposition increasing to 10 kg N/ha/yr rather than to 20 kg N/ha/yr.*
***Missing values, owing to model instability.*

The longer term predictions are less certain, because the model revealed apparent instability at some locations when given continuous high N inputs – possibly owing to luxury N uptake. Thus, in Figure 4.11 and 4.12, NPP was predicted to eventually decline with increasing N deposition alone – whereas we might expect NPP to plateau off at the level reached by about 2000. However, this instability may not invalidate the predictions when continued high N deposition was combined with increasing CO_2. By 2050, NPP was predicted to increase by 38-50% over 1990 levels. As expected, continuously increasing CO2 concentrations became a very important driver during the next century, compared with N deposition which was assumed to remain constant at 1970 values. Increasing CO_2 alone increased NPP by 20 to 30% by 2050, except in Scotland where responses were limited by low temperatures and solar radiation. By contrast, increasing temperatures continued to promote NPP in Scotland to 2050 (and beyond), but had a detrimental effect on NPP in Germany after 2030 and in Sweden after 2060. Increasing temperatures on their own (results not shown) generally increased NPP until at least 2050.

Predicted changes in key ecosystem variables

Increases in NPP were reflected in increases in standing biomass and leaf area index. However, with leaf area indices already exceeding 5 in 1990, further increases in leaf area index did not greatly increase light interception, so most of the increase in NPP was due to increased canopy photosynthesis. With increased N deposition alone, there was an increase in foliar N concentrations, which enhanced canopy photosynthesis. But when atmospheric CO_2 concentrations were increased, either alone or in combination with N deposition and temperature, foliar N levels decreased, so in these treatments the increase in NPP was mainly due to increased atmospheric CO_2 levels.

Annual mineralisation of N was increased by the N deposition treatment, as expected, and was generally increased when temperatures were raised, as a result of greater soil organic matter mineralisation. However, increasing CO_2, on its own or with N deposition, always resulted in slower rates of N mineralisation because the tree litter had a high C/N ratio. This decrease in N mineralisation did not have a marked negative feedback on NPP; NPP still increased in the high-CO_2 treatments as a result of greater N use efficiency by the trees.

4.2.1.3 Discussion

The Hybrid model predictions clearly suggest that, (i) increasing atmospheric CO_2 concentrations are increasing European forest productivity, (ii) the increase in N deposition that occurred over much of Europe in the period 1940-1970 amplified the effect of elevated CO_2 (or vice versa, the increase in CO_2 amplified the effect of N deposition), (iii) increased N deposition from about 5 to 20 kg N/ha/yr probably could not, on its own, account for the large increases in forest productivity (of 30-50%) that have been widely observed in Europe, and (iv) increasing temperatures may have had a relatively minor effect on forest growth this century and may promote or reduce growth in future, depending on the location. In this discussion, we briefly review the literature relating to these four predictions.

Effects of rising atmospheric CO_2 levels on forest growth

Although it is well-known that elevated CO_2 increases leaf-level photosynthesis, owing to reduced photorespiration, two reservations have been raised.

First, in many plants, including trees, some of the gain in photosynthesis is lost by a downward adjustment of the photosynthetic rate. This downregulation is manifest as a depression in light-saturated level of photosynthesis by leaves grown in elevated CO_2, when measured at ambient CO_2. However, this does not mean that canopy photosynthesis is not increasing as a result of increasing atmospheric CO_2 concentrations, because (a) the rate of light-saturated photosynthesis measured at elevated CO_2 is almost always higher than that of trees grown in ambient CO_2 (McGuire et al. 1995), and (b) most foliage in forests canopies is not light saturated, so the rate of canopy photosynthesis is determined mainly by the quantum efficiency of photosynthesis (i.e. the initial slope of the response of photosynthesis to light) and it is highly improbable that the quantum efficiency downregulates (Long and Hutchin 1991).

Secondly, it has been suggested that responses to elevated CO_2 can be limited by nutrient and water supply. However, the evidence is that the CO_2 growth responses (in dry mass) of plants that are nutrient or water-limited are usually proportionately similar to those of plants given adequate nutrients and water. Several workers have examined the literature: Wullschleger et al. (1995) concluded that the difference was slight, Idso and Idso (1994) that nutrient and water-limited plants responded proportionately more, Ceulemans and Mousseau (1994) that nutrient-limited trees responded proportionately less (see McGuire et al. 1995), and Lloyd and Farquhar (1996) that the response is usually similar but can vary depending on relationships between nitrogen uptake, photosynthesis and growth.

The evidence from CO_2 experiments on small pot-grown trees is that the growth response (in terms of total dry mass) is overwhelmingly positive. In a review of 58 studies on 73 tree species Wullschleger et al. (1995) concluded that the mean response to elevated CO_2 (normally a doubling) was 32%. More recent data are consistent with this conclusion, including the EU-ECOCRAFT studies, which show that responses are especially large in tree species with indeterminate shoot growth i.e. many broad-leaved trees, compared with conifers (Jarvis 1997).

The evidence that rising CO_2 levels are currently increasing forest growth in the field is necessarily more indirect and, it has to be said, not conclusive. There are four kinds of evidence.

First, there is some evidence for increasing forest growth in areas of the world where there is little N deposition and where increasing CO_2 concentrations seem the only credible explanation for growth enhancement. In Europe, the accelerating growth (increasing ring widths) of *Pinus uncinata* at the tree line in the Pyrenees (Badeau et al. 1996) and of subalpine *Pinus cembra* in the central Alps (Nicolussi et al. 1995) have been cited as evidence of possible CO_2 enhanced growth. In other parts of the world, there are several tree-ring time series for high-elevation and high-latitude sites that show enhanced growth in recent decades which cannot be explained by changes in temperature or rainfall. At high elevations, the partial pressure of CO_2 is lower than at sea level, so photosynthesis is even more CO_2-limited and increases in CO_2 concentration may have proportionately more effect (Mooney et al. 1966). Perhaps the strongest evidence for CO_2 enhanced growth is the increased ring widths in recent decades in subalpine bristlecone and other pines in New Mexico, Colorado, and California, including areas with almost no anthropogenic N deposition (Lamarche et al. 1984). However, according to some authors, none of the global tree ring series can be confidently interpreted as evidence for CO_2 enhanced growth (Jacoby and D'Arrigo 1995; Hattenschwiler et al. 1996). Another intriguing observation is that the net productivity (as measured by rates of tree mortality and recruitment – the turnover rates) of humid tropical forests throughout the world seem to have increased in recent decades (Phillips and Gentry 1994). Rising CO_2 levels are a possible cause, although N deposition resulting from local deforestation and biomass burning may also be a factor.

Secondly, there is the evidence for a global terrestrial carbon sink (the former missing sink of 0.5-2.5 Gt C/yr) which is required to balance the perturbed global carbon budget. The balance of evidence considered by the IPCC suggested that CO_2 enhancement of plant growth (resulting in a greater carbon storage in vegetation and soils as net primary productivity exceeded soil respiration, Lloyd and Farquhar 1996) is currently contributing a sink of 0.5-2.0 Gt C/yr (Melillo et al. 1996). The main evidence for a sink on land is a discrepancy in recent decades between the terrestrial carbon balance that is derived from ocean-atmosphere models and the known increase in carbon emission from deforestation (Sarmiento et al. 1992). Also, latitudinal distributions of global carbon sources and sinks derived using both forward modelling (Denning et al. 1995) and inverse modelling (Ciais et al. 1995) of the global variation in atmospheric CO_2 concentrations suggest a major sink on land, partly at northern temperate and boreal latitudes. It now seems clear that most of boreal forest areas (not from an increase in forest area) as shown in national forest inventories that northern sink is due to increases in the amount of carbon stored in existing northern temperate and (see Houghton 1996, consistent with Spiecker et al. 1996), but it is not clear what fraction of that is due to CO_2 enhancement of growth. Nevertheless, CO_2 growth enhancement still remains a front runner as a part-explanation for the missing carbon sink (Rotmans and Den Elzen 1993) although King et al. (1995) showed that simple ecosystem models which predict this sink are sensitive to assumptions about relationships between net primary productivity and biomass (their model suggests that CO_2 enhanced carbon fixation cannot explain the missing sink).

Third, tree ring analyses on trees (*Quercus ilex*) growing near to natural CO_2 vents, where they have been continuously exposed to concentrations of about 650 ppm CO_2, suggest that they grow about 12% faster than trees growing nearby in ambient CO_2, especially when the trees are young and in dry seasons (Hattenschwiler et al. 1997).

Finally, there is evidence from complex ecosystem models, like Hybrid, which couple carbon, nitrogen, and water cycles within soil-vegetation ecosystems, that rising CO_2 levels are increasing the net primary productivity (NPP) and net ecosystem productivity1 (NEP) of forests. Thus, Kellomäki et al. (1997) predicted that timber production in Scots pine forests in southern Finland would increase by 20% within a rotation in which CO_2 levels were increasing by 3.3 ppmv/yr. The IPCC consensus of the existence of a CO_2-fertilisation sink on lands rests on the increase in NPP and NEP predicted by almost all ecosystem models – all of which make reasonable assumptions but all of which have unquantified uncertainties (see Mellilo et al. 1996; also Thornley and Cannell 1996, 1997; McMurtie and Comins 1996; Medlyn and Dewar 1996; McGuire et al. 1997).

Amplification of the CO_2 enhancement of forest growth by increased N deposition (or vice versa).

At the leaf level, there is abundant evidence that N enrichment amplifies the CO_2 response of photosynthesis. A strong positive relationship has been found in both herbaceous and tree species between foliar N concentrations and light-saturated photosynthesis (Long 1983; Field and Mooney 1986). McGuire et al. (1995), reviewing the literature, found a linear relationship between the extent to which light-saturated photosynthesis was enhanced and increases in CO_2 and leaf N concentration. The relationship explained 61% of the variability. In other words, elevated CO_2 increased absolute rates of photosynthesis much more when leaf N was maintained or increased as a result of N fertilisation. Downregulation of photosynthesis is much less pronounced, or non-existent, when N is applied, with less reduction in RubisCO activity and less accumulation of starch and sugars in the leaves (e.g. Gunderson and Wullschleger 1994; Jarvis 1997).

At the whole tree and forest ecosystem level, there are many modelling studies which show how growth responses to elevated CO_2 are amplified by N supply (e.g. Rastetter and Shaver 1992; McGuire et al. 1995; McMurtrie and Comins 1996; Medlyn and Dewar 1996; Thornley and Cannell 1996). N-limited systems tend to respond to elevated CO_2 by allocating more carbon belowground, producing thicker leaves and litter with a high C:N ratio and hence potentially slower rates of decomposition and mineral cycling. The net result can be a decrease in leaf area, possibly greater immobilisation of N in the soil and a long-term constraint on net primary productivity. Nitrogen addition lessens these constraints. The experimental evidence for these amplifying effects of N is very strong and will be found in the reviews of Eamus and Jarvis (1989), Poorter (1993), Ceulemans and Mousseau (1994), Idso and Idso (1994), Amthor (1995) and Lloyd and Farquhar (1996) as well as in the modelling papers.

An effect of high C:N litter on increasing immobilisation of N in the soil (the withdrawal of N from the mineral pool available for plant uptake in order to maintain soil organic matter and biomass C:N ratios) was demonstrated in elevated CO_2 experiments by Diaz et al. (1993) and may be one reason why Körner and co-workers observed little response to elevated CO_2 in nutrient-limited ecosystems (Körner 1996). Nitrogen addition will alleviate this negative feedback (see Cannell and Thornley 1997). We must, however, remember that elevated CO_2 can increase the flow of carbon to roots and soil in nutrient-limited ecosystems and that this extra carbon may enhance N_2 fixation, nutrient availability in the soil, and, according to Zak et al. (1993) the amount of microbial biomass and hence potential mineralisation rates.

At the global scale, there is evidence that the promotion of terrestrial net primary productivity by elevated CO_2 alone may not be sufficient to account for the missing carbon sink of 0.5-2.5 Gt C/yr. N-fertilisation may account for a substantial fraction by amplifying the CO_2 response. Modelled estimates made by Schindler and Bayley (1993), Kohlmaier et al. (1988) and Hudson et al. (1994) suggest that the N-fertilisation sink in the 1980s was at least 0.7 Gt C/yr. The development of the terrestrial sink during this century can be reconciled with the increase in CO_2 emissions due to land use change (deforestation) only by invoking N fertilisation as well as CO_2 fertilisation and an effect of increasing global temperatures (Hudson et al. 1994). Hudson et al. (1994) argued that the sink was consistent with the spatial and temporal pattern of N deposition in the northern hemisphere. More recently, this finding has been generally supported by Holland et al. (1997) who modelled the global distribution of N deposition and concluded that it was responsible for a carbon sink of 0.7-1.3 Gt C/yr, largely due to the promotion of forest growth, although globally forests receive less than 10% of the N deposited.

Nitrogen deposition alone probably cannot account for the large (50%+) increases in forest growth observed

There are several reasons why we should believe that N deposition rising from 5 to about 20 kg N/ha/yr may have increased the growth of some forests by 10-20%, as suggested by the Hybrid model. But there are equally good reasons why other factors must be invoked to account for growth increases as large as 50% or more.

First, only a fraction of the deposited N will be taken up by the trees. Much will be deposited in winter. Commonly, only 5-15% of N applied annually in fertilisers is taken up (e.g. Magill et al. 1997; 50 or 150 kg N/ha/yr for 6 years in the Harvard Forest). Most is retained in the soil or lost by leaching or as gases. Even undisturbed, N-limited forests lose some N by leaching because of asynchrony between forest growth and microbial activity: nearly all of the 4 kg N/ha/yr lost from the Hubbard Brook control watershed occurred during the autumn, winter and spring (Bormann and Likens 1979). In Sweden, a fairly constant 20% of N inputs are leached from catchments over the low N deposition range of 2-15 kg N/ha/yr (Binkley and Högberg 1997).

Secondly, if annual N mineralisation was a major factor limiting the growth of European forests in pre-industrial times and is still a limitation in the less polluted areas (Binkley and Högberg 1997) then we might use N mineralisation-productivity relationships to estimate how much productivity may have been increased by increased N deposition in 1940-1970. In a recent study of 16 conifer and 34 broad-leaved stands in Wisconsin and Minnesota, Reich et al. (1997) found linear relationships between aboveground productivity and N availability for all sites taken together and for subsets grouped by forest type, soil type, and land history type. It is only in single-location studies, in areas where there might be N-saturation or where only a few closed-canopy stands are studied, that no such relationship is found. The overall relationship found by Reich et al. (1997) shows an increase of 0.53 t/ha/yr in aboveground productivity for an increase in N mineralisation of 10 kg N/ha/yr, over the range of 5-11 t/ha/yr in productivity and 30-130 kg N/ha/yr. Thus, an increase in N availability of 20 kg N/ha/yr from atmospheric deposition (which would require total deposition to be greater than 20 kg N/ha/yr, given the expected losses) would increase aboveground productivity by about 20% at the lower end of the range (at poor sites) and about 10% at the upper end of the range. Since annual N mineralisation cannot be less than annual N uptake (unless there is substantial foliar uptake) it is reasonable to assume that European forest soils, like those in the USA, mineralise 20-120 kg N/ha/yr (Miller 1978; Binkley and Högberg 1997). Thus, if Reich et al's (1997) relationships apply in Europe, N deposition alone (without increased CO_2) is increasing aboveground productivity by no more than 10-20% except in the very highly polluted areas.

Thirdly, where European forests respond to N fertilisation, it is commonly necessary to apply very large amounts of N to obtain a 30-50% increase in productivity. Thus, applications of 150 kg N/ha per year are needed to increase growth by 30-50% in much of Sweden (Binkley and Högberg 1997). Very large amounts of N (500-2000 kg N/ha/yr) have to be applied to bring about substantial long-term increases in N mineralisation at most sites, because there has to be an appreciable fractional increase in soil N. Large forest growth responses have been obtained in 'optimum nutrition experiments' conducted in Sweden on *Pinus sylvestris* (the SWECON project, Linder 1987) and *Picea abies* (Linder 1995; the Skogaby experiment, Nilsson and Wiklund 1992; NILSSON 1997) Australia on *Pinus radiata* (Linder et al. 1987) and Portugal on *Eucalyptus globulus* (Pereira et al. 1989) in which N or all nutrients have been supplied according to demand (determined by foliar nutrient concentrations and leaching losses) often with and without irrigation. In many of these experiments, growth rates have been doubled, but only with irrigation and an optimum supply of all nutrients, including at least 100 kg N/ha/yr for several years. In the Australian, Portuguese and Skogaby experiments, irrigation enhanced growth more than increased nutrition, and irrigation may have increased N mineralisation rates, releasing some of the original soil N capital at rates that are not sustainable in the long term. At Skogaby, an increase in aboveground productivity of 31% was obtained by applying 300 kg N/ha in 6 small applications of ammonium sulphate over 3 years (Nilsson and Wiklund 1992) while the observed forest growth increase between the 1950s and 1990s has been about 40% (Ericsson and Johansson 1993) and the increase in N deposition has been only about 15 kg N/ha/yr (from 5 to 20 kg N/ha/yr).

Fourthly, many European forests may be receiving excess atmospheric N inputs defined as: (i) critical loads, above which there is leaching leading to eutrophication, acidification and long-term ecological change (Grennfelt and Thornelof 1991) or (ii) N-saturation, which is best defined as when N outputs equal or exceed N inputs (Binkley and Högberg 1997). The NITREX consortium manipulated N inputs in whole catchments or large forest stands at 7 sites spanning the gradient of N deposition across Europe. With annual inputs of about 10 kg N/ha/yr nearly all the N was retained and outputs were very small. As inputs were increased from 10 to 25 kg N/ha/yr there was a transition to increased leaching loss. Above 25 kg N/ha/yr the forests approached N-saturation (Wright 1995). If this is true across Europe, then most of the forest areas in Scandinavia are well below N saturation and will respond to N addition with little risk of serious eutrophication and acidification, as concluded for Sweden by Binkley and Högberg (1997). However, substantial areas in the more polluted areas of central Europe have received 25 kg N/ha/yr for several decades and so may be close to N-saturation. Emmett and Reynolds (1996) estimated that 45% of the plantation forests in Wales receive 10-25 kg N/ha/yr and that nitrate leaching from mature forests (with least demand on soil N) may already be depleting soil base cations.

Fifthly, conifer plantation forests may not take up much of the N which is deposited during that part of the rotation (after canopy closure) when there is efficient internal recycling (typically 75% of foliage N is recycled; Zhang and Allen 1996) and/or efficient N cycling through the litter and soil. This point was made most elegantly by Miller (1981 1986) supported by fertiliser experiments (Miller et al. 1992) and by the fact that there has been no consistent or predictable response of Sitka spruce plantations in Britain to N fertilisation during the 'pole stage' – after canopy closure, before full maturity (McIntosh 1984). During this stage, a greater fraction of the deposited N may be leached and the 'critical load' for N deposition is low (Emmett et al. 1993).

4.2.1.4 Interim conclusions

The model predictions and the analysis of the literature lead us to the following four interim conclusions:

1. We are confident that increasing atmospheric CO_2 concentrations have had a positive, non-zero effect on European forest growth this century. We estimate this effect to be an increase in net primary productivity of 5-10 % by 1990, and predict a continuing acceleration of growth due to atmospheric CO_2 concentrations. During the next century, increasing CO_2 levels may become a dominant driver of growth acceleration.

The Hybrid model predicts an increase in net primary productivity of 10-15% by 1990, rising to 20-30% by 2050. Increases are predicted at all the locations examined, especially those with warm summers and high solar radiation receipts (i.e. greater at continental sites than in Britain) but not suffering regular summer drought.

The literature shows that canopy photosynthesis is enhanced in elevated CO_2 despite the downregulation of light-saturated photosynthesis in leaves grown in elevated CO_2 and measured in ambient CO_2, because (i) leaf light-saturated photosynthesis is rarely less when they are grown and measured in elevated CO_2, and (ii) most foliage in canopies is not light-saturated and the quantum efficiency of photosynthesis is unlikely to be downregulated. There is extensive evidence that elevated CO_2 enhances the growth of tree seedlings/saplings, and by similar proportions in N-limited and N-rich systems, owing to greater N use efficiency and perhaps enhanced N retention and acquisition in N-limited systems. Evidence for CO_2-enhanced forest growth in the field is more circumstantial and has to encompass the world literature. The evidence includes greater ring-widths in recent decades in high-elevation forests in non-polluted environments, apparently faster net productivity of tropical forests in recent decades, the need to invoke N-enhanced forest growth to account for the missing global terrestrial carbon sink, the faster growth of trees growing near natural CO_2 vents and the predictions of other forest ecosystem models.

2. We are confident that increased atmospheric N deposition is not the sole explanation for increases in forest growth as large as 50% or more that have been observed in many parts of Europe this century. Model predictions, and the literature, suggest that N deposition, increasing to about 20 kg N/ha/yr since 1940 over large areas, is unlikely, on its own, to have increased forest net primary productivity by more than 10-20% in most forests. Also, if N deposition stabilises to 1970 levels, the period of growth promotion by N deposition alone is likely to be limited to 1950-2000.

The Hybrid model predicts an increase in forest net primary productivity of no more than 5-12% in response to an increase in N deposition (on its own) from 5 to 20 kg N/ha/yr from 1940 to 1970. Productivity then flattens off at a new level by about 2000. However, models differ in the way they represent the N cycle and differences (and instabilities) exist in model predictions, depending, for instance, on assumptions about effects of foliar N levels on canopy photosynthesis, effects of tissue N content on maintenance respiration and the factors controlling N uptake.

The literature leaves little doubt that N deposition will have promoted forest growth, but only to a limited extent, for the following reasons: (i) Not all the deposited N is taken up by the trees, some is deposited in winter, some leached, immobilised or lost as N gases. (ii) Relationships between annual N mineralisation and aboveground forest productivity suggest that N deposition in most of Europe is unlikely to have increased growth by more than 10-20%. (iii) Very large amounts of N – several times those deposited from the atmosphere – need to be applied in fertilisers, or with irrigation and other nutrients, in order to obtain increases in productivity of 50% and above. (iv) Many forests that have received over 25 kg N/ha/yr for several decades may be close to N saturation. (v) Many plantation forests may not respond to N fertilisation after canopy closure owing to effective N recycling within the trees and the ecosystem.

3. We are confident that increased N deposition has amplified the CO_2 enhancement of forest growth (or vice versa – increasing CO_2 has amplified the N response). Increasing CO_2 and N deposition together may account for 13-20% increases in forest net primary productivity by 1990, and may increase net primary productivity by 30-40% by 2050.

The Hybrid model shows that N deposition greatly amplifies the predicted CO_2 response of forest net primary productivity, or conversely that the N deposition response is large only when combined with the increase in atmospheric CO_2.

There is an extensive body of experimental and modelling evidence showing that N addition increases the absolute growth response to elevated CO_2 owing mainly to: (i) prevention of a decrease in foliar N concentrations, (ii) decreased carbon allocation belowground, and (iii) less negative feedback on growth via N immobilisation in the soil and depletion of soil mineral N pools.

4. Increasing temperatures have probably had only a minor effect on forest growth during this century and the warmer temperatures projected to 2100 may promote or reduce forest productivity, depending on the hydrological balance at the location.

Temperature affects almost all ecosystem processes that regulate forest growth. Effects on photosynthesis, growth and mineralisation rates, which promote forest growth, can be offset by effects on maintenance respiration, stomatal conductance and tree water relations. The models suggest that the net effect of increasing temperatures on forest growth may be positive for many decades in Scotland, but neutral or negative at continental European locations with warmer summers.

4.2.2 Assessment of carbon and nitrogen cycles in terrestrial ecosystems

With nitrogen as a normally limiting element in European forests (Vitousek and Howarth 1991) we should expect that the increasing nitrogen deposition that has occurred during the 20th century also should have promoted forest growth. A crude estimate can be obtained as follows. In fertilisation trials it is generally found that about 30 % of added nitrogen is recovered in the trees (Melin 1986) out of which about a quarter will end up in stems. Nitrogen concentrations in *Picea abies* stemwood is around 1-3 g/kg dw (e.g. Nilsson and Wiklund 1995; Andersson et al. 1995).

Thus, for each additional kg of nitrogen deposition one can expect an increase in stemwood biomass of 300 kg. This agrees with the difference in stemwood production between the control and the irrigated-fertilised treatment in the Skogaby experiment (Nilsson 1997). There, the addition of 600 kg N over a six year period increased the stemwood biomass with 24100 kg dw. However, for a better understanding and insights into the processes that might modify the relation between nitrogen additions and growth we need more detailed models. A different modelling approach than the one by Cannell, Mobbs and Friend is presented here.

4.2.2.1 Methods

Ågren and Bosatta (1996) have developed general formulations for carbon and nitrogen cycles in terrestrial ecosystems. For the purpose of this paper, these general formulations have been specified in the following model (described in more detail in Andersson et al. 1997). The tree is divided into foliage and woody biomass each with a specific turnover time. The nitrogen concentration in wood is fixed whereas that in foliage is flexible and increases with increasing nitrogen availability. Foliage growth is driven by the nitrogen content in the foliage (nitrogen productivity) and wood growth is proportional to foliage biomass. Foliage and woody litter decompose with different specific decomposition rates. The nitrogen liberated by mineralisation is either taken up by the trees or lost from the system. The loss rate of nitrogen from the system is critical for the long-term behaviour of the ecosystem (Rastetter et al. 1997). For preliminary exercises, it was chosen to parameterise it such 10 % of deposition plus mineralisation is lost from the system. The model operates with an annual time step.

This model was applied to the three control plots in a nutritional experiment with Norway spruce stand in southern Sweden (Farabol, 56°26’N, 14°35’O, 150 masl, Andersson et al. 1995). Two levels of nitrogen deposition (5 and 20 kg $ha^{-1}yr^{-1}$) have been assumed and the growth of the initially 57 year old stand followed during 50 years. The results of this simulation for the aboveground wood production (stems and branches) are shown in Figure 4.15 together with measured wood biomasses. Over the 50 year simulation period, the average wood production is 4.41, 4.46 and, 4.13 t dw $ha^{-1}yr^{-1}$ in the three plots with 5 kg $ha^{-1}yr^{-1}$ of nitrogen deposition and 5.10, 5.11, and 4.70 t dw $ha^{-1}yr^{-1}$ when the nitrogen deposition has been 20 kg $ha^{-1}yr^{-1}$. The ideal stem biomass production rate for this stand should, according to yield tables, be around 4 t $ha^{-1}yr^{-1}$ and stem wood constitutes approximately 75% of the wood biomass. The simulated values are thus in good agreement with the empirical values. The growth increment as a result of increasing nitrogen deposition is of the order of 15%, which seems to be about what has been observed in this area between 1955 and 1995 (Eriksson and Karlsson 1996).

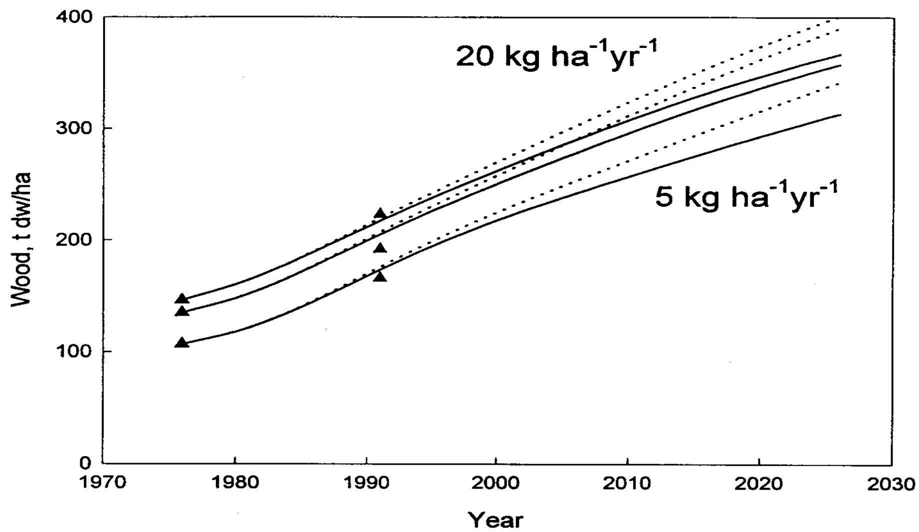

Figure 4.15. Simulated wood biomass development in the three control plots of the Farabol experiment assuming a nitrogen deposition of 5 kg $ha^{-1}yr^{-1}$ (solid lines) and 20 kg ha^{-1} yr^{-1} (broken lines). Measured wood biomasses in 1976 and 1991 are shown by triangles.

4.2.2.2 Discussion

The increases in growth that have been observed in large areas of Europe during the last decades (Spiecker et al. 1996) can have many causes. However, with many forest ecosystems in Europe being nitrogen-limited it is unlikely that the increased nitrogen deposition should not have contributed to this increase. The difficulty resides in assessing the quantitative contribution of various factors. The study reported focused on only nitrogen, assuming everything else unchanging, in order to derive the potential contribution from nitrogen deposition. The increase in nitrogen deposition from 5 to 20 kg $ha^{-1}yr^{-1}$ gives over a 50 year period an increased growth of about 15% which is comparable to observed increases. This increase in growth is, however, not uniformly distributed over the 50-year period. The differences in growth rates are increasing with time, being less then 2% over the first 10 years and 34% over the last 10 years of the simulation period. In the low deposition scenario, the growth rate is levelling off at the end of the simulation period as a result of more and more nitrogen being withdrawn from circulation and locked up in unproductive wood. This is not the case in the high N deposition scenario, but it is not meaningful to extend the simulation period further to try to find out when this would happen without including silvicultural operations and these would the dominate.

The results obtained here are preliminary and need to be viewed with caution, because some of the parameter values are not well known. For example, using a lower wood nitrogen concentration, but still within observed limits, or decreasing the nitrogen losses can change the growth rate as much as the assumed change in nitrogen deposition. Inclusion of other possible factors to explain changes in growth trends would require that some parameters are replaced by functions of these variables. With temperature this is straight-forward although there is uncertainty about the appropriate response functions. Inclusion of CO_2 is in principle easy but as there are yet no empirical studies on mature trees upon which parameter estimates can be based. Some studies aimed at effects of a global change have already been undertaken with a slightly different model (Ryan et al. 1996ab).

5 CLIMATIC CONDITIONS

H.-P. Kahle

5.1 MEASUREMENT OF CLIMATIC CONDITIONS

5.1.1 Measurement standards by meteorological services

For the accurate measurement of climatic conditions and in order to be able to properly compare meteorological measurements in space and time standardised technical rules including those on instruments and methods of observation have to be followed. These rules contain advice on methods required to keep observing stations up to international standards, recommendations for international observing practices for the taking of observations before coding, information about uniform procedures for applying corrections with a view to eliminating errors, and in general, the best methods of obtaining correct meteorological observations.

A high degree of standardisation of meteorological observations and of uniform publication of observations and statistics is achieved world-wide. Routine observations of surface air temperature, precipitation and surface pressure began in western Europe during the late seventeenth and early eighteenth centuries, and gradually spread to most of the rest of the world by the twentieth century (Jones and Bradley 1992). Many countries set up meteorological agencies after the Vienna Meteorological Congress of 1873. In 1946 the World Meteorological Organization (WMO) started to lay down the basic standards of instrument and observing practices that are required by present-day international meteorology (World Meteorological Organization 1983). With this aim in view the WMO has adopted from time to time technical regulations which lay down the meteorological practices and procedures to be followed by the member countries of the organisation. These technical regulations are supplemented by a number of guides, which describe in more detail the practices, procedures and specifications which members should implement in their own technical regulations. These guidelines are not intended to be a detailed instruction manual for the use of observers but to form a basis for the preparation of such manuals by each meteorological service to meet its own particular needs. The purpose was to lead to the desired degree of standardisation and of uniformity of methods of observation throughout the world.

On the national scale the meteorological services specified their particular practices within the WMO framework. Because of the great importance of these issues also in fields outside the meteorological services some technical rules related to meteorological measurements have been worked out and set up as national technical standards (e.g. in Germany: Verein Deutscher Ingenieure 1980, 1985, 1991, 1994).

5.1.2 Other measurement rules

Meteorological observations are not only conducted by meteorological services but also within a variety of environment related studies where meteorological conditions often are measured to characterise the climate part of the complex environment. In most cases, these studies are integrated within programmes on higher levels.

Within the European Programme for the Intensive Monitoring of Forest Ecosystems (Level II Programme; European Commission 1995b) meteorological measurements have been carried out during a test period on a limited number of permanent plots. The meteorological observations include measurements of actual meteorological situation and determination of long-term climatic situation. In Annex IX of the Basic Document for the Implementation of the Intensive Monitoring Programme of Forest Ecosystems in Europe (European Commission 1995b, p. 25-27) common methods for measurements of meteorology on the permanent observation plots are described. Among others, these guidelines address the following topics: location of sampling equipment, methods to measure the actual meteorological situation, collection, storage and submission of information as well as determination of long-term climatic situation. The member states are free in the selection of methods, equipment and measurement frequency during the test period, therefore no restrictions nor explicit installation procedures are given. Parameters to be measured are: precipitation, air temperature, soil temperature in a defined depth, relative humidity, wind speed, wind direction and solar radiation. Parameters could be measured either continuously or in discrete time.

Despite the fact that a high degree of standardisation of meteorological measurements and data is achieved, the respective underlying measurement and reporting standards have to be considered when compiling meteorological data from different sources.

5.1.3 The quality of meteorological measurements

When analysing multiple long-term time series of meteorological measurements and observations the accuracy, and homogeneity of the climatological data and the uniformity of the measurement methods is an essential issue. This is of special concern within the context of climate change research. A high degree of uniformity in measuring methods is achieved through the standardisation efforts discussed in section 5.1.1. Recently Huovila (1996) gave a review of the accuracy of meteorological measurements during the past hundred years with special regard to climate change studies. Especially in long meteorological measurement series made in the past very intricate measuring errors can be found in the records of precipitation, relative humidity, wind speed, and sunshine duration. Whereas pressure and surface air temperature measurements are in general much more accurate and reliable.

Typical causes for inhomogeneities in climatological time series are changes in measurement instruments and procedures, changes in the surrounding environmental conditions of the measurement station and changes in the station location. If the point in time at which such a change occurred is known, and if there are overlapping reference measurements available from the time before and after the change took place, it is possible to statistically correct the measurement data. For the identification and correction of unknown inhomogeneities statistical tests have been developed: absolute homogeneity-tests are built on single time series information, whereas for the more powerful relative homogeneity-tests homogeneous meteorological time series are used as reference series. The underlying theory is well described in Mitchell et al. (1966), Schönwiese (1992) and von Storch and Navarra (1995), and homogeneity test procedures for precipitation data are described in e.g. Chang and Lee (1974), Buishand (1982) and Alexandersson (1986).

5.2 METEOROLOGICAL DATABASES

During the last 150 years a large amount of meteorological measurement data has been assembled especially by the meteorological services all over the world. The availability of high performance computer and network capabilities and the growing demand of research communities of various disciplines for high quality climate data with high resolution in space and time has stimulated the development of international programmes to compile co-ordinated data bases and to provide access to these data bases.

Meteorological data bases hosted by the WMO and meteorological services
The WMO Distributed Data Bases (WMO-DDBs) project has been developed to provide access to data that are needed by WMO and related international programmes. This entry is maintained at the WMO in Geneva, Switzerland (http://www.wmo.ch/web/dbbs/dbbs.html [10.09.1996]). The WMO-DDBs Climate Data Sets are compiled by research centres all over the world. Within the WMO INFOCLIMA project a list of data centres contributing to the WMO data base activities is available at http://www.wmo/web/wcp/wcphtml/infoclim/infoclim.html [29.07.1997]. In the WMO Region 6 (Europe) more than 100 data centres (meteorological service data centres of WMO members, other national data centres and international data centres) are contributing (Appendix 1).

Within various research activities of the World Climate Research Programme (WCRP, http://www.wmo.ch/web/wcrp/wcrp-home.html [18.09.1996]) these meteorological network data bases are analysed under different aspects, and new and aggregated data are derived. The CLIVAR project (Climate Variability and Predictability, within WCRP) is a research effort focusing on the variability and predictability of the slowly varying components of the climate system that occur on seasonal, interannual, decadal and centennial time-scales. CLIVAR provides own data sets as well as links to related data sources. CLIVAR's homepage is located on the WWW-server of the 'Deutsches Klimarechenzentrum' (http://www.dkrz.de/clivar/hp.html [11.01.1996]). Within the Atmospheric Model Intercomparison Project (AMIP, http://www-pcmdi.llnl.gov/amip/amiphome.html [20.11.1997]) model-based data generated by 30 different atmospheric GCM models as well as observational data will be made available for downloading.

The purpose of the Global Precipitation Climatology Project (GPCP, within WCRP) is to provide the climate research community with gridded data sets of monthly precipitation totals covering the entire globe based on all suitable observation techniques and data. Results of this contribution are available at the Global Precipitation Climatology Center (http://www. dwd. de/ research/gpcc/e23. html [08. 1996]).

At the European level the European Climate Support Network (ECSN) under EUMETNET (Conference of the European National Meteorological Services) aims to organise a co-operation of its members, working together as a network and to help them in providing high quality meteorological basic data and products (for description of the ECSN-projects see e.g. http://www.dwd.de/research/klis/ecsn/ecsn.html [18.02.1997]). In order to promote wider international links ensuring complementarity, synergy and coherence in global change research programmes the European Union established the European Network for Research in Global Change (ENRICH, http:// www.enrich.hi.is/ [09.1997]). A major objective of ENRICH is to improve the access by the scientific community to EU mechanisms for support to global change research.

At the national level meteorological data bases are maintained primarily by the particular meteorological agencies and related data centres (the European agencies are included in Appendix 1). In Germany climate relevant data are assembled within the climate information system (KLIS; available at: http//www.dwd.de/research/klis/eng/eklis1.html [27.02.1997]). Within KLIS, the KLIDABA (climate data base) offers on-line access to station information and collective descriptions for all categories of German observation stations. For the German reference climatological stations in addition time series graphs of annual mean temperatures are available on-line. As with other European countries on-line access to the meteorological data within the German KLIDABA is not yet possible. For data release a written request must be sent to the German Weather Service.

Conditions attached to the access to meteorological data bases

During its congress in 1995 the WMO adopted resolution 40 concerning the international exchange of meteorological data and products (World Meteorological Organization 1995). One aim of this agreement between all members of WMO was to maintain the free and unrestricted exchange of meteorological programmes throughout the world. The resolution states that "members should provide to the research and education communities, for their non-commercial activities, free and unrestricted access to all data and products exchanged under the auspices of WMO", free and unrestricted meaning "non-discriminatory and without charge, ... at no more than the cost of reproduction and delivery". However, resolution 40 allows WMO member countries to place restrictions on the use or re-export of their data for commercial purposes outside of the receiving country. Within this WMO framework the particular meteorological services specified their own conditions attached to the release of meteorological data services and products for scientific purposes (e.g. Météo-France, available at: http://www.meteo.fr/meteo/e_cdtnre.html [1997]; Deutscher Wetterdienst, available at: http://www.dwd.de/research/klis/eng/e42.html [03.01.1997]).

Meteorological data bases hosted by other data centres

Meteorological data bases are not only hosted by the WMO and related meteorological services but also by other organisations maintaining data and research centres on international and national levels. The World Data Center System (WDCs), originally established during the International Geophysical Year 1957, functions under the guidance of the International Council of Scientific Unions (ICSU). "The World Data Center System works to guarantee access to solar, geophysical and related environmental data. It serves the whole scientific community by assembling, scrutinising, organising and disseminating data and information" (Mission Statement of the WDCs, available at the WDCs homepage: http://www.ngdc.noaa.gov/wdc/wdcmain.html [19.11.1996]). The World Data Center A for Meteorology (WDC-A) co-operates with the WMO and is one component of a global network of discipline subcentres that facilitate international exchange of scientific data. WDC-A acquires, catalogues, and archives data and makes them available to requesters in the international scientific community. Global data sets destined to be archived by the WDC-A as they become available from contributors include those from the World Climate Research Program, World Climate Data and Monitoring Program, and World Climate Applications Program. For climatological research and research on climate change impact, the meteorological data bases GHCN and GCPS (for explanation see below) maintained by the WDC-A Subdiscipline Centres for Meteorology and Paleoclimatology serve as important data sources.

The Global Historical Climate Network (GHCN) dataset is a comprehensive global baseline climate dataset comprised of land surface station observations of temperature, precipitation, and pressure (available at: http://www.ncdc.noaa.gov/ol/climate/research/ghcn/ghcn.html [16.09.1997]). All GHCN data are quality checked, and are on monthly basis with the earliest record dating from 1697. The data can either be downloaded via anonymous ftp or can be visualised and downloaded using the Climate Visualisation Program CLIMVIS. Monthly precipitation data from meteorological networks within 17 European countries and mean annual air temperature data from stations within 16 European countries are on-line available. Because of country specific restrictions on the use of data some countries' data like e.g. France, Germany, and the United Kingdom are not on-line available.

Interactive on-line climatological products are produced by the Global Climate Perspectives System (GCPS) using the Grid Analysis and Display System GRADS. The gridded datasets can be downloaded via anonymous ftp (http://www.ncdc.noaa.gov/gcps/gcps.html [29.11.1995]). The goals of GCPS are to study the existence and magnitude of climate changes on a global scale, to create high quality global climate reference datasets, to provide access to those datasets to the research community and to create a set of computer tools to aid climate research. Because climate data are extremely sensitive to errant values and outliers, the quality control of long-term climatological data plays an important role especially in the development of high quality climate reference datasets within GCPS. The quality control uses methods of objective data analysis described by BRAKER et al. (available at: http://www.ncdc.noaa.gov/gcps/papers/qc1/qc.html [16.11.1994]) The raw data used in the implementation of the quality control scheme is a subset of the GHCN.

Gridded climatologies of a variety of world regions and for the world as a whole are also developed and made available to download at the Climatic Research Unit of the University of East Anglia, UK (homepage at: http://www.cru.uea.ac.uk/cru/cru.html). A 1961-90 gridded surface climatology for Europe is constructed with a 0.5° resolution comprising more than 12.000 latitude/longitude cells (Hulme et al. 1995). For each grid cell three elevation levels (LO, MN and HI) are considered.

5.3 RECENT CHANGES IN CLIMATIC CONDITIONS

Climate varies on all scales of time and space. Thus the identification of the driving forces of the dynamic climate system, especially the differentiation between natural and anthropogenic effects becomes a very complex task (Mitchell et al. 1966, Mitchell 1968; Jones 1995; Jones et al. 1996; Santer et al. 1996). Whereas the reasons of climate change are various, complicated and not clearly understood (Anderson and Willebrand 1996; Houghton et al. 1996), there is much observational data available on climate change (see previous sections and e.g. Rudloff 1967; Perseke et al. 1987; Pfister and Lauterburg 1992; Gerstengarbe and Werner 1993; Boden et al. 1994; Houghton et al. 1996; Rodo et al. 1997). In the following, results of some selected studies considering European conditions are presented.

Jones and Bradley (1992) analysed climate changes between 1850 and 1988 using the longest available instrumental records. Both hemispheres show a warming of the order of 0.5°C since the mid-nineteenth century. It is indicated, that in the northern hemisphere the fastest warming occurred between 1920 an 1940. Warming is evident in all seasons except summer where little if any warming has occurred since the 1850s. Figures 5.1 and 5.2 shows Central European yearly and summer (June-August) temperature anomalies for the period 1761-1996. Data from four observation stations spread over Central Europe (De Bilt, Potsdam, Basel, Vienna) were used for these time series.

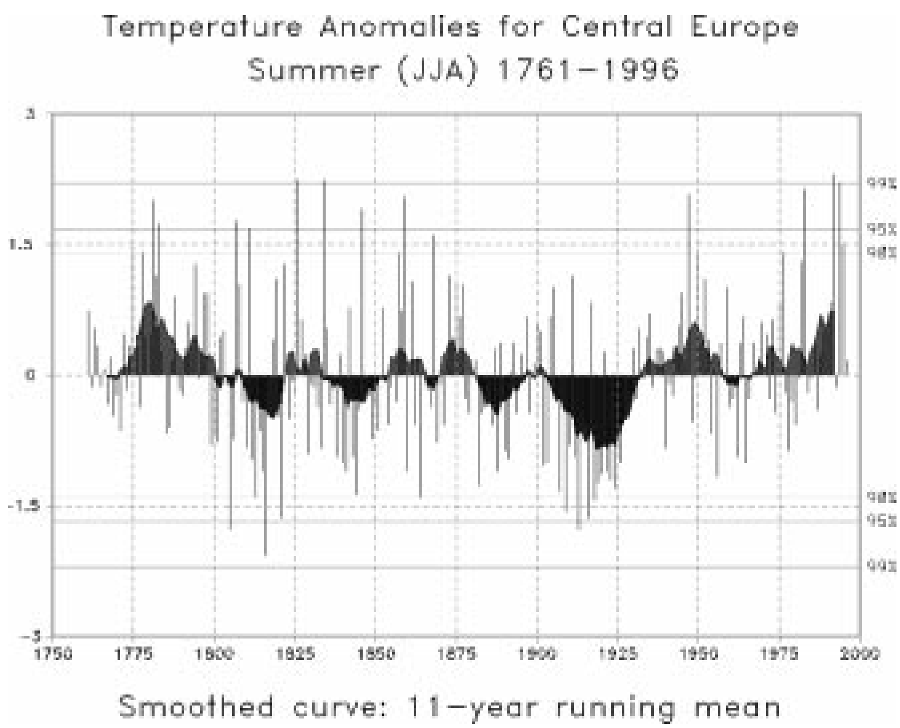

Figure 5.1. Yearly temperature anomalies for Central Europe for the 236-year period 1761-1996. Smoothed curve: 11-year running average (source: http:// www. uni-koeln.de/math-nat-fak/ geomet/ meteo/Klimastatistik/baurtemp.htm [08. 1996]).

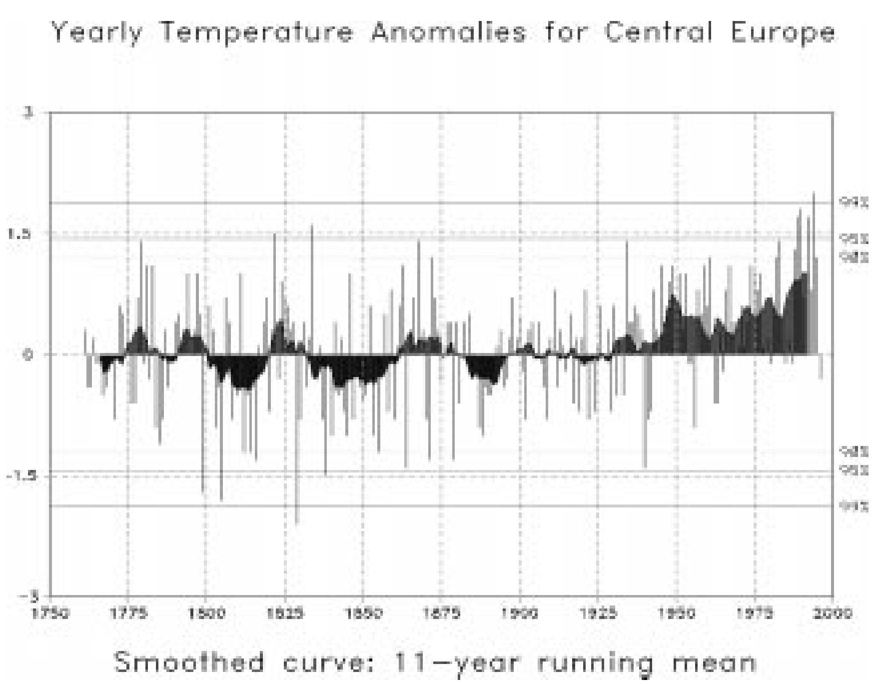

Figure 5.2. Seasonal temperature anomalies for Central Europe for the 236-year period 1761-1996. Smoothed curve: 11-year running average (source: http:// www. uni-koeln.de/math-nat-fak/ geomet/ meteo/Klimastatistik/baurtemp.htm [08. 1996]).

For each station, the deviations from the long-term mean are calculated and averaged over the ensemble of stations. The data were collected and processed by Baur (1887-1977) and the Meteorological Institute of the University of Berlin). The graphs and explanations are available at: http://www.uni-koeln.de/math-nat-fak/geomet/meteo/Klimastatistik/baurtemp.htm [08.1996]. Starting in the mid-1920s, an ongoing warming trend can be found in the annual, but not in the summer temperature series, indicating, that the trend aggregated in the yearly data is mainly due to winter warming. In the recent decade the highest annual and summer mean temperatures are observed for the whole period. In recent years, an unprecedented high concentration of extremely warm years which exceed the 95% threshold is indicated.

In the Climate Trends Atlas of Europe (Schönwiese and Rapp 1997; Rapp and Schönwiese 1996; Schönwiese et al. 1993) provide observational-statistical information using change charts of selected climate elements specified for different months or seasons of the year. The trend charts allow an overview and a detailed analysis of the geographical and temporal patterns of climate change in Europe. The figures on pages 84-93 of Schönwiese and Rapp (1997) show charts for seasonal and annual temperature trends and the figures on pages 182-187 show charts for seasonal and annual precipitation changes in Europe based on observations 1891-1990.

The annual temperature trends show different regional patterns: warming clearly prevails with a secular maximum of ca. 1.5 K in Eastern Europe, whereas only small changes occurred in Central and Northern Europe. On the seasonal scale warming is the dominant feature with maximum values in spring (Eastern Europe: ca. 2 K) and especially in winter (Eastern Europe: ca. 2.5 K). A season cooling is indicated in the Central European summer (- 0.5 K).

Much more diverse and complicated than in the case of temperature are the precipitation trends. In spring increasing precipitation can be found in Southwest and Northwest Europe, whereas in Central Europe drier conditions prevail. In the summer drier conditions are detectable in major parts of Central Europe compared with increasing precipitation in Eastern Europe. During autumn and especially during winter a decrease of precipitation in the central Mediterranean region is observed, contrasted by increasing precipitation in nearly all Western parts but also for example in Southern Germany and the Alpine region.

For southern Germany König and Mayer (1989, 1990) and Rall and Mayer (1989) analysed climatic effects with special regard to their potential contribution to forest decline (see also Cramer 1984; 1987; Cramer and Middendorf 1984).

In the growth study of Kahle et al. (1999) the climatic water balance in two regions of south-western Germany is derived from meteorological data. The data presented in figure 5.3 are derived from measurement data of three (Kaiserstuhl) resp. four (Feldberg) observation stations. Climatic water balance is calculated based on Thornthwaite`s formulae (Thornthwaite and Mather 1955). In the first step the climatic water balance data are pre-processed using as a sym metric 5-year running average (Kahle 1996; Kahle and Spiecker 1996; Primault 1995). To amplify medium- and long-term oscillations the data are smoothed in a second step using splines with a 50 %-frequency cut-off of 10 years. Both regions are in very close neighbourhood (horizontal distance ca. 30 km), but differ largely in elevation (ca. 280 m a.s.l., resp. 1500 m a.s.l.). There are clear medium-term oscillations, partly synchronous, partly asynchronous between the two regions. The very dry period in the late 1940s is much more pronounced in the Feldberg region (Black Forest) than in the Rhine Valley (Kaiserstuhl). Beginning in the mid 1970s, in the Black Forest region an unprecedented large divergence between annual and seasonal climatic water balances can be found: above average annual water balances are contrasted by very low values of the summer seasonal water balances. In the recent decade in both regions the climatic water balance of the late summer period (7-8) decreases to absolute minimum values. The observed changes clearly indicate the temporal and spatial variability of growth relevant climatic conditions (Briffa et al. 1994). In addition, the diverging courses between the annual and seasonal time series in the Feldberg region in the recent decades indicate, that a structural shift towards drier late summer months with simultaneously above average annual water balances occurred.

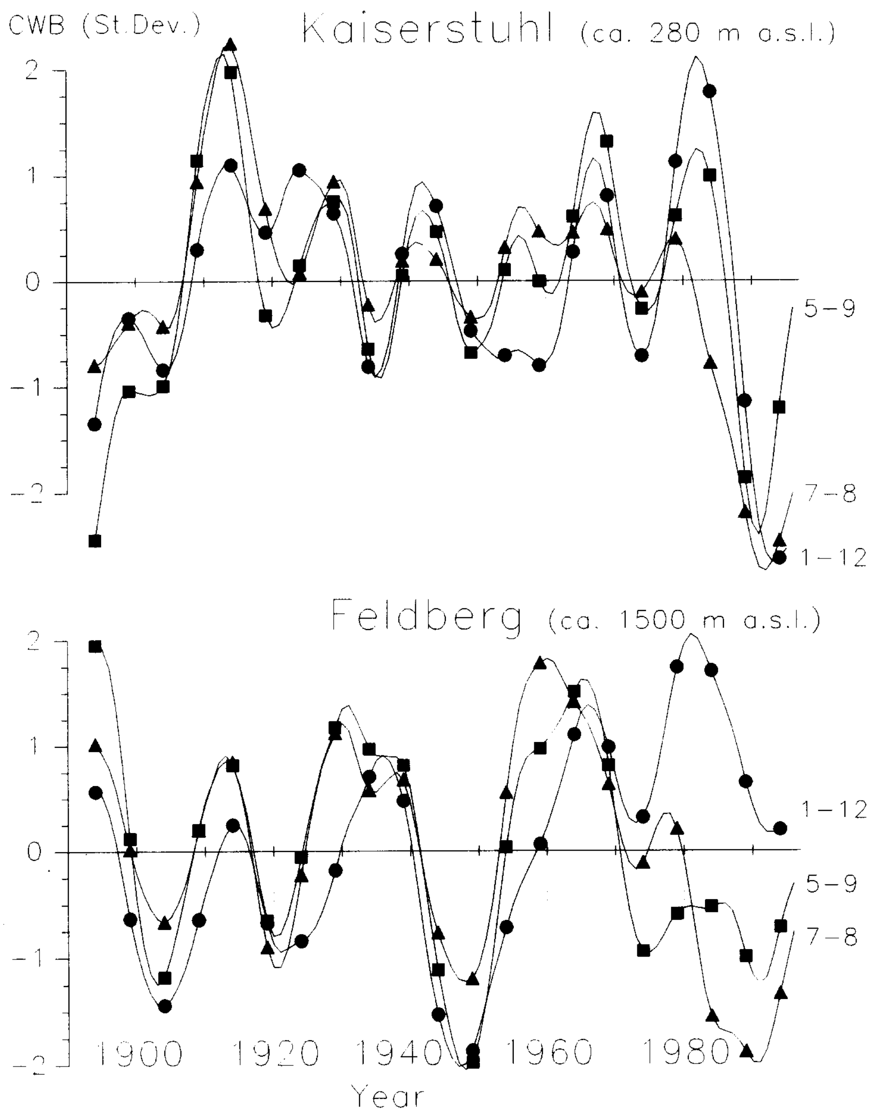

Figure 5.3. Courses of the annual (1-12) and seasonal (5-9 and 7-8) climatic water balances (CWB) in two regions of south-western Germany.

5.4 Expected impacts of climate change on forest ecosystems

Mechanisms, models and potential impacts of climate change on forests and forest ecosystems are discussed in a variety of recent papers for example in Kirschbaum and Fischlein (1996), Linder et al. (1996), Loehle (1996), Ryan et al. (1996a,b), Watson et al. (1996, 1998). In the studies of Sykes and Prentice (1995, 1996) and Sykes (1997) potential individual European tree species' range changes are forecasted under a double CO_2 climate change scenario.

In the "Assessment of Vulnerability Report" (Watson et al. 1998) of the Intergovernmental Panel on Climate Change, expected regional impacts of climate change on forest ecosystems are summarised. The primary influence of anthropogenic climate change on ecosystems is expected to be through the rate and magnitude of change in climate means and extremes and through the direct effects of increased atmospheric CO_2 concentrations. Increased atmospheric CO_2 concentrations are likely to increase the productivity and efficiency of water use in some plant species. Secondary effects of climate change involve changes in soil characteristics and disturbance regimes like fires, pests, and diseases. Since these effects are likely to be species specific changes in the species composition of ecosystems are expected.

Climate change is projected to occur at a rapid rate relative to the speed at which forest species grow, reproduce, and re-establish themselves:

> "For mid-latitude regions, an average warming of 3.5ºC over the next 100 years would be equivalent to a poleward shift of the present geographic bands of similar temperatures approximately 150-550 km, or an altitude shift of about 150-550 m. Therefore, the species composition of forests is likely to change; in some regions, entire forest types may disappear, while new assemblages of species and hence new ecosystems may be established. As a consequence of possible changes in temperature and water availability under doubled equivalent-CO_2 equilibrium conditions, a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world likely would undergo major changes in broad vegetation types with the greatest changes occurring in high latitudes and the least in the tropics. In tropical rangelands, major alterations in productivity and species composition would occur due to altered rainfall amount and seasonality and increased evapotranspiration, although a mean temperature increase alone would not lead to such changes"
>
> *(Watson et al. 1998, p.3-4 of Summary for Policymakers)*

Web sites:

- AMIP: http://www-pcmdi.llnl.gov/amip/amiphome.html [20.11.1997].
- CLIVAR: http://www.dkrz.de/clivar/hp.html [11.01.1996].
- CRU.UEA.UK: http://www.cru.uea.ac.uk/cru/cru.html.
- Deutscher Wetterdienst: http://www.dwd.de/research/klis/eng/e42.html [03.01.1997].
- ECSN: http://www.dwd.de/research/ klis/ecsn/ecsn.html [18.02.1997].
- ENRICH: http://www.enrich.hi.is/ [09.1997].
- GCPS: http://www.ncdc.noaa.gov/gcps/gcps.html [29.11.1995].
- GHCN: http://www.ncdc.noaa.gov/ol/climate/research/ghcn/ghcn.html [16.09.1997].
- GPCP: http://www. dwd. de/ research/gpcc/e23.html [08. 1996].
- INFOCLIMA: http://www.wmo/web/wcp/wcphtml/infoclim/infoclim.html [29.07.1997].
- KLIS: http//www.dwd.de/research/klis/eng/eklis1.html [27.02.1997].
- Météo-France: http://www.meteo.fr/meteo/e_cdtnre.html [1997].
- WCRP, http://www.wmo.ch/web/wcrp/wcrp-home.html [18.09.1996])
- WDC: http://www.ngdc.noaa.gov/wdc/wdcmain.html [19.11.1996].
- WMO: http://www.wmo.ch/web/dbbs/dbbs.html [10.09.1996].

Appendix 1: Demonstration version for CCl XII – August 1997, WMO REGION 6: Europe

Data centers contributing to INFOCLIMA

Country	Data Center
Austria	Zentralanstalt für Meteorologie und Geodynamik
Austria	Umweltbundesamt
Austria	Hydrographisches Zentralbüro
Azerbaijan	State Hydrometeorological Committee
Belarus	State Hydrometeorological Committee
Belgium	Institut Royal Météorologique
Belgium	Royal Belgian Institute of Natural Sciences, Brussels
Belgium	Department of General Botany, University of Antwerp
Belgium	Department of Geochronology, Vrije Universiteit Brussel
Belgium	Service d'Études Hydrologiques, Bruxelles
Belgium	International Data Rescue Coordination Center (IDCC), Brussels
Bulgaria	Service Hydrométéorologique
Croatia	Meteorological and Hydrological Service
Cyprus	Meteorological Service
Cyprus	Department of Water Development
Czech Republic	Hydrometeorological Institute
Denmark	The Danish Meteorological Institute, Database Section
Denmark	Geological Survey
Denmark	International Council for the Exploration of the Sea (ICES)
Finland	Meteorological Institute
Finland	Water and Environment Research Institute, Hydrological Office
France	Direction de la Météorologie
France	IFREMER Center de Brest
France	TOGA/WOCE Sub-surface Data Center
France	Intergovernmental Oceanographic Commission (IOC)
Germany	Deutscher Wetterdienst, Zentralamt Offenbach
Germany	Deutscher Wetterdienst, Seewetteramt Hamburg
Germany	Deutscher Wetterdienst, Meteorologisches Observatorium Hamburg
Germany	Deutscher Wetterdienst, Met. Observatorium Hohenpeissenberg
Germany	Deutsches Ozeanographisches Datenzentrum
Germany	Alfred Wegener Institute for Polar Research
Germany	Umweltbundesamt, Berlin
Germany	Institut für Geophysik und Meteorologie, Universität Köln
Germany	Institute for Wood Biology, Universität Hamburg
Germany	Altorientalisches Seminar, Westfälische Wilhelms Universität
Germany	Deutsche Forschungsanstalt für Luft- und Raumfahrt
Germany	HYDABA, Bundesanstalt für Gewässerkunde
Germany	Institut für Meteorologie, Freie Universität Berlin
Germany	Deutscher Wetterdienst, Met. Observatorium Lindenberg
Germany	Global Runoff Data Center, Bundesanstalt für Gewässerkunde
Germany	European Space Operations Center
Germany	Global Precipitation Climatology Center (GPCC), Offenbach
Greece	Div. of Climatology, Hellenic National Meteorological Service
Hungary	Meteorological Service
Iceland	Meteorological Office
Iceland	Hydrological Survey, National Energy Authority
Ireland	Meteorological Service
Israel	Meteorological Service
Israel	Hydrological Service Water Commission, Ministry of Agriculture
Italy	Meteorological Service
Italy	Istituto Idrografico della Marina
Italy	Centro Meteorologico Regionale, Milano
Italy	CNR, ICTR
Italy	Aeronautica Militaire

Country	**Data Center**
Italy	Food and Agricultural Organization (FAO)
Jordan	Meteorological Department
Latvia	Hydrometeorological Agency
Malta	Meteorological Office
Netherlands	Koninklijk Nederlands Meteorologisch Instituut (KNMI)
Netherlands	National Institute for Coastal and Marine Management / RIKZ
Netherlands	Rijkswaterstaat RI2A, Lelystad
Netherlands	Institute of Applied Geoscience TNO-DGV, Delft
Norway	Meteorologiske Institutt
Norway	Water Resources and Energy Administration, Hydrology Department
Poland	Institute of Meteorology and Water Management, Warsaw
Poland	Marine Geology Branch, Institute of Geology
Poland	Maritime Branch, Institute of Meteorology and Water Management
Poland	Forest Botany and Nature Protection Dept., Academy of Agriculture
Poland	Institute of Meteorology and Water Management, Krakow Branch
Portugal	Instituto Nacional de MeteorologÝa e Geofisica (INMG)
Portugal	Direccao Geral dos Recursos Naturais
Romania	National Institute of Meteorology and Hydrology
Russian Federation	All-Russia Research Institute of Hydrometeorological Information
Russian Federation	World Data Center B1 for Meteorology
Russian Federation	World Radiation Data Center (WRDC)
Russian Federation	World Data Center B for Oceanography
Slovakia	Slovak Hydrometeorological Institute
Spain	Instituto Nacional de Meteorologia
Sweden	Meteorological and Hydrological Institute
Switzerland	Meteorologische Anstalt
Switzerland	University of Bern
Switzerland	Federal Institute for Forest, Snow and Landscape Research
Switzerland	National Hydrological and Geological Survey
Switzerland	Institute for Atmospheric Science, ETH
Switzerland	Hydrological Information Referral Service (INFOHYDRO), WMO
Switzerland	World Glacier Monitoring Service
Syrian Arab Republic	Climatological Section, Meteorological Department
Turkey	State Meteorological Service
United Kingdom	Meteorological Office
United Kingdom	Marine Information and Advisory Service (MIAS)
United Kingdom	Permanent Service for Mean Sea Level (PSMSL)
United Kingdom	University of East Anglia
United Kingdom	Plymouth Marine Laboratory (PML)
United Kingdom	University of Cambridge
United Kingdom	University of Durham
United Kingdom	Biology Department, Liverpool Polytechnic
United Kingdom	Biology Dept., Royal Holloway, University of London
United Kingdom	Palaeoecology Lab., Geography Dept., Univ. Southampton
United Kingdom	British Antarctic Survey
United Kingdom	British Museum, Natural History
United Kingdom	Grant Institute of Geology, University of Edinburgh
United Kingdom	Environ. History Research Center, London Guildhall Univ.
United Kingdom	The National Water Archive, Institute of Hydrology
United Kingdom	European Center for Medium-Range Weather Forecasts(ECMWF)
Yugoslavia	Federal Hydrometeorological Institute

Sources: http://www.wmo/web/wcp/wcphtml/infoclim/infoclim.html [10.1997]
http://www.dwd.de/research/klis/infoclim/ra-vi.html [10.1997].

6 RESEARCH APPROACHES

G. Ågren, F. Andersson, J. Prietzel and L. Hallbäcken

To provide a broad scope investigations of interrelationships between recent changes of growth and nutrition of European forests should utilise different, complementing research approaches. With our first approach (Correlative approach, 6.1), we aim to identify for a great variety of different sites interrelationships between temporal changes in forest growth, stand nutrition, soil features, climate variables, and – where available – other relevant factors and to characterise these relations in mathematical and statistical terms. In a second approach (Modelling approach, 6.2), systems of mathematical expressions, including parameterised biochemical reactions and cybernetic feedback loops, are combined into models with different spatial and temporal resolution (physiologically based models, population models, ecosystem/tissue models) to assess the effects on tree physiology, biomass, element turnover in the ecosystem, as well as on the growth of trees and forests of previous and future modifications of the environmental conditions. These research approaches have also been applied in the analysis of a climatic and soil fertility gradient in northern Europe (Gradient analysis, 6.3). A combination of all these approaches is also intended (Combined approach, 6.4).

6.1 CORRELATIVE APPROACH

In the Correlative Approach, already-existing, but not yet evaluated suitable data sets characterising growth, nutritional status, climate conditions, and deposition, from intensively-studied stands of (i) long-term forest amelioration and fertilisation experiments as well as of (ii) forest ecosystem monitoring plots spread all over Europe (e.g. Solling, Höglwald, ARINUS, and level II network plots), are analysed by a variety of uni- and multivariate statistical procedures (e.g.. correlation analysis, factor analysis, trend analysis, linear and multiple regression analysis). The aim of the Correlative Approach is to identify site-specific, regional, and temporal patterns of relationships between the growth of European forest stands and their nutritional status, as dependent on changes in soil chemistry. Moreover, the effects of a changed nutrition shall be separated from those of climate variation and climate trends using adequate statistical methods.

The *Correlative Approach* comprises two different concepts of data analysis, each of them being conducted on different collectives of suitable sites.

6.1.1 Historical Development Investigation concept

In the *Historical Development Investigation* concept, data of plots from long-term forest nutrition and yield studies (control plots and experimentally-manipulated plots of fertilisation and amelioration experiments) in various European countries are analysed and compared with each other. Basic requirements for the suitability of a plot to be included in the Historical Development Investigation include (i) a quasi-continuous (every-year sampling) or frequent monitoring of the stand's nutritional status by foliar analyses of important elements for at least a period of 20 years and (ii) a controlled and well-documented silvicultural management history of the stands in study. In order to assess effects of climate fluctuations, also the availability of meteorological data (at least precipitation and air temperature) is desirable, but not obligatory, since the latter can be estimated using data of nearby meteorological stations. Records of data concerning soil chemistry and atmospheric deposition would further increase the scientific value of a plot for the Historical Development Investigation concept. The existence of data concerning forest growth (height, radial and volume increment) is helpful, but not obligatory; it also can be assessed retrospectively by dendroecological methods (stem analysis).

For each plot, interrelations between the temporal development of stand growth and the nutritional status of the stand can be identified and quantified statistically. If in addition time series of soil and climate characteristics and deposition data exist, also effects of the latter on forest growth can be analysed. Based on the results of these calculations, hypotheses on site-specific cause-effect relations will be derived.

Since there are – according to an inquiry conducted among 25 research institutions – many (>50) plots fulfilling the requirements mentioned above in different European countries for the tree species of interest (Norway spruce *[Picea abies]*, Scots pine *[Pinus sylvestris]*, and European beech *[Fagus sylvatica]*), a detailed picture, characterising the influence of different site-specific factors regulating forest growth and stand nutrition in different regions of Europe can be drawn; at least changes of the nutritional status of European forest stands on selected sites and the effect of these changes on forest growth can be regionalised.

In summary, the Historical Development Investigation seems to be a promising research concept, since it allows a direct formulation of cause-effect relations for each studied site. However, the following problems and uncertainties have to be addressed properly:

(i) Effects of changing analytical procedures during the investigation period must have been excluded or controlled (e.g. by repeated analyses of reference samples).
(ii) Old fertilisation experiments often are located on particularly poor sites (e.g. due to devastative forest utilisation as litter removal). Here the effects of a changed site fertility on forest growth might be different (e.g. more pronounced after N eutrophication as consequence of elevated N deposition) compared to other stands of the respective region.

6.1.2 Present State Analysis concept

In the *Present State Analysis* concept, current growth and recent growth changes of forest stands throughout Europe are assessed together with a determination of important variables describing their actual nutritional status as well as soil chemical variables, atmospheric deposition, and climatic conditions. The first step is an adequate stratification of the available data, e.g. into classes of identical tree species, similar stand age, similar climatic conditions of the sites together with the water-storing capacity of the soil, and similar levels of atmospheric deposition, (particularly that of N), or gradients thereof. Then, patterns in the spatial distribution of the present growth and nutritional status of the different stands are identified and compared. Finally, various methods of multivariate statistical data analysis (e.g. multiple regression analysis, factor and cluster analysis, panel data analysis and geostatistical methods) are used to isolate and quantify relationships between present forest growth, recent growth changes, and site fertility.

The *Present State Analysis* could be carried out in an ideal way by using the level II forest intensive monitoring plots of the European Union. The level II network consists of 643 forest ecosystem monitoring plots distributed over vast parts of Europe. 440 sites are located in the EU Member States, 203 in Non-EU Countries. The plots represent typical forest ecosystems of the surrounding region. The sum of all plots gives an overview over the forested area in Europe with respect to tree species, stand age, elevation, stand growth, stand nutritional status, and soil chemistry. As all plots are located near meteorological stations, meteorological data are also available. By the end of 1996, first survey data were submitted to the European Commission.

Publication of first results is expected in autumn 1997. These data and results would constitute an ideal data base for the Present State Analysis. Additionally, the forest growth and yield data could be supplemented by measurements of basal area and standing volume as well as by retrospective assessment of long-term growth trends by conducting stem analysis on selected sites, in particular for those where extremely high/low actual increment rates are expected.

The level II sites can be supplemented – or, if they should not be available – also substituted by sites, which have been monitored intensively in the course of forest ecosystem research projects by various European universities and forest research stations. Compared to the level II plots, many of these sites have been monitored – often in much more detail – for many (5 to 10) years, yet in most cases not long enough to be suitable for the Historic Development Investigation concept. Moreover, they often include manipulation experiments (fertilisation, simulation of various levels of atmospheric deposition, climate variation) which might provide helpful additional information.

Within the Present State Analysis, several gradient analyses (e.g. with respect to the variables N deposition, present forest growth, water availability, or base cation supply) on different scales (e.g. comparison of various stands and investigation of stand-internal variation – edge effects in different regions) can be implemented. In this concept, interrelations between site fertility and other variables regulating present forest growth and recent growth trends will be studied for sites carefully selected after adequate classification and stratification, where each is part of one or more transects. Each transect should cover a large part of Europe and/or environmental conditions in Europe and should be established on a gradient of one of the variables noted above.

The Present State Analysis concept is characterised by several advantages: (I) The studied sites give an overview over large forested areas in the respected region and (ii) they cover almost the entire area of Europe. Additionally, the level II data (iii) have been achieved using standardised methods, and (iv) are already available; therefore costsome sampling and analyses are avoided. Major drawbacks of the approach are that (i) only the current state, but not the temporal development of interrelations between forest growth and forest nutrition (or other factors) can be analysed, and thus (ii) a direct causal analysis between the dependent variable (growth) and the different site factors is not possible.

The combination of the Historical Development Investigation with the Present State Analysis in the Correlative Approach appears to be a powerful tool to assess past and recent interrelationships between site fertility, forest nutrition, and forest growth in Europe. Modelling (see next paragraph) should allow the linkage of cause-effect-relationships as identified and quantified for several distinct sites with regional patterns of site fertility/growth relations as revealed by the Present State Analysis. The combination of both research concepts is particularly promising, since some of the sites studied as part of the Present State Analysis concept (e.g. the Solling level II network sites) have been monitored for more than 20 years and are also studied in the Historic Development Investigation. These sites constitute an interface between both research concepts, allowing a direct combination of the results achieved with different methods.

First contacts have given evidence that the whole set of data from the level II network will probably not be available at present. However, some of the states involved have demonstrated their willingness to participate and to allow access to the data collected by them. Together will the information already published from the long-term ecosystem forest studies interesting gradient analyses seem to be feasible.

6.2 MODELLING APPROACH

Large amounts of data are available to describe states and changes in European forests. There is also an abundance of data and knowledge about plants and soils at several levels of resolution. From all this information we need to select what is relevant in a given circumstance; in this context what is needed in order to understand recent growth changes in European forests caused by changes in nutrition, soils, climate and management changes and to predict its consequences for the future. A powerful tool at our disposal is a process model; the word model will in this section only refer to process models. Since forest responses occur at different scales in both time and space, it is necessary to employ a variety of models. These models should synthesise isolated empirical and theoretical results, and forest responses predicted by the model represent the best estimates that current knowledge can supply. A recent general review of different approaches to forest ecosystem modelling has been done by Ågren et al. (1991).

We recognise here two partially overlapping levels where models can be used: the plant physiological level and the populations and ecosystem level. At the physiological level plant processes are described in great depth, down to biochemistry. The ecosystem scale integrates the physiology to whole-plant or major plant components and adds a feedback interaction to the environment, in particular the soil. Population models generally operate at the same scales as ecosystem models, but deal with plants at the level of population dynamics. In the context of this project, the HYBRID model (Friend et al. 1997) encompasses both levels whereas the approach by Ågren and Bosatta (1996) is a genuine ecosystem level formulation.

6.2.1 Physiologically based models

Our understanding of processes such as leaf energy balance, carbon uptake through photosynthesis, exchange of water vapour through transpiration, and respiration has in recent years been improved through advances in both instrumentation and ecophysiological theory, see Landsberg and Gower (1996) for recent update. The objectives of physiologically based models of canopy process are to integrate up from the micro-environmental scale to the functioning of communities of plants. A modelling framework is required to interrelate the various environmental variables over space and time.

The basis for description of photosynthesis is the Farquahr-von Caemmerer biochemical model. This model relates the rate of assimilation to the intercellular concentration of carbon dioxide, but the rate of assimilation is also determined by temperature and nitrogen concentration through physiological variables. Stomatal conductance is crucial and often calculated based on the Penman-Montieth equation (e.g. Jarvis 1985). The calculation of stomatal (or canopy) conductance requires information about radiation, plant water status, air humidity and temperature with a within-day resolution. When such detailed climatic information is not available, interpolation schemes for coarser time resolution data can be used.

Respiration is generally divided into growth and maintenance respiration, with growth respiration assumed to be in constant proportion to tissue production, and maintenance respiration of various biomass compartments related to temperature by either an exponential or Arrhenius function. Computation of stand-level maintenance respiration requires scaling according to surface area, sapwood volume, dry mass of tissue, or nutrient content, which are considered to reflect the metabolic activity of live biomass.

Allocation between different tissue components is not well understood at a mechanistic level but a number of semi-empirical or empirical descriptions can be used (Warren Wilson 1988; Ågren and Wikström 1993).

6.2.2 Population models

Various models have been developed that simulate tree growth as affected by competition among individuals and population dynamics. In these models, the effects of climate on tree growth and population dynamics are either explicitly or implicitly simulated. These models apply to either single-species or multiple species stands, either explicitly simulate spacing among trees or greatly simplify spatial relationships, either follow individual trees through time or only summary variables such as number of trees, etc., but all consider birth or recruitment, growth of individuals and limiting factors, stand structure and spacing, and mortality (Shugart 1984).

The JABOWA/FORET class of models (and to which HYBRID belongs) begins with a priori assumptions about how environmental factors affects growth of individual trees. Depending on the version, various processes are stochastically simulated, so model predictions are usually reported as means of many model runs. In the earliest version of these models, tree growth depended only on climatic factors but more recent versions also simulate effects of nutrient limitations, e.g. LINKAGES and HYBRID (Friend et al. 1997).

6.2.3 Ecosystem/tissue models

Ecosystem/tissue models include models that consider carbon flows between the plant and soil subsystems. Within this group of models, the plant compartments are highly aggregated and will typically lump all green biomass into one compartment. This contrasts with the previously discussed plant physiology models that divide plants up into a number of morpho-physiological different parts and include many detailed plant physiological processes. The objectives of the ecosystem/tissue models are quite diverse; however, they generally include the ability to simulate ecosystem responses to changes in the abiotic driving variables (light intensity, soil water, and soil temperature) and the impact of different management options at the ecosystem level. Two important characteristics of the ecosystem/tissue models are the time step used by the model and whether the model is connected to a nutrient cycling model.

Forest ecosystem models can generally be divided into models that use short (1 day or less) or long (1-12 mo) time steps. Models that include the linkage of carbon flow to nutrient flows are more useful for evaluating the impact of climate and soil changes and management on ecosystems. Without this linkage, models are unable to simulate the interactive impact of aboveground and belowground plant residue on nutrient availability and the resultant impact on plant production.

The CENTURY model is one of the more well-known low-resolution simplified ecosystem models, initially developed to simulate plant-soil systems in the United States Great Plains region. Later versions have also been developed for applications to forests (Sanford et al. 1991). The soil component of the model has, however, attracted much interest and is now used in several other models (e.g. HYBRID). The basic structure of the soil component of CENTURY is two soil organic carbon pools with turnover times of around 25 and 1000 yr and where the fluxes between these and respiration losses are generated by a rapidly overturning microbial biomass. A parallel structure for nutrients exists.

A different approach to ecosystem element cycling has been taken by Ågren and Bosatta (1996). Their basic idea is that with the very large number of organic compounds that exist in ecosystem organic matter, it is not practical to divide it into a small number of fractions. Instead, one should look at the organic matter as consisting of a continuum of compounds where each compound is assigned a quality value that expresses its usefulness as growth resource for the decomposer community. This assumption can be developed into a set of equations describing the turnover of soil organic matter and specifically the release of nutrients through mineralisation. Plants take up the available nutrients in the soil and these nutrients drive plant growth through the nutrient productivities. The advantages of this approach are that it ensures a consistency in model formulations and that only a few parameters need to be estimated. The use of this approach requires, however, understanding of more advanced mathematics than in most other models.

6.2.4 Discussion

The effects of climate change operate at the molecular level of the living organisms. Yet it is at the ecosystem or population level that we want to know the consequences of climate change. Since we question the efficacy of predicting ecosystem-level phenomena directly from our knowledge of interactions at the highest level of resolution, we need some means of integrating up from knowledge at one level of resolution to the next. Rigorous progression from one level to the next in an extensive way, such as the derivation of thermodynamics from statistical mechanics, has not yet been achieved in an ecophysiological context (Ågren 1996; Ågren and Bosatta 1990; Bonan 1993). However, recent discussions of hierarchies (Allen and Starr; 1982; O'Neill et al. 1986; Luxmoore et al. 1991) point to future lines of development. The different modelling approaches presented here should be viewed as representing levels in a hierarchy.

A variety of models, each with its domain of applicability, will be required to answer the diverse questions to be asked. What we want to emphasise is the need to select a model that is appropriate with respect to the scale of the problem in question, particularly in time but also in space. Viewing the same system from different space and time perspectives makes different phenomena important or unimportant. Models based on plant physiology are ideal to analyse and interpret the detailed reactions of plants to the various components of climate change. Their temporal resolution is much too short to pick up slowly evolving external variables, which might set severe constraints in terms of factors such as water and nutrient availability. In the HYBRID models this is solved but letting different submodels operate with different time steps. On the other hand, for the population and ecosystem models emphasising longer time scales, insights from the physiologically based models are required to ensure that no major impact of climate change is neglected and that formulations of growth processes are realistic. In principle, physiologically based models whose assumptions and parameter values are derived from careful experimentation should more reliably predict growth responses than models with more empirical formulations. There is, however, a balance between complexity and simplicity that has to be found to make a model operational and understandable by others than the developer (Hauhs et al. 1996; Van Oene and Ågren 1995).

6.3 GRADIENT ANALYSIS OF FOREST NUTRITION AND GROWTH RELATED TO BIOGEOCHEMICAL CYCLING

6.3.1 Background

Recently a Nordic project on nutritional status and growth of Norway spruce forests has been presented by Andersson et al. (1997, 1998). The background to the investigation was the assumption that the continued deposition of acidity and nitrogen will lead to imbalanced nutritional status of forests and with possible disturbances on resistance properties and growth. In order to understand the nutritional status as well as the reaction of the forests to the deposition 11 fertilisation experiments were analysed in a biogeochemical cycling perspective. The experiments from North Finland, through Finland, Norway and Sweden down to W Denmark represent a climatic gradient as to temperature and deposition as well as soil fertility.

As to growth limiting mineral nutrients an interesting regional pattern was found. A simplification of the result tells that at all inland sites forest growth was limited by nitrogen. In the north the N limitation was pronounced and if nitrogen was added boron deficiency occurred. Towards the south, e.g. S Sweden, P and K seems to approach a gradual limiting situation. Coming to coastal areas in W Denmark and S Norway a situation with P limitation seems to prevail.

The investigation analysed tree nutritional status and growth in relation to biogeochemical cycling principles. A number of concepts based on ecosystem principles were used and also developed and tested, which will allow a deeper understanding of nutrition and growth of forest trees and stands. It is now a challenge to extend the Nordic gradient to the south and east in Europe and intensify the use this more complete information in applying mechanistic models.

6.3.2 Concepts and methods

The following variables were used:

- Site fertility – *site index*
- Chemistry of leaves/needles – *concentrations and ratios (CR), deviation from optimum (DOP), vector analysis*
- Efficiency of the tree to accumulate carbon as a function of leaf/needle mass and its nitrogen content – *biomass and nitrogen/nutrient productivity*
- Nutrient pools of total biomass and soil – *nutrient distribution*
- Relation between accumulated nutrient pools in above-ground biomass, nitrogen in particular, and forest production expressed as accumulation of carbon – *relative nutrient accumulation, RNU*
- Estimated amount of compensatory nutrients needed to maintain the original status of a stand under e.g. influence of long-term nitrogen stress – *Nutrient requirement NRQ*. A basis for the estimation is calculated changes in RNU and net carbon accumulation rates.

By means of the variables mentioned, the link between tree/stand production and nutritional conditions was analysed as affected by deposition and other factors. The information from control plots in a gradient will give the ”normal” behaviour. Effects due to differences in physical and chemical climate should in this way be possible to demonstrate. Changes in the ecosystems will affect the ability of the tree to utilise available nutrients. When an element becomes less available the tree utilises the nutrients more effectively. This is described by the nutrient productivity of the tree/stand – the ability of the nutrient in the leaf biomass to produce stem biomass or above-ground biomass. This analysis will require information on tree biomass growth and nutrients pools.

It is important to link changes in the nutrient conditions of the soil with changes in the different nutrient pools of the trees/stand. On the same time, the functioning of the trees has to be considered, i.e. in particular the utilisation of the nutrient taken up for carbon assimilation and accumulation. In this context, the interpretation of pool changes due to effects by different impacts or treatments must consider both changes in dry mass and nutrient concentrations. The dynamic feature of tree growth means that as long as a tree stays alive there is usually a positive net growth leading to increased pools if the nutrient concentrations are not substantially decreased.

A reduced uptake may not always lead to a reduced tree/stand growth or biomass pool of that nutrient. The *RNU-concept* has been developed as a tool to interpret long-term responses on nutrient pools and carbon accumulation on above-ground biomass due to different effects of treatments. The idea is to transform calculated changes in nutrient pools over time, as a quantitative, dynamic variable, to a qualitative ´concentration´ measurement This variable is used to compare effects between treatments without interference of differences in absolute nutrient pools sizes primarily due to differences in dry mass. Ratios between the estimated net accumulation of C and a specific element during the experimental period is calculated. RNU is expressed by the relation between these ratios for treatments and control. Subsequently carbon is used as an internal standard and the RNU for a specific element denotes *the relative change of the element pool over time compared to unit carbon accumulated*.

The ecological significance of RNU is that changes in the efficiency of accumulation of carbon – the forest production – is expressed as a sum of processes involved on single element pools such as nutrient uptake, translocation within the tree and productivity of the leaf mass. In combination with foliar analyses (CR) it is possible to link the different types of nutritional criteria of the leaf mass (current leaves/needles) of the whole tree to forest growth rates. The *relationship between CR and RNU* could further be used *for validation of nutrient imbalances and quantification of compensatory nutrients needed – the nutrient requirement of a stand NRQ*.

At present the RNU concept can be used for individual experiments. It needs further development in order to handle comparisons between experiments and to make comparisons between site classes and differences in stand age.

In Figure 6.1 the variables used and the analytic procedure are summarised. A ”maximum” list of information needed for the analyses are found as Table 6.1

6.4 COMBINED APPROACH

All three approaches presented above will be combined in order to validate and to further improve the different models. In addition, prognoses of the future development of the variables of interest (e.g., stand growth, stand nutrition, soil chemistry) will be conducted and the risk of a future disharmonic forest nutrition will be assessed for different sites. If possible, the results will be extended to describe the reaction at larger regional units (e.g. site types, biogeoclimatic zones).

6.5 AIMS, WORKING HYPOTHESIS AND RESEARCH STRATEGY

6.5.1 Overall aims

Out from the description and analyses of the problem area the overall aims of a coming project could be as follows:

- *to identify potential causes of recent growth trends in European forests and investigate their interactions focusing on the relative importance of nutrients (primarily nitrogen), climate (CO_2, temperature and precipitation) and land use changes,*
- *to focus on growth analyses on selected sites, where conditions and availability of historical and more recent data allow testing of specific hypotheses about causes of changes in site productivity,*
- *to analyse the long-term consequences for sustainability of observed changes (site productivity / risk analysis) and to draw attention to future management strategies;*

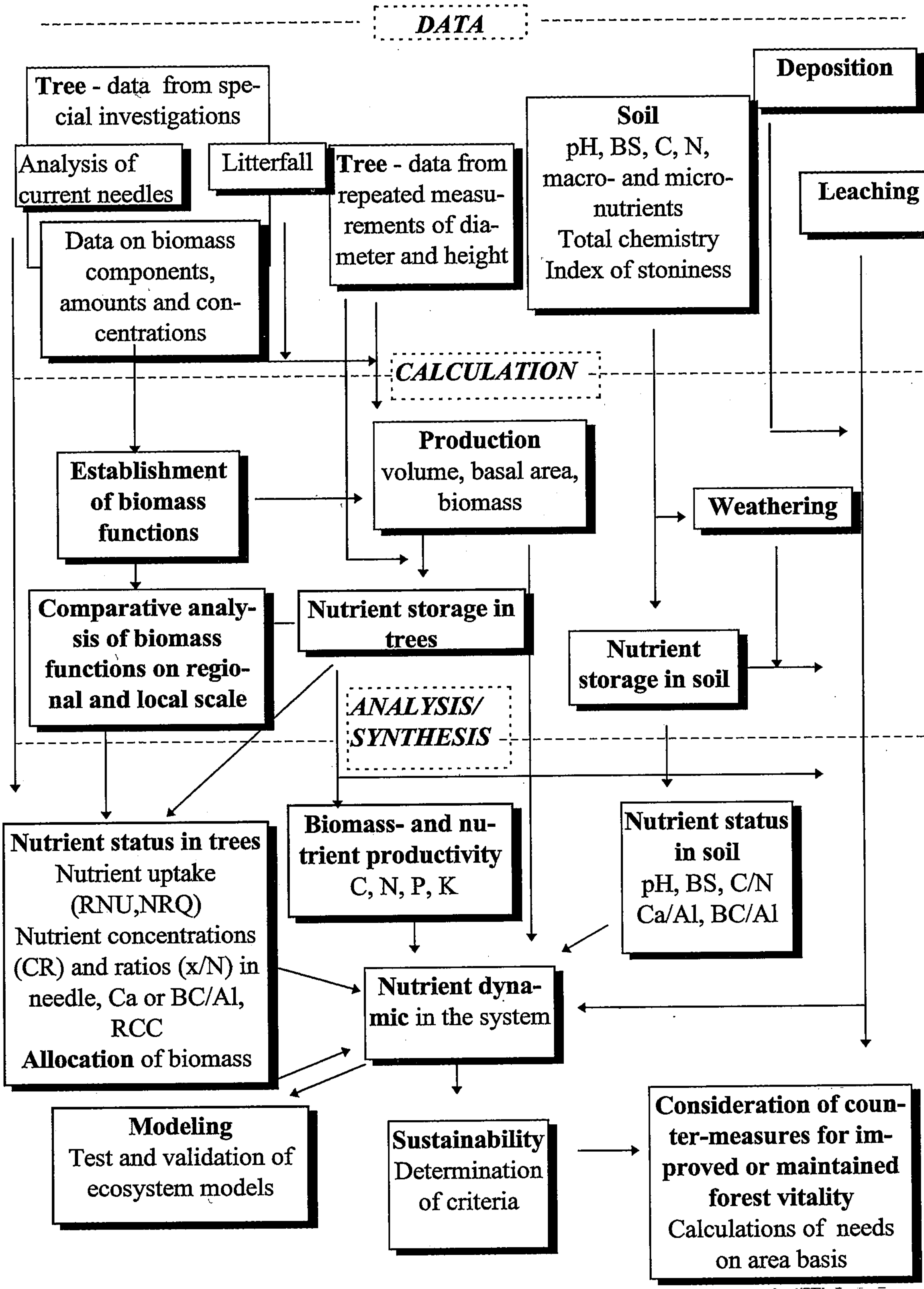

Figure 6.1. Flow diagram of measured and calculated variables as well as functional properties of forests focusing on nutrition and forests growth.

Table 6.1. Static and dynamic variables analysed in the gradient analysis of forest nutrition and growth related to biogeochemical cycling.

Vegetation/Trees	**Soil**
Stand inventory	***Structure***
1. Diameter 1.3 m	1. Classification of soil and soil type
2. Height	2. Stoniness index
3. Tree density	3. Density of soil material < 2mm
4. Age	4. Mineralogy
5. Needle sampling for nutrient status analysis	
	Chemistry
Sample trees	***1. pH_{H2O}***
Stem and crown	2. pH_{KCl}
1. Diameter 1.3 m	3. Exchangeable acidity
2. Height	4. Exchangeable base cations
3. Volume m^3 ha^{-1}	5. Total acidity (at pH 7.0)
4. Crown limit	6. CEC (buffered/unbuffered)
5. Basal area	7. BS %
6. Stemwood biomass	8. Total C, N, P, K, Ca, S, Mg, Na, Al +micronutrients
7. Stemwood biomass growth	
7. Stembark biomass	9. Historical weathering rates
Living branch biomass	***Deposition***
	Open field – amount and chemical content
	Throughfall -amount and chemical content
1. Needle biomass by age classes in general C_0, C_1 and C_{2+n}	***Soil water***
2. Unit weight of 200 needles	1. Chemistry
3. Shoot biomass by age classes in general C_0, C_1 and C_{2+n}	2. Fluxes
4. Branch wood biomass	
5. Branch wood biomass growth	
Concentration of total N, P, K, Ca, Mg, Mn, S, Cu, Zn, Fe, B, Al	
Dead branch biomass	
Fine roots	
1. Total biomass by tree and field-layer species, size and living and dead	
2. Growth rates	
3. Concentration of total N, P, K, Ca, Mg, Mn, S, Cu, Zn, Fe, B, Al	

6.5.2 Working hypotheses

The observed changes of site productivity are the result of complex interactions between a number of factors. The changes have taken place with different intensities in different regions. We have chosen nutritional factors as a focus and other factors need to be analysed in relation to nutritional aspects. We view the problem in the following way (Fig 6.2).

We see the changes of site productivity (Box 1) as related to changes in nutrient availability for tree growth (Box 2). The changes in nutrient availability leads to changes in nutrient uptake (Box 3) and is manifested in new patterns of carbon allocation resulting in changes in nutrient efficiencies (Box 4). The nutrient availability is a result of decomposition and mineralisation of organic matter, deposition, and finally weathering of primary minerals (Box 5). The latter process together with more resistant humus material is the major decisive factors determining long-term sustainability.

Changes in temperature and water availability/precipitation (Box 6), will affect the availability of nutrients for uptake by trees and vegetation as well as it will affect tree growth directly. Finally the long-term increases in atmospheric CO_2 has a direct effect on trees and growth (Box 6). The effect of CO_2 will also be determined by available nutrients in the ecosystem. The availability of mineral nutrients is also a function of previous land use history and forest management (Box 7).

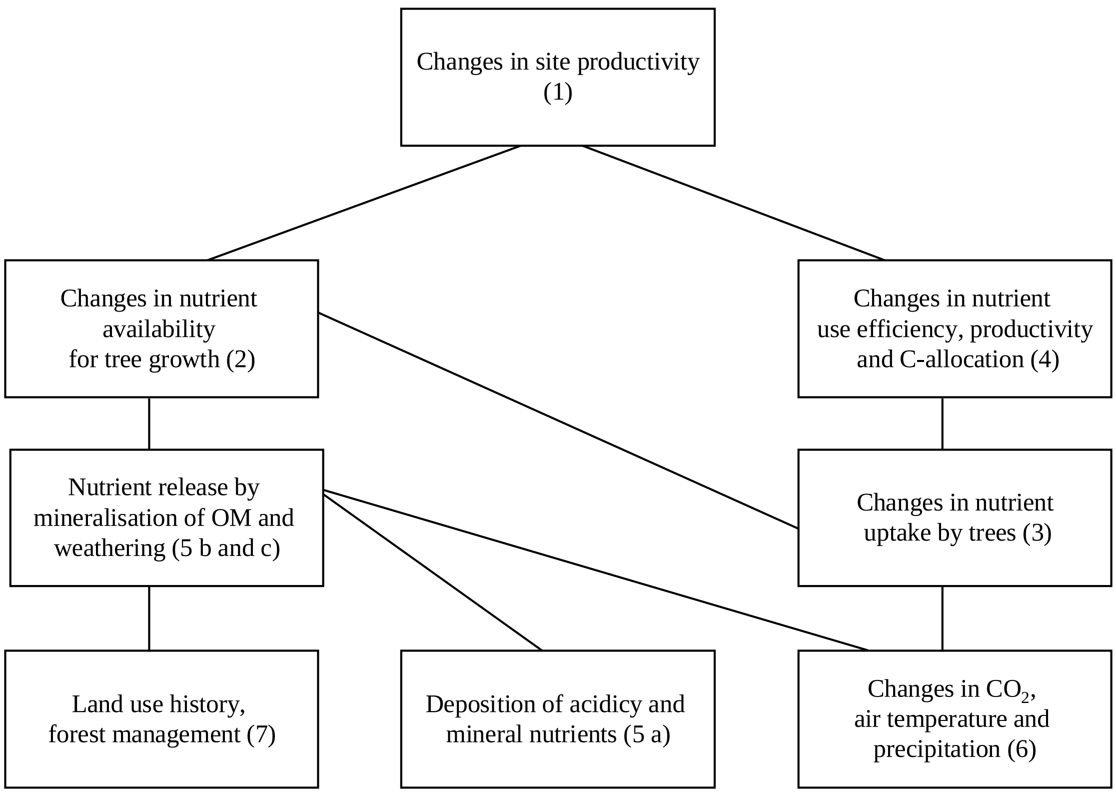

Figure 6.2. Schematic presentation of working hypotheses.

The overall aims can be approached by testing a number of specific hypotheses:

- changes in site productivity can be accounted for by trends in temporal and spatial patterns of
  - anthropogenic nitrogen deposition interacting with different site conditions,
  - soil inherent nitrogen availability
  - availability of water as determined by soil water storing capacity, precipitation and evaporation regime,
  - nutritional status of the stand;

- changes in nitrogen availability is not sufficient to explain changes in site productivity (CO_2 is important);
- changes in NPP and volume growth are highly correlated;
- nutrient losses are important for the magnitude of growth changes;
- management is a minor factor (in most cases);
- increases in growth will continue to 2100 as CO_2 concentration increases, with temperature increases also playing an important role;
- precipitation changes in the future will modify growth trends significantly, if we believe current climate change scenarios;
- all tree species will benefit.

6.6 RESEARCH NEEDS

The following research needs have been identified from the overall aims and hypotheses:

- identification of temporal changes in nutrient concentrations in foliage for sites with long-term series of foliage analysis, and (where available identification of temporal changes in the chemistry of the rooted top soil);
- identification of temporal changes in local climate conditions;
- identification of the sensitivity of increment variations to temporal climate variations;
- comparison of the interrelationships between the various factors and growth on the different study sites including results of analysis of selected nitrogen deposition and acidification gradients as well as climatic gradients on different scales:
    - validation of data,
    - identification of patterns,
    - characterisation of patterns;
- generalisation of the findings to specific site types or geographic areas;
- analysis of the long-term consequences for sustainability of observed growth changes of the European forests.

6.7 DATA NEEDS

The following information is desirable for each object to be included in the study:

Sample design of the investigated objects:

- sample unit
- number of trees per unit
- selection criteria (e.g. dominant trees) and exclusion criteria (e.g. severe injuries)

Site characteristics:

- geographic location
- elevation/altitude
- exposition, inclination
- aspect
- bedrock
- soil type (FAO classification is preferable)
- plant community
- water and nutrition regime

- climate (temperature, precipitation; time series are desirable) annually and during vegetation period (definition required!)
- history of land use (litter raking, grazing, former vegetation cover, others)
- liming and fertilisation
- special events (fire, insect damages, extreme climate events, others)
- atmospheric changes (atmospheric deposition, air chemistry, others)

Stand characteristics:

- species composition
- age or age structure
- vertical and horizontal structure
- stand density
- height (top height recommended)

Stand history:

- origin (natural, planted, if planted: spacing)
- weed control
- browsing
- intermediate treatments
- thinning (type, intensity)
- pruning

Tree characteristics:

- tree species
- age (for example cambial age at 1.3 m)
- breast height diameter
- height
- competition situation: social class, competition indices, development of height-diameter
- relationship
- crown characteristics: length, area, surface, defoliation
- damages (mechanical, biotic, fire)
- description of measurements
    a) Radial increment/basal area increment (measured on cross sections): Sampling height, number of discs, number of radii per disk and direction of radii on the disks as well as measurement techniques (equipment, preparation of the wood samples, moisture content etc.).
    b) Ring width (measured on cores): Number, height and direction of the cores, and measurement techniques (radiodensitometric measurements etc.).
    c) Height increment: Annual shoot length (by whorls), counting of rings at different height intervals, verification by ring count, method of interpolation between disks.
    d) Volume increment: Methods of calculating tree volume increment, description of time resolution of the data (annual, periodical) and of measurement techniques (equipment, preparation of the wood samples, moisture content etc.).

7 GENERAL DISCUSSION AND CONCLUSIONS

K.-E. Rehfuess; J. Prietzel and F. Andersson

Various studies carried out by different research groups prove clear evidence for a substantial recent increase of forest growth in many European forest regions (Chapter 2). A whole bunch of growth or site factors is described to also have changed in the recent past, as e.g. soil chemistry and stand nutrition, atmospheric CO_2 concentration, physical climate, and others (changed silviculture, etc.). Each of these factors can theoretically be responsible for or at least contribute to the observed growth changes. The rate of change of the different factors and also their relative impact on forest growth obviously vary for different regions and sites; their interrelationships are not yet elucidated even for the very few more sophisticated case studies which have been published. Probably a general attribution of the recent growth changes to the simultaneous change of one particular factor is not possible. Rather, it seems more reasonable to assume that for different sites changes of different factor constellations may have caused the temporal changes of growth patterns of forests.

According to the results summarised in Chapter 5, there exist significant, but regionally and seasonally varying temporal trends of temperature and precipitation during the past 100 years in Europe. Some case studies have produced clear observational evidence that acidification of forest soils due to various reasons has proceeded and that the nutritional status of forest stands has changed during past decades (Chapter 3). Chapter 4.1 demonstrates that elevated S and particularly N inputs (as compared with pre-industrial levels) will persist and will influence European forest ecosystems for a long while, but with widely differing intensities in the various forest regions. The general increase of CO_2 concentrations in the atmosphere will proceed and will affect the composition and the growth of forests in Europe both directly (fertilisation effect) and indirectly (greenhouse effect).

It is expected that fertilisation effects of increased CO_2 levels in the troposphere will show up mainly on those sites where growth is not – or no longer – limited by restricted supplies of nutrients (mainly N) and water (Chapter 4.2). The presentation of various modern models and their preliminary results convincingly demonstrates the potential value of this instrument for identifying possible causes of increased growth. There is some evidence that the temperature increase is of minor importance, whereas CO_2 fertilisation in interaction with improved N nutrition may be a more relevant driving force. The different models, however, still produce different and to some degree inconsistent or even contradictory results, and the interactions with changes in precipitation and in the supply with nutrients other than N or pollutants like photo-oxidants are not yet incorporated. Consequently, the models have to be further developed; this holds especially true concerning the regionalisation of results.

The site- or region-specific factor sets and their changes might be extremely complex for some sites (and comparably simple for others). However, the knowledge of the causes and driving factors for the changed forest growth in Europe is crucial for a better understanding and for the sustainable management of European forest ecosystems. Thus, the current deficit in knowledge concerning the site-specific interrelationships between recent changes in forest growth and stand nutrition, soil and air chemistry, physical climate, and management practices must be overcome (Chapter 6).

The multi-causal dimension of the issue "changed growth of European forests" requires an interdisciplinary and Europe-wide approach of research. Forest scientists experienced in the disciplines Forest Growth Assessment, Forest Nutrition, Forest Soil Science, Plant Physiology, Ecosystem Research and Modelling, as well as Physiological Modelling will have to co-operate in order to (i.) reveal, quantify, and parameterise the complex site-specific interrelationships between the various parameters influencing tree growth, (ii.) set up a regionalised concept concerning the spatial dimension of different factor constellations responsible for the observed recent changes in forest growth, and (iii.) predict whether and at which rate the current growth trend will be likely to persist at the different sites.

The proposed research project RECOGNITION consists of two different concepts of scientific perception (chapter 7). The first concept, the Correlative Approach, uses all the already existing and available data regarding forest growth, stand nutrition, soil chemistry, climate, and atmospheric deposition determined for a great variety of European forest sites. With appropriate statistical techniques, the temporal changes during the recent decades (*Historical Development Investigation*), as well as the present spatial pattern of these variables and their interrelationships (*Present State Analysis*) will be analysed. For the retrospective study of historical changes, control plots (but in addition also the manipulated plots) of long-term fertilisation and amelioration experiments seem most suitable. For the investigation of present spatial patterns, the data of the European Union Level II network – if they should be at least partly available – would constitute a promising data collective; enabling the participants to perform gradient analyses. The second concept, the Modelling Approach, comprises the utilisation of existing sophisticated models integrating various ecosystem levels (physiological level, tissue level, tree level, ecosystem level, region level). The adequate functioning and the validity of the models to simulate and predict real changes can be tested by a comparison of model results with observations from long-term fertilisation experiments. The Scandinavian fertilisation trials, which have been investigated with particular high intensity during the last years, seem to be an especially promising object of study for this purpose. On the other hand, the future development of forest growth, stand nutrition, and soil chemistry for a given deposition, climate, and atmospheric CO_2 concentration scenario can be forecasted for those sites. Using all information provided by the *Present State Analysis*, and for the particular stands studied in the *Historical Development Investigation*, improved models may produce forecasts which are valid for larger spatial units as biogeoclimatic zones, and/or areas with distinct levels of atmospheric N deposition. The comparison of the correlative and the modelling approach, as proposed in this paper, is unique in the world and seems to be adequate to the complex problem and promising valuable results.

Once the site-specific interrelations between the growth of three main forest tree species (*Picea abies, Pinus sylvestris, Fagus sylvatica*) and changes in soil fertility, climate, and management have been analysed and once the driving key variables have been detected and quantified, a regionalisation of the observed trends in forest growth, soil properties, and in forest nutrition may be possible, hopefully also a prediction of future growth trends with appropriate models. This knowledge will provide a basis for a sustainable forest management including site-adapted harvesting and forest regeneration techniques as well as fertilisation in order to prevent nutrient imbalances and to maintain site fertility and ecosystem stability.

In summary, the RECOGNITION project has the following aims, which can be attributed to three different levels. Project success concerning the aims summed up in a level of higher rank requires previous successful processing of the tasks in all levels of lower rank. Thus, the hierarchic system can also be considered as a working schedule.

Level 1: Implementation / improvement of adequate tools for the

- analysis of the relative importance of various growth-affecting factors
- development of more mechanistic growth models

Level 2: Prediction of effects of future changes of

- external environmental factors
- future forest management strategies

Level 3: Development of basis information for

- future types of site classification
- maintenance of sustainable forest management under changed or
- changing environmental conditions

concerning European forest ecosystems

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DEFINITIONS

(F. Andersson)

Biomass	Ecological analysis or estimations of available energy material or mineral nutrients require information on total amount of biomass or dry matter in kg or ton per unit area. It can be given per tree or stand and as total or by fractions such as stem, bark, branches leaves or needles or stump and roots.
Biomass productivity	The relation between total stand or stem production to leaf or needle biomass (as dry matter or carbon).
Growth	Change, usually increase, of diameter, basal area (1.3 m above ground), height, stem volume or stem or total biomass of a tree or stand.
Growth trends	Long-term site induced deviations from former site productivity.
Growth, current annual	Growth of a specific year.
Growth, mean annual	Mean growth over a longer period, usually the whole rotation period.
Nutrient productivity	The relation between total stand or stand production to nutrient content of leaf or needle biomass. Changing environmental conditions will result in changes in biomass and nutrient productivities indicating changes in the efficiency of utilizing the mineral nutrients.
Site	Totality of environmental conditions existing at a particular location.
Site productivity	Timber or biomass production potential per unit time of a site for a particular species or forest type.
Site quality	The ability of a site to produce stem volume or biomass. The site quality usually corresponds to the time during the stand development when the yearly mean growth culminates.
Stand	A population of trees growing together characterized by uniform age, tree composition etc.
Stand productivity	Growth or production of stem volume or biomass per unit area and time.
Sustainable productivity	A long-term ability of a site to maintain productivity in spite of stresses. Changes in stand growth need to be analyzed in relation to nutrient budgets of whole ecosystems including consideration of changes in nutrient pools of trees and soil as well as inputs (deposition, decomposition/mineralization of organic matter and weathering of primary minerals) as losses by leaching and harvest.
Tree nutritional status	A static property of a tree described by the concentration of mineral nutrients in the current year leaves (summer values) or needles, (usually winter values). Concentrations quotients of the different elements to nitrogen can also be used as well as other techniques as deviation from optimum (DOP) and graphic or vector analysis.
Yield	See Growth

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