The Role of Quality Assurance in the Spruce-Fir Forest Research Cooperative

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Abstract

Quality assurance is an integral part of the Forest Response Program providing administrators with data of defined and documented quality for the synthesis and integration of research results. The broad range of research conducted and the large number of projects participating in the Forest Response Program make the close coordination of activities important to ensure that the objectives are accomplished. Some of the quality assurance activities discussed include; the development of research protocols, the establishment of interlaboratory sample exchanges, and the review of project internal quality control procedures. The role of quality assurance in the Spruce - Fir Cooperative is described.

Introduction

The regulatory function of the U.S. Environmental Protection Agency (EPA) necessitates that all environmentally related data from research and monitoring projects it supports be of known and documented quality. Projects funded by the EPA provide information to decisionmakers formulating or changing current environmental policy and legislation (U.S. EPA 1986). Due to this highly visible role the EPA began developing guidelines for data collection in the late 1970's. The guidelines ensure that each facility generating data establishes procedures to document that the precision, accuracy, completeness, comparability, and representativeness of data satisfy the objectives defined by the projects it supports. Unknown data quality, lack of comparability, differing methodologies, and sample degradation due to delays in sample collection and analysis efforts are some of the problems that can be minimized if quality assurance is made an integral part of project and/or program design (U.S. EPA 1987).

The establishment of formalized quality assurance programs is still relatively new to the U.S. EPA. In 1984, the first mandate was issued by the Agency requiring that QA be incorporated into all environmental data collection activities (U.S. EPA 1986). This paper reviews the role of quality assurance in the Forest Response Program (FRP) which is funded in part by the U.S. EPA, in part by the USDA Forest Service, and in part by the foresty industry. It discusses, specifically, the implementation of quality assurance in the Spruce-Fir Research Cooperative (SFRC) and, in general, the coordination of quality assurance (QA) activities in the FRP.

Organization and Objectives

The Quality Assurance Management Staff, of the EPA's Office of Research and Development is responsible for the establishment and oversight of an agencywide QA program. They develop guidance materials and review the activities of QA programs while requiring the individual organizations set up mechanisms for assuring an effective QA process is in place (U.S. EPA 1986). Each EPA program office, laboratory, and regional office has personnel assigned to implement QA for every program and project it supports. The EPA's Environmental Research Laboratory, in Corvallis, Oregon, has oversight for QA in the FRP. They provide guidelines for achieving data quality and regularly evaluate the effectiveness of FRP QA activities (U.S. EPA 1985).

The FRP is organized into four research cooperatives covering the contiguous 48 states. Each cooperative works to evaluate the effect of air pollutants on their respective forest regions. This organization lead to the assignment of one QA Specialist at each cooperative. Figure 1 shows the direct line of QA administration from the EPA offices to the FRP.

Two other groups formed within the FRP support the research cooperatives; their data-gathering activities also require QA. The National Vegetation Survey (NVS), one of these groups, has many projects, each designed to contribute to one of the four cooperatives. These projects, therefore, receive QA review by the respective cooperative QA specialist. The other FRP support group is the Atmospheric Exposure Cooperative (AEC). The AEC, not shown in Figure 1, is funded entirely by the EPA and QA oversight is provided by the EPA's Environmental Monitoring Systems Laboratory in Research Triangle Park, NC.

The goal of QA is to provide data of known and documented quality for the evaluation of air pollutants effects on forest ecosystems. In order to accomplish this special demands for flexibility and innovation are placed on QA in the FRP. The combination of large numbers of projects, the broad scope of the research, and the wide distribution of research locations, which characterize the FRP, is unusual in EPA funded research programs. QA in the FRP, therefore, emphasizes methods testing and the development of research-oriented data quality evaluation. The general objectives to accomplish QA goals for the FRP are stated below:

1. Document data quality through qualitative and quantitative assessments;
2. Ensure comparability of data collection, observational information and/or analytical procedures within and among cooperatives, where appropriate, and
3. Examine, evaluate, and adjust research and QA activities to ensure compliance with standard or approved protocols and procedures (U.S. EPA 1987).

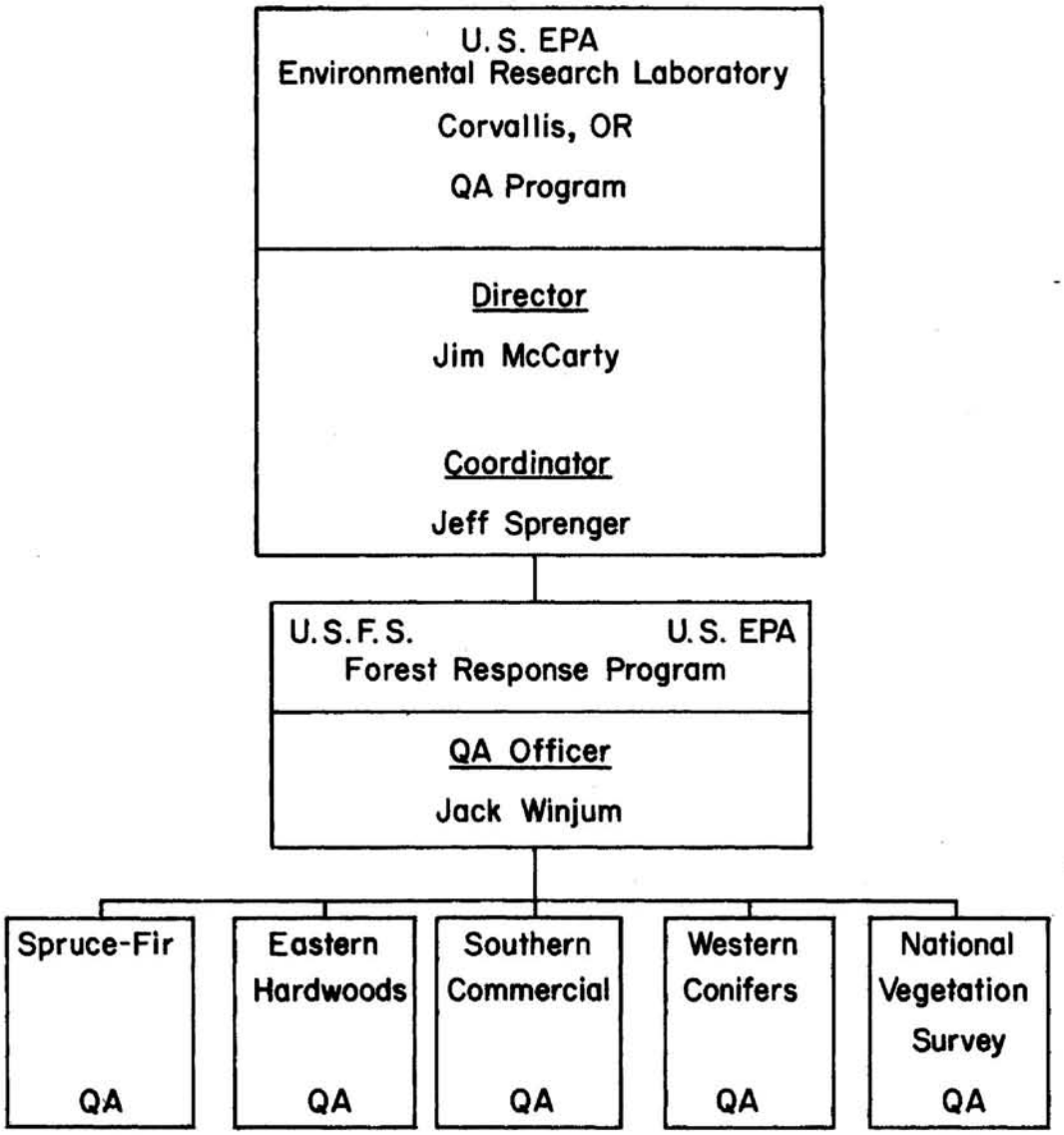

Figure 1.--The organization of the Forest Response Program quality assurance staff within the Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C.

Quality Assurance Implementation

Quality assurance is defined as a process for obtaining data of known quality (U.S. EPA 1986). How the process is applied is dependent on the research, testing, or monitoring goals. In the FRP cooperatives the process is implemented at three different levels; project internal, among the projects in a cooperative, and among the cooperatives of the FRP. It is important that the research administrators at each level determine the intensity of data quality control needed to achieve the goals set. If this is not the case then both time and money are wasted by either over or under-evaluating data quality.

Establishing and implementing quality assurance is, therefore, guided by the scientists and administrators, and it is their responsibility to provide data of known quality. QA staff work with the scientists and administrators and are charged with: providing the resources and materials to allow for the definition and documentation of data quality; developing methods to compare differences in equipment, analytical procedures, and measurement methods; and reviewing the processes developed to define data quality and making sure they comply with EPA guidelines.

Project QA

QA implementation in the SFRC begins at the project level. In compliance with the funding agreement, each project submits a detailed description of the methods used to define and document data quality. Successful QA implementation depends primarily on documentation, with the following objectives:

1. To demonstrate that data quality is monitored. For example, good laboratory practices may require that a conductivity meter be calibrated each time it is used. QA dictates that the analyst write down that it was calibrated, record the results, and note any indication that the meter was not functioning properly.

2. To assure accountability of the data, e.g. the data reported do represent analyses on the sample as submitted. Sample tracking is carried out to show that there are safeguards against sample mix-up.

3. To provide traceability of reported data. Each result reported should be easily traceable to the analyst, the method, the sample collected, and the condition of the instrument used.

4. To show that reasonable precautions are taken against data falsification. For example, computer programs used are write protected.

Documentation is essential to QA. It is not adequate to conduct checks on data quality, but the fact that they were conducted must be documented, as well as by whom, when, and with what results. Data integrity is necessary to good science, and many of the requirements of QA in the FRP are regular activities in the participating projects. But the level of documentation required is new. QA requires more work for the same amount of output. But an effective QA program means that the scientist not only knows the quality of the information generated but has the data to prove it. The FRP requires this level of documentation because of the potential use of the FRP assessments to alter existing air pollution regulation.

Due to the emphasis on research, as opposed to monitoring in the SFRC and the FRP, the QA Project Plan normally required at the initiation of projects is not adequate. Instead, the QA Project Plan is submitted as a draft and updated regularly as methods are refined and tested. It is also incorporated into the Work Plan to minimize documentation efforts on the part of the scientist.

The documentation submitted to QA staff at the initiation of a project includes; information on the experimental design and statistical analyses planned; the equipment/instrumentation used including calibration and maintenance activities; personnel and their training; sample collection, preparation, and analysis procedures; data quality objectives; and data mangement, including validation and verification methods. Perhaps the most important component of this documentation are the data quality objectives.

Data quality objectives describe the precision and accuracy of a specific measurement technique, analytical procedure, or observation considering the equipment used. For example, analysis of aluminum content for spruce foliage digestions on the atomic absorbtion spectrophotometer. Because the level of precision and accuracy attainable is not necessarily known at the beginning of a project, this information is provided as estimates. As the project proceeds, control data, in the form of checks on duplicates, spikes, reference samples or remeasurements allows the scientist to refine the estimates into realistic objectives. Data quality objectives are then used throughout the duration of the project to monitor the quality of the information or data generated.

To evaluate whether the documentation is thorough and actually represents project activities audits are conducted. There are several ways they are carried out. Audits are conducted on every aspect of the research from sample collection through analysis and data management. These are called technical systems audits; they provide the quality assurance staff with a good basis from which project compliance may be assessed. Another method is to review, in detail, data quality checks, for example, data from certified and in-house reference standards on analytical equipment, or plot remeasurement data on the field work. These are called performance audits.

Following the increased documentation required, audits are one of the least popular QA activities with the participating scientists. At most facilities (unless one is dealing with a certified laboratory which is audited annually) audits are an entirely new phenomena.

Unpopular though they may be, audits have proven essential to keeping up with changes in both the focus of research, as well as changes in procedures and personnel in the projects.

Cooperative QA

The implementation of quality assurance within the SFRC is carried out following the research priorities for this cooperative. Two basic approaches are used to study the effects of atmospheric pollutants in the SFRC: (1) epidemiological studies are used to identify spatial or temporal patterns in forest condition which may be related to natural or anthropogenic impacts; and (2) physiological/ecological research, which study the effects of environmental conditions on the health of trees or stands. The research includes controlled laboratory, greenhouse, and field studies which expose tree species to various pollutants, alone and in combination. Scientists observe such phenomena as; changes in carbon allocation, metal mobilization and nutrient leaching in soils, foliar leaching, altered incidence of winter injury, changes in regeneration and reproduction, and increased susceptibility to insects and pathogens.

Many of the epidemiological studies in the Cooperative are conducted on the six intensive field study areas located in the Appalachian Mountains. On these sites insect and pathogen surveys, stand inventories, soil and foliar chemical and physical properties, and disturbance histories are evaluated. QA staff work with the scientists to ensure that comparable methods are used. Joint training sessions and workshops are commonly employed.

In the physiological research within the Cooperative project goals differ widely and QA activities are directed at ensuring consistency in the methods used. Methodology testing, equipment testing, and workshops are the major activities of the QA staff. Independent equipment testing has been organized for all gaseous pollutant analyzers under the guidelines described in the EPA's Handbook for Air Pollution Measurement Systems. Analyzers are independently calibrated with equipment certified by the EPA. All analyzers used in the Cooperative are scheduled for calibration at the initiation and shortly prior to conclusion of the exposure regime. This check verifies the calibration and quality control procedures at the research site. If problems are noted corrective measures are recommended.

Methodology testing is established by QA staff through initiatives funded to evaluate how differences in procedures or equipment can affect research addressing the same mechanism or studying the same aspect of epidemiology. This activity is an especially important part of QA in the FRP because of the emphasis on developing or adapting research methods, as compared to the emphasis on established monitoring procedures in other EPA programs. Several initiatives are currently underway including, cold tolerance testing, wet versus dry analysis of soils, automatic injection of aliquots into a gas chromatograph in comparison to manual injection. This area needs to be expanded if QA is to provide information needed for the integration of research results at the conclusion of the Program. A number of other initiatives are currently being considered for funding in 1988.

Communication between the scientists in the SFRC is important if the Cooperative is to achieve its objectives. The QA effort enhances communication by organizing workshops and meetings designed to develop common experimental protocols or adapt instrumentation and methods to test specific hypotheses. For example, QA workshops and meetings have been organized successfully to coordinate projects working independently on one site and those working together on different sites, to develop tests of different procedures used to study the same hypothesis, and to encourage the exchange of material between projects and thereby increase the information gathered from each effort. Joint training sessions have a similar function and have been used effectively with the field crews collecting vegetation and insect and pathogen data on the six intensive research sites in the Cooperative. This training is especially important because some of the information collected in these projects is subjective, i.e. crown vigor, percent needle loss, and the identification of insect or pathogen damage. This activity, in turn, reduces variability in the results by ensuring all personnel are trained in the same manner and provides the basis for quantifying repeated measurement error in and between field crews.

Forest Response Program QA

Coordinating QA activities is the focus of the Program-level implementation. Coordination requires the greatest effort because of the large number of projects and their diverse locations. Some of the QA activities implemented at the Program-level to help coordinate QA include; the development of common research procedures, the establishment of an interlaboratory testing, and the development of a tracking system.

The development of standard operating procedures for laboratory analytical techniques, field measurements, exposure systems, physiological measurements, and data management have been compiled through workshops with the participating scientists, into a series of Methods Manuals. The standard operating procedures are common research methods formed through a consensus among FRP scientists on the recommended technique for measuring, analyzing, or observing a specified variable. The purpose of these manuals is to:

1. Provide common research methods to aid the synthesis and integration of results for assessment purposes;

2. Provide standardized QA techniques within the research protocols to allow for the evaluation of data quality; and

3. Prevent duplication of documentation efforts among investigators using these protocols.

The Methods Manuals have been especially useful in coordinating activities at the six intensive research sites and in the exposure research studies in the SFRC. However, the development and use

of standard operating procedures does not have as large a role in the FRP it has in other programs because of the emphasis on experimentation and methods development in this Program.

Interlaboratory testing is another aspect of QA organized at the Program-level. The goals of interlaboratory testing are; to provide a measure of the precision and accuracy of analytical methods run routinely by different laboratories, to estimate the precision and accuracy between laboratories, and to identify weak methodology or training problems. Standard samples have been developed for foliage and soils, and are being developed for rainwater, soil solutions, and stem tissue. Samples from the homogenized standard are distributed to the scientists and the results from their analytical procedures are sent back to the QA staff for evaluation.

A tracking system for all projects in the FRP is currently being developed (Steve Byrne, pers. comm.). The tracking system will contain detailed information on all projects, e.g.: type of study, variables measured or observed, equipment and instrumentation used, and number of samples or observations. This system will provide QA staff and other FRP participants with a convenient way to access needed project information. For example, QA staff will use the tracking system primarily to determine whom to distribute standard samples for interlaboratory analysis or the number of projects using the same type of equipment so that comparability studies can be carried out.

Conclusions

Effective control of data quality within the projects, and consistency of data quality among the projects, is important to the success of QA implementation. The ongoing establishment of interlaboratory testing, equipment testing, comparability studies, and other QA activities, further enhance FRP QA. Its implementation in forestry research, however, is relatively new and time is needed to develop a strong QA component in the FRP. QA was established well after the FRP began, limiting its scope. Ideally, QA should be a part of the initial planning stages of a program and direct the type of information provided in the objectives which guide the administrators.

Every quality assurance program must have a set of objectives which are clearly stated and supported by both management and staff (Garfield 1984). The objectives of the Forest Response Program provide general statements of the overall goals. These, in turn, are interpreted in the Cooperative plans into a sequence of tasks which must be accomplished to meet the goals for the ecosystem of study. The tasks are scientific approaches, which do not include statements on the quality of data needed by policymakers for creating new or altering existing legislation. The lack of detailed qualitative, not to mention quantitative, statements of data quality has hindered the establishment of QA within this Program. It focuses QA activities on the projects instead of the program goals, when it is the Program goals which should determine the intensity of QA implementation in the projects.

Both the late initiation of QA in the FRP and the lack of more specific data quality objectives have caused problems for the QA staff. But the strong support give the QA staff by the cooperative administrators and the participating scientists have helped the QA staff to minimize these problems. QA is involved in developing and adapting methods as much as the projects are in the FRP. Its implementaiton is becoming more effective with time. The successful application of QA concepts, which are widely used in industry, in analytical laboratories and in monitoring programs will determine the role it will have in future programs.

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Seed and Seedlings for the Spruce-Fir Research Cooperative

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Introduction

We provide seed or seedlings of known geographic origin to investigators in the size, quantity, time, pot, and/or physiological condition necessary to optimize experiments. Except for unusual circumstances, all seed and seedlings are handled under uniform environmental protocols.

When investigators request specific seed or plant material, the project staff makes every attempt to collect, purchase, or acquire seed of the three research species (red spruce, balsam fir, or fraser fir) to fill requests. The goal of the project is to have available 10 individual tree seed collections from each of 20 sites throughout the natural range of each species. In addition, six specific sites are being sampled: the so called "intensive" study areas of Mt. Mitchell, North Carolina; Mt. Rogers, Virginia; Clingmans Dome, Tennessee/North Carolina; Mt. Moosilauke, New Hampshire; Whiteface Mt., New York; and the commercial forests near Howland, Maine. Collections from the intensive sites are more than 50 percent completed and the rangewide species collections are approximately 30 percent completed. We are still waiting for a bumper cone crop rangewide for each species to fill out the collections.

Individual tree collections and provenance collections since 1985 are extracted, tested, and stored by Dr. Frank Bonner, USDA Forest Service, Starkville, Mississippi. Pre-1985 collections were extracted by the supplier and are stored at the Forestry Sciences Laboratory, Durham, New Hampshire, until requested or needed.

Quality Control

Seed Quantity and Quality

Evidence is accumulating for red spruce that fewer viable seeds per cone are produced the higher in elevation of source collection. Hoover (1904) found viability at approximately 5 percent for high-elevation black spruce in New Hampshire. Bonner (personal communication) has found from our collection that the percentage of viable red spruce seeds from high elevation ranges from 2 to 5 percent. Bonner's data are from cones collected from poor cone crop years and poor viability may be due in part to a high percentage of self seeds or to poor pollination. We need to gather information from a bumper cone crop before a general statement of low seed set and viability from high-elevation red spruce can be made. In any event, the consequences to the program are that we pay a quantity and quality price in red spruce seed as we collect at higher elevations. Depending on future research needs for quality and quantity seed, we may have to use lower elevation collections to meet these requirements.

Growing Media

To ensure that all investigators receive seedlings that are as similar as possible, we grow the seedlings in standard media. The following mix works well:

Quantity	Description
1 bag	6 cubic feet "Mr. Pete" peat moss
2 bags	22-pound bags of "Terra Lite" vermiculite (W.R. Grace)
1512 grams	High Mg Lime (Agway)
2268 grams	Osmocote 18-6-12 (8-9 month)
453.6 grams	Aqua-Gro "G" Granular
38 grams	Micronutrients (Peters)
269 grams	0:45:0 fertilizer (Agway)

The ingredients are mixed for 10 minutes in a 1-cubic-yard soil mixer prior to use.

Containers for Seeding

All seedings are grown the first year in either 1½-by 1½-by 8-inch paper tubes or 1½-by 8-inch "Ray Leach conetainer" plastic tubes. The paper tubes have a larger media capacity and allow for larger 1-0 seedling growth.

Seeds sown in the fall (November) are grown in paper tubes. Seeds sown in the winter (February) are usually grown in "conetainers." These "conetainers" are for back-up, for late requests, and for transplanting in the State of New Hampshire Nursery. There is a trade off between the containers. The paper tubes allow larger seedlings and better moisture retention but are subject to more fungus problems. The "conetainer" seedlings are easier to transplant and have fewer disease problems, but they are smaller and tend to have end-of-season moisture retention problems.

Containers for Transplanting

We will transplant seedlings into any type container that investgators need for their research. However, for comparison purposes we have chosen two pots as standards; the 4 by 4 by 14-inch citro pots and the 6 by 6 by 16-inch citro pots. These pots are very economical on space yet have enough media volume for good seedling development. Because the containers are high, they require side support or need to be partially buried.

Environmental Conditions

Seedlings are grown in their respective containers on greenhouse benches under constant 70° F, 12-hour (5 p.m. to 5 a.m.) supplemental lighting, and automatic watering. The water protocol is as follows: 16 minutes of water between 10:00 a.m. and 12 noon (system is shut off on overcast days and dry spots are watered by hand as needed).

After 16 weeks, seedlings are fertilized once a month through early July with 15:15:15 fertilizer at 24 ounce dry weight per 4 gallons of water and applied with a Hozon at the rate of 1:15.

Seedlings receive fungicide on a weekly rotation of THIRAM (2½ tablespoons per gallon), BENLATE (½ tablespoon per gallon) and CAPTAN (2½ tablespoons per gallon) and are treated with insecticide (MALATHION) if needed.

Shade

All first-year and potted seedlings are moved to lath houses by June 1. The trees receive approximately 50 percent sunlight, fungicides and insecticides, and water as needed. The seedlings receive no supplemental fertilization, i.e., only the residual from the soil mix. This prepares the seedlings to be less succulent as they enter the fall dormant season.

Maintenance and Repair of Equipment

The greenhouse and headhouse are protected by a 24-hour alarm and call system to ensure that the facilities will have minimum "down time". The system monitors high and low temperatures in each of the two glass houses, and checks for furnace failure, electrical failure, and fire. Electrical service is assured to the complex with an automatically controlled propane fueled 60-kw electrical generator. Also, spare furnace parts are on hand to ensure minimum furnace down time. Items on hand include two complete circulator pumps and motors, fuel pump, relief valves, electric motors, and electrical items. We do not stock major plumbing parts, such as pipe, fittings, or fin tubes. We do stock extra greenhouse glass, timers, watering controls, and lighting elements and bulbs.

Lessons and Information Learned

Growth of Red Spruce

We have been growing red spruce from seed collected in Nova Scotia, Maine, and New Hampshire in 1½ by 1½ by 8-inch paper tubes. Our 1986 seedlings averaged 25 cm by mid September with no visual symptoms of stress caused by container size. There were significant differences among sources for total height indicating there are juvenile genetic differences among sources. Also, there were differences in height of seedlings within sources indicating there are genetic differences within sources. Red spruce seems to have ample genetic differences within and among sources to possibly accommodate environmental and anthropogenic stress.

Red spruce seedlings seem to be quite resistant to environmental stresses when they are supplied with adequate fertilization and moisture. Before we could move the 1986 seedlings from the greenhouse to a shade house, the temperature reached over 95°F for three days in a row. The high temperatures plus movement to a shade house did not initiate bud set. The seedlings continued to grow until late September with no supplemental fertilization.

Seedlings stored outside in pots or trays need to be protected from winter desiccation and small mammals. Bailed hay stacked around the storage area protects the seedlings from wind and acts as a trap for blowing snow. The trapped snow acts as additional insulation. Approved rodent baits (HAVOC) need to be applied and monitored throughout the winter to ensure that the storage area is free of feeding and nesting rodents.

Growth of Firs

Our limited experience with container-grown firs has taught us that Fraser fir is easier to grow than balsam fir because it seems to be more tolerant to variations in moisture and temperature though we have no hard quantitative data to back-up our observations. During the second season of production, we were able to grow larger and more uniform seedlings from the same seed source with less fungus problems by reducing the duration of watering to the present red spruce water protocol.

Rooting of Red Spruce Cuttings

In 1986, we tried to root 2- to 4-inch cuttings from the middle of the crown of 10 31-year-old red spruce in the following three media; (1) 100 percent perlite, (2) 75 percent perlite-25 percent ground sphagnum, and (3) 50 percent perlite-50 percent ground sphagnum. All media were crossed with three treatments, dip in Hormodin 3, dip in 25,000 ppm NPIBA (2½ percent), or no treatment (control). The cuttings had under-bed heat, mist for 5 seconds every 5 minutes, and continuous lighting. We graded the cuttings by diameter, the largest in block I to the smallest in block IV. Results ranged from no root callus for some trees to 40 percent root formation for one tree in block I with no treatment and in the 3:1 perlite-ground sphagnum media. The same tree rooted 30 percent in the same block with no treatment and in the 1:1 perlite-ground sphagnum media. We feel we can improve our rooting percentage by selecting larger diameter cuttings with larger buds and needles. However, we also feel we will probably get very little rooting with cuttings from some physiologically mature trees. Rooting of plant material from high-elevation trees seems to be an alternative to waiting for a high-quality and high-quantity seed crop. Hopefully, cutting from mature trees will root well enough to make studies practical.

Conclusions

1. The project has developed protocols to produce quality spruce-fir seedlings for investigators.
2. The project is obtaining seed of known origin for use in spruce-fir research studies.
3. Cuttings from some mature red spruce trees will root in a ground sphagnum/perlite rooting medium.
4. Rooting of cuttings of high-elevation red spruce may be the alternative to poor quality and quantity seed crops at these elevations.
5. Facilities and equipment need a quality monitoring program with proper replacement parts and back-up systems to ensure quality seedling production.

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Modeling Activities Within the Spruce-Fir Research Cooperative

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Abstract

The Spruce-Fir Research Cooperative is actively involved in a diversity of modeling approaches to address the effects of atmospheric deposition on the spruce-fir forests of the Eastern United States. Initially, a conceptual model was developed to assist in the research planning stages of the cooperative. Subsequently, efforts have been focused on stand level modeling with FIBER, a highly empirical model, and FORET, a more mechanistically based, ecological model. These will be used for analysis of temporal/spatial variability and alternative pollution scenarios. Recently, an individual tree, process based modeling approach has been initiated that will be instrumental in synthesizing and integrating the dose-response, mechanistic research that is being conducted by the principal investigators.

Introduction

Recently, considerable attention has been focused on the decline of the red spruce--fir forest types in the Eastern United States. In the high-elevation forests of the Northeast, for instance, declines have been documented by Scott et al. (1984) on Whiteface Mountain, New York, and Vogelmann et al. (1985) on Camels Hump, Vermont. Similarly, declines have been reported in the spruce-fir forests of the Southeast by Bruck (1984) on Mt. Mitchell, North Carolina, and Adams et al. (1985) in the mid-Appalachian forests. Although considerable mechanistic research is being conducted to determine the causal factors, both natural and anthropogenic, the role that atmospheric deposition plays is unanswered. Thus, the Spruce-Fir Research Cooperative (SFRC) has been developed under the Forest Response Program (FRP) of the National Acid Precipitation Assessment Program (NAPAP) to provide information on the response of red spruce--fir forests to atmospheric deposition. The SFRC has been addressing the following three broad policy questions.

1. Is there a significant problem of forest damage in North America that might be caused by acidic deposition, alone or in combination with other pollutants?
2. If so, what is the causal relationship between acid deposition alone or in combination with other pollutants and forest damage in North America?
3. If there is a causal relationship, what is the dose-response relationship between acidic deposition, alone or in combination with other pollutants and forest damage in North America?

Within the SFRC, modeling will be used in a variety of ways to help address these issues.

Objectives

The modeling effort within the SFRC will be focused on the following objectives:

Objective 1 - To synthesize and integrate the current state of knowledge of red spruce--fir forests in the Eastern United States and, thus, aid communication among interdisciplinary scientists and interagency policy makers.

Objective 2 - To formulate a model that can be used as a research planning tool in developing and testing new hypotheses for study by cooperative scientists and in redefining research direction for cooperative management.

Objective 3 - To estimate the dose-response effects of atmospheric pollutants on red spruce--fir trees and stands.

Objective 4 - To develop a regional red spruce--fir model for the Eastern United States.

Objective 5 - Perform and interpret pollution scenario analysis for decisionmakers in an attempt to evaluate alternative strategies for controlling atmospheric deposition.

The SFRC will be solely responsible for Objectives 1, 2, and 3, while it will cooperate with the Synthesis and Integration Project (EPA - Corvallis, Oregon) on Objectives 4 and 5.

Modeling Characteristics

In the development of a multi-objective, complex modeling effort, it is desirable to specify various characteristics that the modeling approach should adhere to in order to formulate a useful, flexible system capable of responding to future demands and alterations. Several of these characteristics that will be used in our models are described below.

1. The design, development, and implementation of the models should be conducted by a multi-discipline team consisting of modelers, scientists, and decisionmakers.
2. The models should represent a synthesis and integration of the current state of scientific knowledge.
3. The modeling architecture should be of a modular design so that future alterations could be easily accomplished when new research results become available. To further facilitate modification, a structured programming style should be used throughout the computer simulators.
4. In order to increase interaction among other interested agencies and organizations, the simulators should be written in a standard, portable computer language using as few systems dependencies as possible.
5. An attempt should be made to use the simplest modeling formulations possible that will produce the desired output. This will increase understanding and produce additional interaction leading to future modifications.
6. The models should be implemented in an interactive manner and possess user-friendly properties. Graphic capabilities should lead to a "dynamic" modeling approach represented by temporal "snapshots" of the red spruce--fir forests under various atmospheric deposition scenarios.

7. The models should strive to be explicit in treating the uncertainty incorporated in the system.
8. To facilitate model use, future development, and modification, well-documented model descriptions and user guides should be formulated.

Strategy

The development of a model to satisfy the stated objectives is extremely difficult to achieve since the basic phenomenon of tree growth and stand dynamics is poorly understood in natural red spruce--fir ecosystems as is the impact and pathways for physiological mechanisms of pollution damage. Thus, the SFRC has developed a modeling research strategy that will encourage a maximum of scientific creativity within the confines of specific objectives and allow for interaction among scientists within the cooperative, between other FRP components and other national and international organizations. The structural framework for the modeling approach is illustrated in Figure 1.

A.E.A. Model

The SFRC initiated efforts to formulate its research strategy by contracting with Adaptive Environmental Assessments, Inc. (A.E.A.), a Toronto, Canada, based consulting service, to develop a set of rational, defensible research recommendations based on the combined expertise and perspectives of research scientists, managers, and policy makers concerned with the red spruce--fir forest resource.

The specific objectives of the project were to:
1. develop a rational, defensible research program for assessing and understanding the effects of atmospheric deposition on the spruce-fir forests of the Eastern United States.
2. develop a common understanding of the state of knowledge of spruce-fir decline and the possible role of atmospheric deposition, and
3. develop a prototype model of atmospheric deposition effects on spruce-fir forests.

The project objectives were met through a series of scoping, workshop, and technical meetings from September 1985 to January 1986 including 38 participants.

A conceptual model was developed that consisted of a set of natural and anthropogenic stresses that influence the physiological processes and, in turn, are manifested in changes in tree growth, yield, mortality, and decline symptoms (McNamee et al. 1986). The model was further defined by specifying the valued ecosystem components that are ultimately influenced by the stresses. These consisted of (1) growth and yield variables (stem density, basal area, volume), which are appropriate for commercial stands, and (2) esthetic attributes (leaf area index, foliage color, species composition, percent dead biomass, genetic variation), which are of more interest in the recreational, high-elevation forests.

The conceptual model was also used as the framework for developing a distant-independent computer simulation model of a red spruce--fir stand that operates on an annual time step for outputs and a weekly time step for calculating stresses on physiological processes. Workshop participants developed functional relationships for the model processes based on published and unpublished research and professional judgment. Instead of developing a stand model upon which to base the stress components, we used the existing FIBER model (Solomon et al. 1986) to simulate red spruce--fir stand development. This is an empirically based model that uses a two-stage matrix projection technique to simulate growth, mortality, and regeneration.

The major function(s) of the conceptual and simulation models are to synthesize knowledge and aid communications (Objective 1) and for use as a research planning tool (Objective 2). Since current understanding of the effects of the stresses on the dynamics of spruce-fir forests is poor and the required data is too intensive for parameterization, the predictions from the simulator cannot be viewed with confidence. However, it does serve as a prototype model that has been useful within the cooperative.[1]

FIBER Model

Background. FIBER is a two-stage matrix model used for predict growth and yield of even-aged and multi-aged spruce-fir, mixedwood, and northern hardwood stands in the northeastern United States. (Solomon et al. 1986, 1987). One stage of the model consists of regression equations relating transition probabilities for 0-, 1-, and 2-inch diameter growth in 5 years to stand basal area, tree diameter, and proportion of hardwoods. In the other stage, these probabilities are used in projection matrices that predict the stand diameter distribution over time. In addition, equations were developed to predict ingrowth of each species into the smallest allowable diameter class (5 inches) as a function of stand basal area, proportion of hardwoods, and proportion of that species in the stand. The model was calibrated from three data sets that consisted of 359 permanent plots in a softwood forest (Penobscot Experimental Forest, Bradley, ME), 48 plots in an uneven-aged northern hardwood forest (Bartlett Experimental Forest, Barlett, NH) and over 2,500 growth plots from independent sources in northern Maine, New Hampshire, northern New York, and Vermont.

FIBER allows the user to simulate the effects of several management practices and silvicultural treatments over a range of stand densities, harvest intervals, species compositions, and sites. Stands can be managed either by stating the allowable stocking level (basal area, cubic volume) or the time interval to thinning. Thinning can be achieved by specifying the stocking level desired or by using B lines in stocking charts. Thinning options include thinning from above, thinning from below, thinning along a q-line, removal of trees from any diameter class, or thinning uniformly across all diameter classes.

[1]For more information on the A.E.A. model, see McNamee, Peter; Jones, Michael L.; Greig, Lorne A.; Webb, Timothy M., "Research Planning for the Spruce-Fir Research Cooperative" in the proceedings of this symposium.

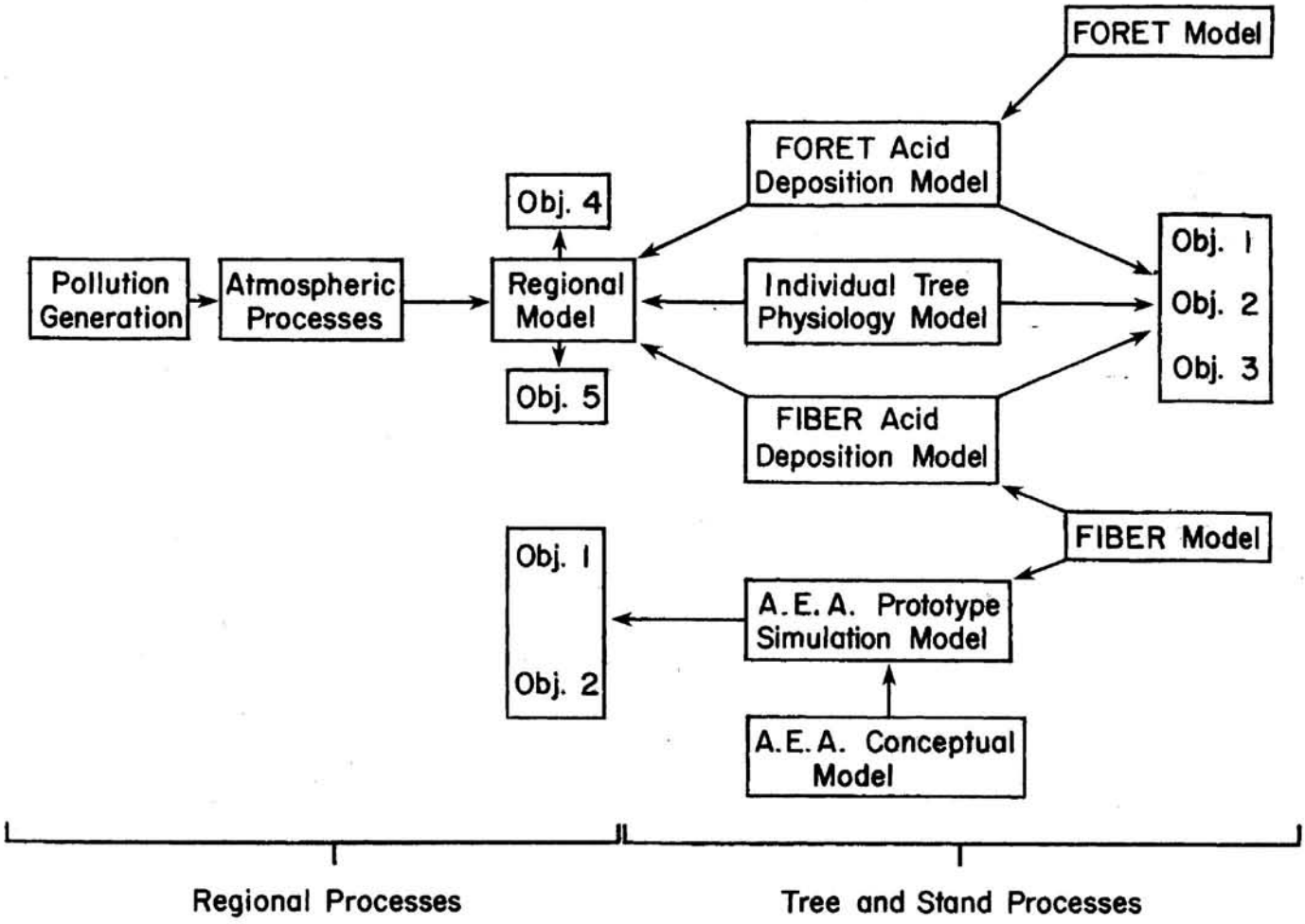

Figure 1.--Structural framework for the modeling approach in the Spruce-Fir Research Cooperative.

Proposed Work. FIBER will be used by Dr. Dale Solomon, USDA Forest Service, Orono, Maine, to address several issues in the SFRC. Activity is initially focused on analyzing the temporal and spatial variability of growth and mortality within the spruce-fir forest through application and modification of the FIBER model. Currently, FIBER predicts stand dynamics subject to ambient conditions upon which the model was parameterized that included low pollution levels (pre 1965 data) and high pollution levels (post 1965 data). Hence, the data set will be partitioned into low and high pollution segments and then the model will be reparameterized. Optimistically, this will lead to estimation of changes in forest condition and lead to the separation of natural and anthropogenic stresses on spruce-fir forests.

In addition, FIBER will be fitted to the spruce-fir plot data that is being collected at the six SFRC intensive sites. This will further test the reliability of this modeling approach over a larger

geographical area and shed insight into how the northern and southern red spruce--fir growth components may differ. Moreover, since this data will consist of soil, insect, and pathogen information as well as detailed vegetation measurements, the regression equations can be modified to incorporate these effects.

It is desirable in any prediction system to estimate the degree of reliability in the estimates by means of confidence intervals. Merely stating a point estimate will not suffice. Recently, considerable attention has been focussed on error propagation and variance estimation in growth and yield models (Gertner and Dzialowy 1984, Reynolds 1984, Mowrer and Frayer 1986, Gertner 1987, Gregoire 1987). Hence, effort will be given to determining a feasible technique for confidence interval estimation in a matrix projection model.

Additional effort will be given to evaluating the influence of stress on the temporal and spatial variability of tree growth and mortality within FIBER using changes in foliar conditions. This is of vital concern to the SFRC since the foliage is the initial point of contact between the pollutant and the tree. Previously, Hayslett and Solomon (1983) developed a matrix model to predict the annual foliage growth of balsam fir. This structure will be further developed and applied to red spruce in expressing the relationships between the influence of external stress and foliage production. The model predicts foliage biomass by age class of needles as a function of (1) foliage biomass production in each age class, (2) the photosynthetic efficiency of the foliage age class, and (3) the proportion of foliage that is retained in each age class. The SFRC is supporting research on three hypothesized mechanisms that may potentially be affected by atmospheric deposition and are directly responsible for foliage biomass. These are foliar nutrient leaching, alterations in carbon production and allocation, and winter injury. Dose response functions could be developed to relate foliage biomass production, photosynthetic efficiency, and foliage retention to various levels of atmospheric deposition. Analytical procedures, such as the Weibull modeling techniques used in the National Crop Loss Assessment Network (Rawlings and Cure 1985), will be investigated for applicability.

FORET Model

Background. FORET (Shugart and West 1979) is a simulation model originally developed for predicting forest dynamics in mixed-aged, mixed-species stands in east Tennessee. It is based on a modification of the JABOWA model (Botkin et al. 1972), which was originally conceived and parameterized using the Hubbard Brook Ecosystem Study database.

The FORET model is an example of a spatial gap model (Shugart 1984) that simulates annual forest dynamics on a small plot (1/12 hectare) by calculating tree growth, sapling ingrowth (from seeds and sprouts), and mortality based on stochastic processes. The model attempts to represent dynamic phenomena by parameterizing general equations based on physiology, morphology, and forestry principles. Unlike empirically based models, FORET does not require large data sets for parameterization and, thus, data could be reserved for independent validations of the model. Currently, the FORET model has been parameterized, modified, and studied for pollution effects (West et al. 1980), nutrient retention properties (Weinstein et al. 1982), landscape dynamics (Weinstein and Shugart 1983) and spruce-fir stand dynamics (Busing 1985).

Proposed Work. Initial efforts are being focused by Dr. Lynn Maguire, Duke University, on parameterizing FORET to the three southern intensive sites currently being surveyed. If promising results are obtained, the model will be fitted to the northern intensive sites which will allow comparisons between northern and southern red spruce--fir forests. In addition, a comparison will be performed between the FORET and FIBER models to assess the strengths and weaknesses of both modeling approaches. It is anticipated that FIBER will be of greater value in predicting while FORET will be more applicable for research planning/hypothesis testing purposes.

The effects of air pollution on red spruce--fir forest dynamics will be incorporated by modification of the growth and mortality functions to reflect physiological processes. Interaction with SFRC principal investigators will yield knowledge of the required physiological processes.

Individual Tree Model

An individual tree, process model will be developed for red spruce based on the theoretical modeling efforts of Dr. David Ford, University of Washington. The process model will have parameters that are biologically meaningful, and, hence, will be useful in addressing policy questions 2 and 3 pertaining to causal factors and dose-response estimation. The three major components of the model--carbon allocation, water balance, and nutrient uptake--will consist of a system of differential equations whose parameters will be estimated from the data generated by the mechanistic studies conducted by the SFRC principal investigators.

Other Modeling Efforts

Several modeling efforts that are not sponsored by the SFRC are of interest and may lead to valuable results that could be utilized in the cooperative's models. For instance, an individual tree physiological model is being developed by Dr. David Weinstein, Cornell University, under the project "Response of Plants to Integrated Stress" funded by the Electric Power Research Institute. The objective is to explain the relationship between plant, soil and litter and the effects of ozone and simulated acid rain. The model will be based on the experimental results obtained in an open-top chamber study focusing on the effects of ozone and acid rain on sapling trees (1 to 1.5 m tall). It will yield a simulation model for predicting photosynthesis, carbon allocation, soil and plant moisture stress, nutrient cycling, canopy leaching and soil solution chemistry subjected to ozone and acid rain. The components of the model will emphasize theoretical aspects and will not be primarily regression functions.

Recently, the International Institute for Applied Systems Analysis

(IIASA) in Laxenburg, Austria, has made considerable research contributions to the problem of acid deposition in forest resources. The RAINS (Regional Acidification Information and Simulation) model developed by IIASA provides the decision maker with a tool for evaluating alternative energey scenarios in Europe (Hordijk 1985) by using an optimization algorithm. The four submodels currently available deal with sulphur emissions, sulfur transport, forest soil acidification, and lake acidity (Alcamo et al. 1985). In addition, a dynamic tree growth model has been developed (Makela 1985) based on the assumptions of the pipe-model theory (Shinozaki et al. 1964a, b), which partitions growth between foliage and wood. In an independent effort, Valentine (1985), also developed a tree growth model based on the pipe-model theory and has extended it to a stand level model (Valentine 1986). Hence, close scrutiny of the IIASA effort and the pipe-theory models will be followed and possibly used in future efforts within the SFRC.

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Modeling Stand Dynamics of Spruce-Fir Forests in the Northeast

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Abstract

Spatial and temporal variability of diameter growth will be calculated across the spruce-fir geographical range and compared to the spatial pattern of atmospheric deposition. This research addresses two scientific questions in the Spruce-Fir Research Cooperative (SFRC): (1.1): Are changes in growth and mortality and the presence of unusual foliar symptomology in red spruce-fir forests greater than those that can be attributed to typical trends and levels of natural variability? (1.2): What spatial patterns, if any, exist in growth and mortality and in the presence of unusual symptomology in red spruce-fir forests, and how do these patterns relate to spatial patterns of pollutant exposure? The forest growth model FIBER will be modified to incorporate elevational effects into diameter growth equations for different time periods for red spruce over the last three decades. The model has been adapted to account for stresses from environmental influences by incorporating additional variables. These variables include changes in the amount of foliage weight as altered by stress.

Considerable attention has been focused on the growth decline within the red spruce-fir forest types in the Eastern United States. In the high-elevation forests of the Northeast, declines have been documented by Vogelmann et al. (1985) on Camels Hump, VT, and Scott et al. (1984) on Whiteface Mountain, NY. Similarly, Bruck (1984) on Mt. Mitchell and Adams et al. (1985) in the mid-Appalachian forests report decline in the spruce-fir forests in the Southeast. Although considerable research is being conducted to determine the causal factors, both natural and anthropogenic, the role that atmospheric deposition plays is still unanswered. Thus the Spruce-Fir Research Cooperative (SFRC) has developed broad policy questions under the Forest Response Program (FRP) to provide information on the response of forests to atmospheric deposition.

The following are two scientific questions from the SFRC:

1. Are changes in growth and mortality and the presence of unusual foliar symptomology in red spruce-fir forests greater than those that can be attributed to typical trends and levels of natural variability?

2. What spatial patterns, if any, exist in growth and mortality and in the presence of unusual symptomology in red spruce-fir forests, and how do these patterns relate to spatial patterns of pollutant exposure?

FIBER (Solomon et al. 1987) was expanded to include a broad-base data set. The growth can be modified within the model to compare the growth response of spruce-fir trees at different years, locations, elevations, and both with and without spruce budworm (SBW) attacks. The structure of FIBER and the broad data base provide a basis for refinements that will allow predicting the growth components of the spruce-fir forest prior to known major stress from external or environmental sources.

Growth and yield research of red spruce and balsam fir forests intensified during the spruce budworm (*Choristoneura fumiferana*) epidemic that began in 1973. Under the CANUSA program, cooperative research was conducted to investigate how spruce budworm attacks altered foliage biomass and productivity of red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) trees and how these attacks affected the growth and dynamics of the spruce-fir forest. To measure the impact of growth reduction, it was necessary to develop a method of predicting stand growth both with and without stress from SBW attacks. FIBER was developed for predicting the stand growth of different tree species from data within the spruce-fir forest type prior to the onset of the SBW epidemic (Solomon et al. 1986). The transition probability equations in FIBER have been modified to incorporate the magnitude of defoliation on each species being stressed and the proportion of the susceptible species in the stand. The SFRC has the task of determining the temporal and spatial consistencies in growth, mortality, and symptomology of the red spruce and fir forest in the east and this research may provide a technique for modeling stress caused by atmospheric pollutants. Analysis of representative data with the FIBER model provides a means of addressing whether the problem of forest decline in eastern North America can be determined.

The foliage is the first point of contact between the pollutant and the tree. Simulating the effects of the different pollutants on the photosynthetic efficiencies of foliage age classes for spruce and fir would be of major importance to the growth modeling of the spruce-fir forest. Similarly, physical damage to the foliage such as from frost would also be important in carbon production and allocation. Modeling photosynthetic efficiency based on physical damage can be attempted through modification of an existing foliage production model (Hayslett and Solomon 1983).

Preliminary research has been conducted to model the relationship between the amount of current foliage produced and the existing physical changes to the foliage for balsam fir and red spruce (Solomon and Hayslett 1986). Modeling efforts have attempted to incorporate alterations in foliage production with changes in photosynthate available for translocation to the stem (Solomon 1985). Expansion and modification of this existing individual tree modeling framework should allow testing for a consistent growth response to environmental pollutants on the above ground portion of the tree.

Spruce-fir Data Base

A fundamental requirement in the analysis of temporal and spatial trends in the spruce-fir forest is the development of a data base which could be (1) used presently by scientists exploring alternative approaches to the problem and (2) used as an archival benchmark for future generations of scientific study.

Approximately 2,500 remeasured growth plots from Maine to New York were used to develop FIBER and could be used as an initial data base (Solomon and Hosmer 1986). Additional data from 1,000 plots has been added to expand the geographical base to New Brunswick and Nova Scotia, Canada. The dates of measurement range from the mid-1950's to the 1980's and cover a range of basal area, species compositions, and elevations (0-3,200 ft). This information will be supplied to the SFRC Database Management Group at North Carolina State University, Raleigh, NC, in appropriate formats and documentation for present and future use.

Temporal Variability of Growth and Mortality

Changes in forest growth and mortality usually can be attributed to typical trends and levels of natural variability. Using the data base described, we will compare forest growth over the past three decades, spanning the pre-pollution to pollution era. If significant growth declines have occurred, the magnitude of the decline and the present condition of the forest can be compared. Prediction of the natural variability within the spruce-fir forest enables us to suspect that anything beyond the expected levels is caused by alterations in environmental conditions such as from air pollution.

Subsets from the data base will be used to isolate the growth rate and stand growth response for the spruce and fir species. The subset consists of unthinned plots with 65 percent or more of the basal area in softwood species. The plots were further stratified by having at least 25 percent (basal area) of the subject species. By separating the data set into different time frames and calculating annual diameter growth rates, the different growth periods for unthinned spruce-fir stands in the Northeast can be compared.

Spatial Variability of Growth and Mortality

Spatial patterns in the spruce-fir forest will be addressed in two ways. First, an elevation variable will be tested for significance in regression equations that estimate the annual diameter growth. Residuals will be plotted over elevation to locate spatial trends. This may give important insight into possible pollution effects. However, other natural factors also are associated with elevation and, hence, caution will be used in such interpretation.

Second, spatial variables will be examined by predicting the growth in spruce-fir forests using existing data at the six different SFRC intensive sites that were not used in model development. Analyses will determine how well FIBER can predict forest spatial dynamics. The implications and possible causal factors for any unreasonable variation from the estimations will be addressed.

The R^2, bias, and variance developed from the multivariate regressions within the model will be used as goodness-of-fit statistics.

FIBER Modification

The model contains nearly all the commercially important species across the New England states. Expansion of the data set will allow the model to be used for transition hardwoods that may be present in spruce-fir stands in the Northeast. In addition, the transition probabilities and regression coefficients will be modified to predict growth on an annual basis.

An initial attempt has been made to modify FIBER and test its predictability of forest growth response through time for both stressed and nonstressed species. One method of modeling extraordinary stress, such as a SBW attack, is to modify the transition probability equations.

Acid deposition data are only now being collected, so 214 remeasured, unharvested, softwood plots measured during a SBW outbreak in Maine from 1975 to 1985 were utilized (Ashley et al. 1976). A measure of projected total foliage weight remaining at the end of each 5-year period, along with the percent basal area of the species being modeled, was added to the regression equations used to predict the transition probabilities. Since the spruce budworm usually consumes the current foliage on spruce and balsam fir trees, the foliage weight remaining for a tree of a size equal to the midpoint of the diameter class was obtained by calculating the total foliage weight of the tree and partitioning that foliage into current through 6+ age classes (Baskersville 1965, Fraser et al. 1964). Average plot defoliation per year for fir and spruce was used to project defoliation for each age class. The age classes were then summed to give the total foliage remaining at the end of the projection.

The original and foliage weight variables were then regressed on the data set using an iterative-reweighted least squares regression technique with the NLIN procedure in SAS (1985). The coefficients for the original variables were forced to stay the same. The new equations were used to predict transition probabilities that account for any growth response to defoliation of spruce or fir trees.

The actual volume by species was compared to the predicted volume using FIBER before and after modification (Table 1). Between 1975 and 1985, the actual and predicted volume growth was approximately the same for all species except the spruce and balsam fir. The nonstressed version of FIBER overpredicted the volume of these species indicating the extent of volume growth reduction. The stressed version of FIBER predicted very close for spruce and fir during the first 5-year period and close for spruce during the second 5-year period. Balsam fir, however, was overpredicted for the second 5-year period. This was primarily due to the increased mortality of fir during the second 5-year interval.

Table 1.--Average actual, predicted stressed, and predicted unstressed yields (m^3/ha) for 214 softwood plots impacted by spruce budworm in northern Maine, 1975-85

	Species[a]														
Yield	BF	Sp	He	Ce	OS	SM	RM	YB	PB	Be	WA	As	OH	Total	Percent Diff.
							5 years								
Actual	39.5	67.4	10.3	24.8	4.7	1.4	8.0	4.3	3.9	0.8	0.0	2.3	1.0	168.4	
Predicted															
Unstressed	49.5	69.7	9.9	25.0	4.3	1.3	8.2	3.5	4.2	0.8	0.0	2.1	1.0	179.5	6.6
Stressed	40.4	66.5	9.9	25.0	4.3	1.3	8.2	3.5	4.2	0.8	0.0	2.1	1.0	167.2	-0.7
							10 years								
Actual	19.9	65.2	11.3	24.1	5.6	1.5	8.5	4.4	3.4	0.8	0.0	2.1	0.8	147.6	
Predicted															
Unstressed	49.8	75.1	10.7	25.1	4.4	1.5	9.0	3.6	4.2	0.9	0.0	1.9	1.0	187.2	26.8
Stressed	32.5	67.9	10.8	25.1	4.4	1.5	9.0	3.6	4.2	0.9	0.0	1.9	1.0	162.8	10.3

[a]BF = balsam fir *Abies balsamea* (L.) Mill.; Sp = spruce *Picea* spp.; He = eastern hemlock *Tsuga canadensis* (L.) Carr.; Ce = northern white cedar *Thuja occidentalis* L.; OS = other softwoods *Larix laricina* (Du Roi) K. Koch and *Pinus strobus* L.; SM = sugar maple *Acer saccharum* Marsh.; RM = red maple *Acer rubrum* L.; YB = yellow birch *Betula alleghaniensis* Britton; PB = paper birch *Betula papyrifera* Marsh.; Be = American beech *Fagus grandifolia* Ehrh.; WA = white ash *Fraxinus americana* L.; As = aspen *Populus tremuloides* Michx.; OH = other hardwoods *Betula populifola* Marsh., *Acer pensylvanicum L., Prunus pensylvanica* L. f., *Fraxinus nigra* Marsh.

One reason for overpredicting the volume may be from subjective estimates of defoliation damage. The probability of mortality of the average stand may mask the amount of stress placed upon indvidual trees and may result in overprediction of growth. It is recommended that stress history of individual trees by species within stands is necessary for models to produce a reliable and accurate prediction of mortality.

Acknowledgments

The author recognizes the contribution of Mr. Richard Hosmer, computer programmer; Dr. Stanley Zarnoch, research modeler; and Dr. Donald Seegrist, statistician, to the progress of the research project.

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Disease Types in Norway Spruce Stands in Southern Germany--Extent and Causes

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Abstract

The paper reviews the present state of knowledge with regard to the Norway spruce diseases and their causes in southern Germany. Four distinct disease types are described. It is demonstrated that with some diseases, pollutants and acid precipitation play a decisive role, according to the opinion of most scientists involved. On the other hand other types of disease are mainly determined by natural stress factors. All these different disease types of Norway spruce seem to be synchronized by one common trigger factor. Since diseases occur on all types of parent rock and soil and in regions, where the pollution load varies considerably, this general trigger factor is unlikely to be a pollution- or soil-induced stress. Regarding the large scale occurrence of disease phenomena all over central Europe, there is more evidence that weather stress (presumably frost events) acts as a trigger or synchronizing factor.

Extent of Damages

According to the fourth nationwide inventory of forest damage in the Federal Republic of Germany, carried out from July to September 1986, 54 percent of the total forest land was classified as damaged or diseased (BML 1986). Diseased means that the affected stands carried less foliage than normal, since the inventory technique is mainly based on an estimate of foliage losses as compared with regional "standard" conditions. Forests are classified as healthy and unaffected (damage category 0) as long as they carry at least 90 percent of the estimated normal amount of foliage. Slightly damaged stands (category 1) have foliage losses from 11-25 percent, moderately diseased ones (category 2) from 26-60 percent. Severely damaged stands (category 3) carry less than 39 percent of the normal amount of leaves.

However, the standard, or normal, situation as the basis for comparison has been inaccurately defined, and the correlations between foliage losses on the one hand and growth, vigor or physiological parameters of the trees on the other are not yet established for most species.

The distribution pattern of damage intensity reveals distinct differences between the northern and the southern parts of Germany. The forests in the South are considerably more affected than those in the North, although the concentrations of most pollutants in the atmosphere are lower. In the south, damage was highest in the eastern Bavarian Mountains along the border to Czechoslovakia, in the Black Forest and in the Alps. From 1985 to 1986 the percentage of affected forests rose in the Black Forest, with oaks (*Quercus robur* and *Q. petraea*) and with European beech (*Fagus sylvatica*). It decreased considerably in northeastern Bavaria, and in the foothills of the Alps, in Norway spruce (*P. abies*) as well as in silver fir (*Abies alba*) and Scots pine (*Pinus sylvestris*) forests. Damage intensity normally increases with age and exposure of the trees.

The most important species in Germany, in terms of acreage, production, and economic value, is Norway spruce. In summer 1986, 32 percent of all spruce forest was in the lowest damage category, 20 percent was moderately defoliated and only less than 2 percent was severely damaged or already dead. Serious defoliation was restricted to higher elevations of the so-called German subalpine mountains and of the Alps (Fig. 1).

A careful comparison of the various disease or crown damage phenomena in Norway spruce, silver fir, Scots pine, European beech, and in oak forests in the Federal Republic reveals a great diversity in symptoms, growth responses and in the occurrence of possible stress factors. Nobody seems capable, at the moment, of developing a general hypothesis covering this diversity. Therefore it is plausible to assume, as a first approach, that we have to deal with the more or less simultaneous outbreak of quite separate diseases, differing pronouncedly from species to species, and even within one particular species. Consequently we suggest that these various diseases are caused by different sets of stress factors. This approach, on the other hand, does not exclude the possibility that one common cause is involved in all those disease phenomena, but obviously with different significance and consequences.

I would like to present this specific approach describing some disease types for Norway spruce. I have chosen this particular species for demonstration because it is severely affected by diseases under a great variety of forest conditions and since several research groups have quite recently published important findings.

Death of Spruce Forests in the Ore Mountains

The Ore Mountains along the border between Czechoslovakia and the German Democratic Republic are one of the largest SO_2 pollution areas in central Europe. On exposed ridges and plateaus at elevations of more than 800-900 m a.s.l., about 30,000 ha spruce forests have been killed, mainly during the past 10 years, and have been clearcut. Even the youngest plantations are severely affected and will die within 10 or 15 years. The understory mountain ash *(Sorbus aucuparia)* trees, however, still persist on the vast clearcuts, from which all Norway spruce have vanished. Mountain ash is even capable of regenerating naturally, if enough seed trees are present. Due to the sudden decrease in transpiration after the death of the forests, the ground water table may rise, peat and bog formation starts or is accelerated.

The average annual concentrations of SO_2 in the atmosphere in the damaged areas normally exceed 40 $\mu g \cdot m^{-3}$ and often amount

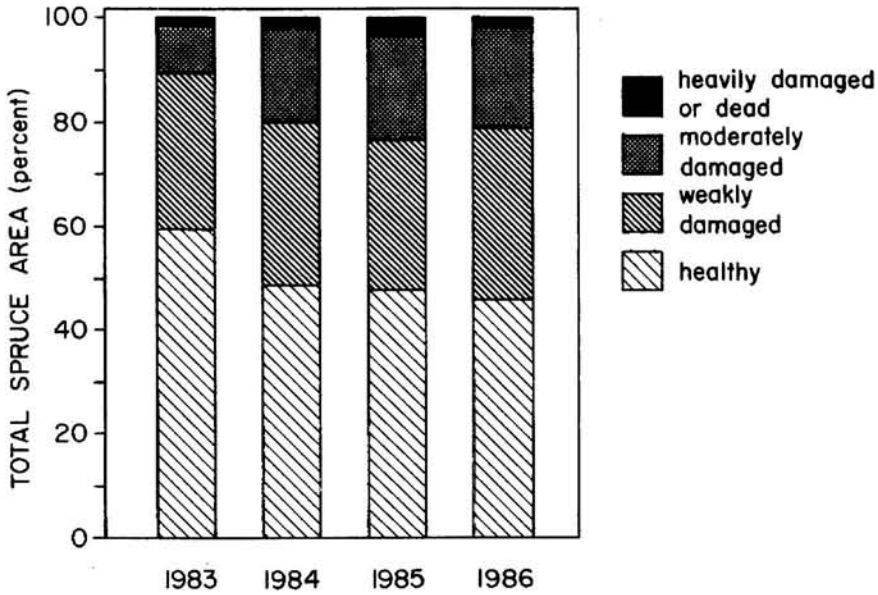

Figure 1.--Development of crown damage in Norway spruce stands in the Federal Republic of Germany (from BML 1986).

to 80 or even 90 $\mu g \cdot m^{-3}$. Therefore, in that region, classical damage of SO_2 to the foliage of evergreen conifers, disturbing mainly photosynthesis and transpiration of the trees, must be taken into consideration as the most prominent stress factor. However this factor alone cannot explain the rapid death of extensive spruce forests, which started, or was at least dramatically accelerated, in spring and early summer of 1979. According to all knowledge about the effects of SO_2, mean concentrations between 40 and 80 $\mu g \cdot m^{-3}$ can induce a substantial decrease in vitality and growth and even the death of individual trees, but not the more or less sudden mortality of thousands of hectares of spruce forests. Therefore, all our Czechoslovakian colleagues unanimously ascribe this type of damage to the combined action of SO_2, directly affecting the needles, and of frost shocks, causing the spruce forest catastrophe. According to their findings the decrease in soil fertility through the impact of acid deposition from the atmosphere, although present, is not a prominent stress for the trees. Proton deposition in the Ore Mountains is estimated to amount to up to 8-10 $kmol \cdot ha \cdot a^{-1}$.

Norway Spruce Disease at Higher Altitudes on Acidic Soils in Germany

Since 1980 an apparently new disease of Norway spruce has been observed at higher altitudes of the German subalpine mountains on acidic soils derived from crystalline parent rock or from sandstones. This disease type occurs for example, in the Bavarian Forest as well as in the Black Forest, generally at elevations of more than 700 m above sea level (Bosch et al. 1983, Zech and Popp 1983, Zöttl and Mies 1983).

The disease starts with a pronounced yellowing of older needle age classes, followed by necrosis and shedding. This leads to a marked transparency of the crowns, mainly at the center and base. Only the older foliage is chlorotic; the youngest shoots are normal green. The discoloration starts at the tips of the needles, while the needle base remains green .The gold-to-yellow chlorosis is generally much more severe on the upper side of the needles and branches than on the lower, and is characteristic of severe magnesium deficiency.

Direct effects of SO_2 on spruce foliage can be ruled out as a plausible stress factor. The concentrations of this pollutant in the ambient air (10-15 $\mu g \cdot m^{-3}$ annual average) are well below the IUFRO limits for damage.

The disease affects old stands as well as young trees. A long term growth depression was detected as a characteristic feature. A pronounced tree-to-tree and stand-to-stand variation of disease intensity occurs on the same soil. Autochthonous populations in the subalpine spruce belt of the Bavarian Forest are suffering considerably less than obviously foreign spruce provenances which were introduced, presumably from lower elevations, on to vast clearcut areas or to former pasture land.

The apparently healthy, as well as the diseased trees, are very well supplied with N and P, and adequately with K. There is no indication of Cu, Mn or Zn deficiency or toxicity. The foliar contents of these elements are low. If a significant difference shows up in the Cu, Mn or Zn nutrition between affected and control trees, the latter are always superior. The Cd, Pb, Ni and Cr contents in the needles of all disease categories are extremely low. The S, Cl, F, and Al levels are far from critical.

The most striking and consistent difference arising from our comparison of diseased and healthy spruces, as well as from the

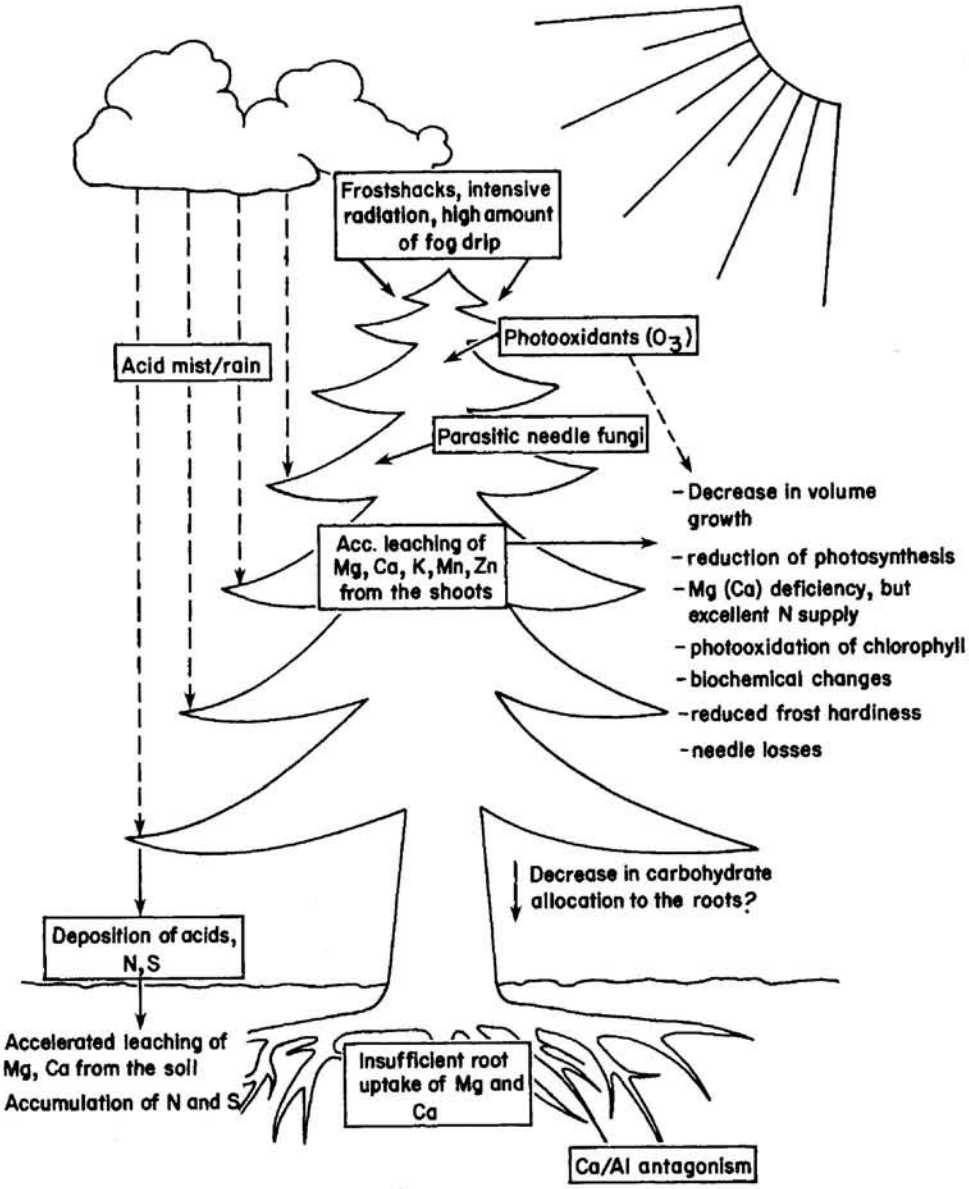

Figure 2.--Working hypothesis to explain Norway spruce decline on acidic soils at high altitudes of the mountainous regions (according to Rehfuess and Bosch 1986).

investigations of other colleagues concerned Mg and Ca. The level of supply is in general rather poor, even with healthy trees, but the diseased spruces always have lower foliar concentrations of both elements and suffer from extreme Mg deficiency. Needle analysis thus supports the foliar symptoms.

Affected stands occur on soils which are moderately acidic, but obviously not more acidic than they were 20 or 30 years ago. The pH (H_2O) values in the mineral horizons range from 4.5 to 5.0., Magnesium deficiency of spruce was observed on soils derived from granite very poor in Mg. It also occurs on soils derived from paragneiss or even metagabbro with high contents of total Mg throughout the solum. The contents of exchangeable Mg however, are always very low in these more or less podsolized soils (< 50 $\mu g \cdot g^{-1}$ dry soil). Thus scarcity of readily available Mg is one important precondition for this particular disease type.

Looking at the needle surfaces by scanning electron microscope we occasionally observed gypsum ($CaSO_4$) crystals, which were more frequent on green than on yellow needles and occurred predominantly in or around the stomatal cavities. All the available observations and a series of experiments lead to the conclusion,

that the Ca part of the crystals must originate from the interior of the needle and was not deposited on the needle surface from the atmosphere. Green needles in November consistently had more raffinose, but less starch than chlorotic ones, and this difference may indicate a higher frost resistance at the time of sampling (Bosch et al. 1983). In spring 1985, in an affected stand, we observed frost injury symptoms only on yellowish branches and not on green trees. All these findings were combined to develop the following working hypothesis about the causes of the high altitude disease of Norway spruce in southern Germany (Rehfuess and Bosch 1986) (Fig 2):

During fine, sunny weather in summer, intensive formation of ozone and other photooxidants may occur at higher elevations, where the radiation is high and where the precursor pollutants like nitrogen oxides and hydrocarbons are transported from the emission sources down in the valleys by winds blowing up slope during the day. The photooxidants may cause some deterioration of the cell membranes and cuticular waxes, making them more permeable to cations (Magel and Ziegler 1986). Later on, the mountain summits are again covered by clouds for long periods. During cloud drip precipitation events, acid mist with pH values down to 2.6 will efficiently leach cations like Mg and Ca from previously damaged needles. In the long run this may cause Mg deficiency, provided the trees are not capable of compensating for those leaching losses by uptake from the soil. The root absorption of Mg and Ca is restricted on acid substrates because the readily available amounts are rather low. These amounts may even be diminished via accelerated leaching from the soil by increased acid deposition. The proton input in throughfall at these sites ranges from 1-2 $kmol \cdot ha^{-1} \cdot a^{-1}$. High contents of exchangeable Al - which have long been present in these soils - will antagonize the root uptake of Mg and Ca. The Mg deficiency of the trees slows down their photosynthetic capacity and volume growth and may decrease frost hardiness in particular. That is presumably the reason why the damage, latent at first, suddenly became evident after a series of severe frost shocks between 1979 and 1983, when strong convectional frosts occurred after extended periods of mild weather (Fig. 3).

The intensity of this specific damage must be highest at the summits of the mountains, where the O_3 concentrations show peak values during periods with intensive radiation, the number of fog days is highest, photooxidation of the chlorophyll is

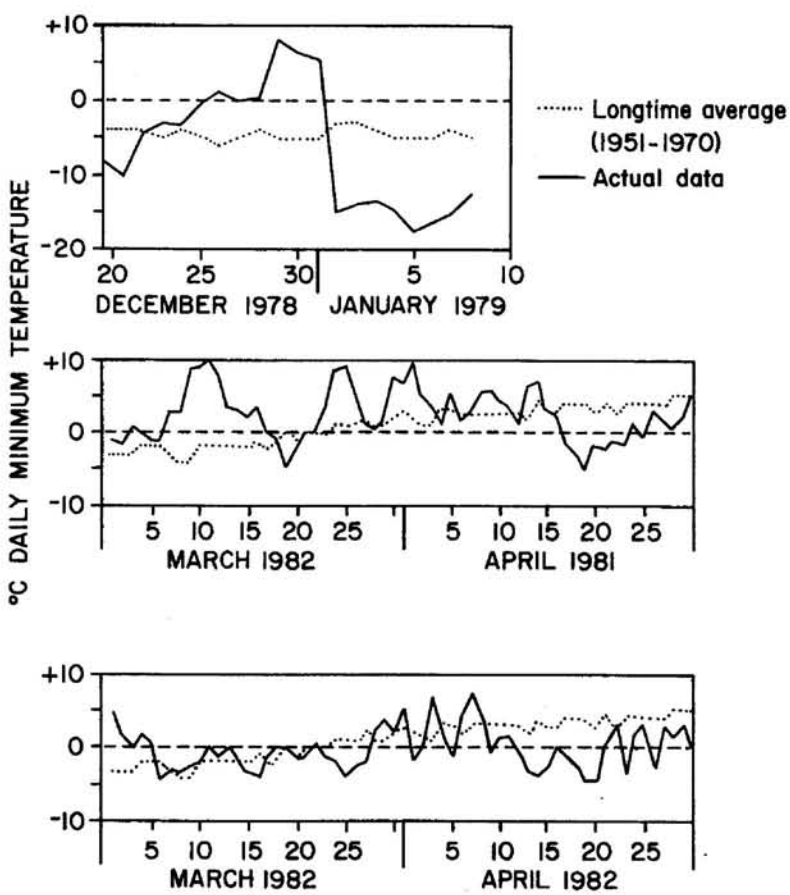

Figure 3.--Documentation of a series of frost shock events between 1979-1982 at the weather monitoring station München-Riem (Rehfuess and Rodenkirchen 1984).

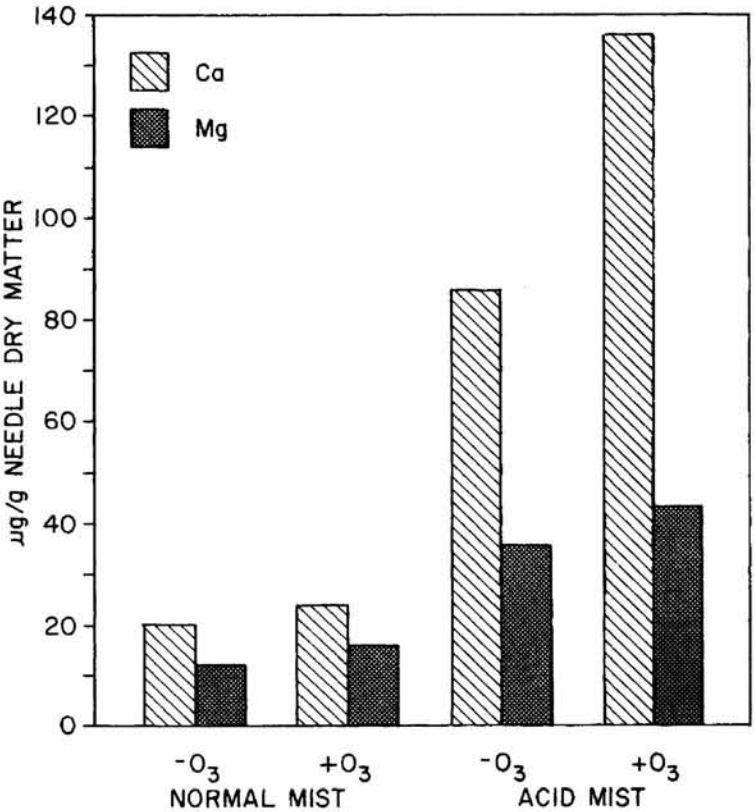

Figure 4.--Leaching of Mg and Ca by mist from spruce crowns under normal climatic conditions (Averages for treatments fertilized and not fertilized with MgCa; Bosch et al. 1986).

intense, many soils are rather poor in readily available Mg but provide plenty of N, and frost events are frequent. The involvement of frost among the stress factors offers an elegant explanation for the striking tree-to-tree and stand-to-stand variation of damage intensity in the affected regions, since it is well known, that the frost resistance of conifers is closely controlled by genetic factors.

This working hypothesis is currently under test in experiments at various research institutions. The preliminary results of a pilot trial were published recently (Bosch et al. 1986, Magel and Ziegler 1986). It was conducted in newly established climate and exposure chambers of the GSF at Neuherberg/Munchen (Payer et al. 1986). Four-year-old saplings of a Norway spruce clone, growing either in a Mg and Ca deficient soil or in the same substratum fertilized with Mg and Ca were subjected to different treatments with O_3 and mist. Spraying with acidic mist (pH 3.0) increased foliar leaching of Mg and Ca significantly (Fig. 4). Trees growing on a soil well provided with readily available Mg and Ca, however, were able to maintain an adequate Mg supply (Fig. 5). In contrast, on a substratum poor in Mg and Ca, acid mist treatment together with exposure to high O_3 levels was associated with extreme Mg deficiency of the spruce saplings (Fig. 6). The frost hardiness of Mg deficient trees was 2-5°C less than that of specimens well provided with this element. In another experiment, Brown et al. 1986 have demonstrated interactions between the genotype of Norway spruce saplings, fumigation with O_3, and their frost hardiness. Consequently, some experimental evidence is already available to indicate that at least parts of the working hypothesis described above may hold true (Rehfuess and Ziegler 1986).

Needle Reddening of Older Norway Spruce Stands in Southern Germany at Lower Elevations

In late autumn of 1982, the sudden outbreak of another specific disease type occurred in older Norway spruce stands at lower elevations all over southern Germany. This disease type in fact seems to be the most widespread in the South (Rehfuess and Rodenkirchen 1984, 1985).

The symptoms were as follows: Most stands looked healthy and perfectly green during the whole summer. Starting in late September, several age classes of older needles simultaneously began to change their color to red within a fortnight. This needle reddening occurred at the edges of the stands as well as in the interior. We observed it in very vigorous and fast growing stands on fertile soils and in suppressed and starving spruces on very acidic substratum under the overstory of pine or larch. The red needles showed black dots and bars indicating heavy infestations

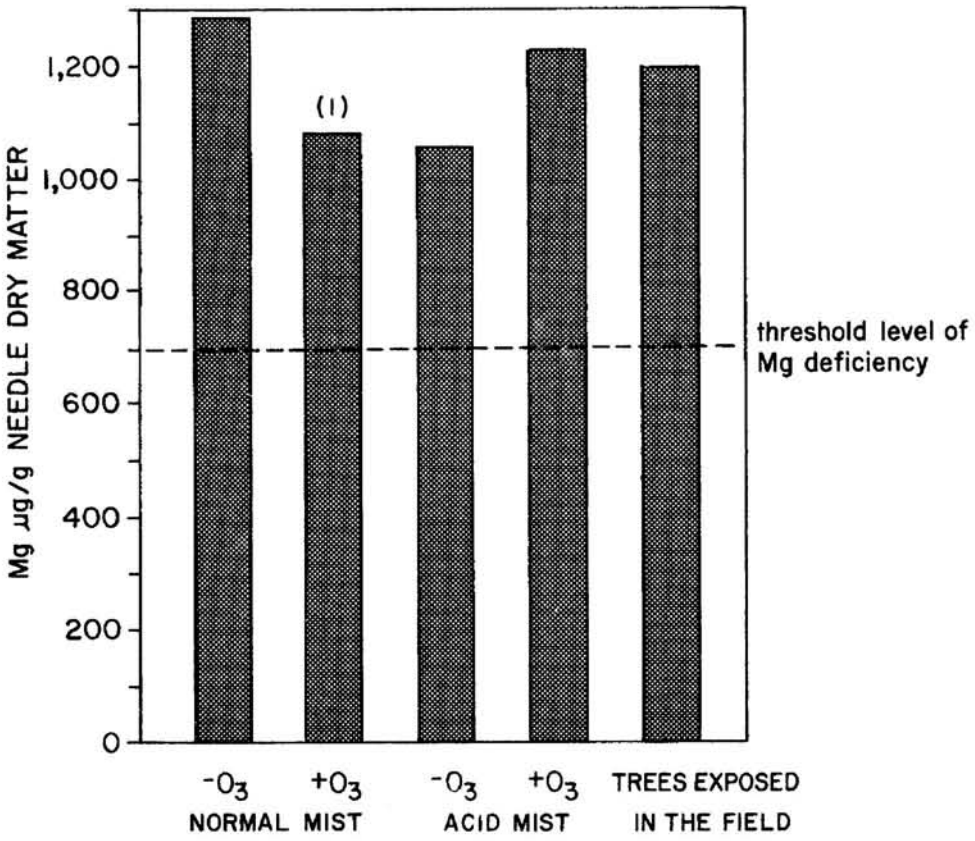

Figure 5.--Foliar Mg contents of spruce saplings fertilized with MgCa at the end of the exposure experiment (needle age class 1984; composite samples). (1) = value corrected for change by mistake of two trees (Bosch et al. 1968).

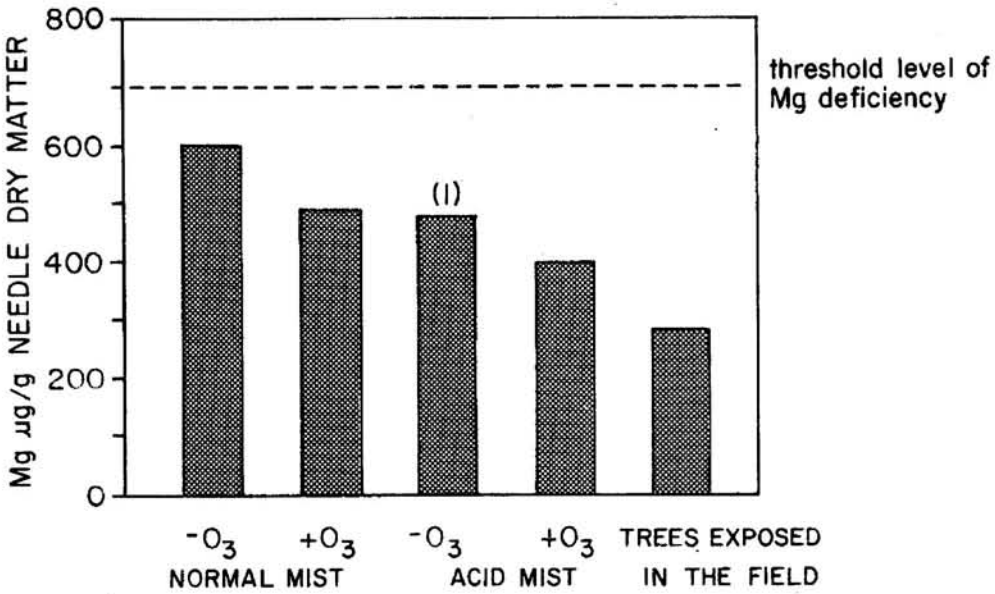

Figure 6.--Foliar Mg contents of unfertilized spruce saplings at the end of the exposure experiment. For comments see Fig. 5.

by two species of needle cast fungi *(Lophodermium piceae* and *Rhizosphaera Kalkhoffii*). The needles were shed from the branches during November or December. The secondary branches lost most of their older foliage towards the base of the shoot, and the so-called "silver tinsel symptom" appeared on comb type spruces, with secondary twigs which hang down perpendicularly from the main branch. The outer mantle of the crown remained green and was built up from the 4 or 5 youngest age classes of needles. The crowns got more and more transparent in their inner and basal parts, since the needle reddening process was repeated during 2 or 3 subsequent years. As soon as the affected reddish-brown needles are shed, there are no further symptoms than loss of older foliage. Growth depressions are observed only if the foliage losses exceed 40-50 percent.

Until now this disease has only seriously affected stands which are older than 60 years. So one can find very poor looking old trees side by side with healthy plantations on exactly the same site. No long term growth reduction has been detected in spruce stands suffering from this disease. Another observation is still more astonishing: In the foothill region of the calcareous Alps, silver fir, which is known to be the most susceptible of all tree species with regard to pollutants, shows healthy growth, whereas spruce in the immediate neighborhood is severely affeced by foliage losses.

Needle reddening and fungal infection occurred on all types of parent rock and soil in southern Germany. In contrast to other disease types, no correlation exists between the nutritional status of the trees and the occurrence or intensity of damage. For most stands we can rule out SO_2, NO_x, fluorides, chlorides, heavy metals, photooxidants or acid deposition as general stress factors. The disease occurs for example, in the Lake Constance region, where an annual proton deposition of 0.1 $kmol \cdot ha^{-1}$ was determined. All observational evidence points to the conclusion that we are dealing with a conventional needle cast disease or epidemic, which was already described in the literature by Hartig (1889) about 100 years ago and which seems to be mainly determined by weather factors. We speculate that a series of frost shocks in the late 1970s and early 1980s (Fig. 3) may have caused sublethal damage to the older needles. The infestation of those predamaged needles by secondary needle parasites may have been favored subsequently by high rainfall and high air humidity in early summer. This assumption of an episodic interaction of frost shock events and common pathogens is supported by another striking feature of this disease type:

One observes the initiation of an intensive recovery process. On the upper side of the main branches new shoots are formed. The trees obviously try to compensate for the severe foliage losses by forming adventitious branches. These recovery shoots started to grow in 1982 or 1983, they sprouted and branched vigorously in 1984 to 1987. In the formerly diseased stands one can still observe the naked "silver tinsels" of the older secondary branches hanging down sadly. The main branch, however, is already densely covered by new recovery shoots. In the fall of 1985 and 1986, needle reddening and fungi attack occurred again, but they caused only minor needle losses. In all these years needle reddening did not affect the recovery shoots, but was restricted to the oldest branches. So we can really hope that this disease type will disappear quite soon.

Norway Spruce Disease at Higher Elevations of the Calcareous Alps

At higher elevations of the Calcareous alps in southern Bavaria, mainly built up from limestones and dolomites, rather sudden decrease of vigor in Norway spruce stands and the appearance of decline phenomena started in about 1981 on south-facing slopes. The decline is accompanied by chlorosis and premature shedding of older needles, and the crowns again become increasingly transparent. In general, old and young trees are affected similarly. Spruce exhibits symptoms of Mn deficiency, namely a yellow to pale discoloration of the youngest shoots. It also suffers from K deficiency as indicated by a yellow-tip chlorosis of older needles. In contrast to the trees on acidic soils in the Bavarian Forest, the needles contain plenty of Mg and Ca, whereas the supply of N and P is rather poor. This very specific nutritional status can be explained by the soil conditions. The stands are growing on shallow, stony or even rocky soils derived from dolomite on steep slopes of southern aspect and in ridge positions. These soils show alkaline reaction. They are extremely rich in Ca and Mg but poor in available manganese and potassium. Soil acidification cannot be a stress factor under these conditions, since the amount of acids deposited from the atmosphere is low (1-1.5 kmol $H^+ \cdot ha^{-1} \cdot a^{-1}$ in throughfall) and since it is imported into well buffered soils. In spite of high annual precipitation, periods of water stress are common as a consequence of the low water holding capacity of the substrate. Frequent desiccation of the soils will decrease the availability of N, P, and K. Well known root rot fungi like *Heterobasidion annosum* and *Armillaria mellea,* and secondary needle fungal parasites are also involved.

It is my feeling that this disease type, occurring on calcareous soils in fairly unpolluted regions, is at least partly caused by extreme edaphic conditions and by weather events like dry spells and/or frost shocks, pushing the less vigorous older trees toward disease or rapid death. However, there are two pollution factors which could also play a significant role: the interaction of ozone and other photooxidants on the one hand and the direct impact on the foliage of episodic acid precipitation events on the other.

The consequences of a true and long lasting decline of old spruce stands in the Alps would be extremely dangerous, because the natural, as well as the artificial, regeneration of these forests is made impossible over extended areas by an overpopulation of roe and red deer. It is only in these areas that the existence of the forest is really in danger and that there is a potential, in the long run, of the formation of avalanches, land slides and of erosion.

Conclusions

A comprehensive review of the time courses and symptoms of the recent "damages" in Norway spruce stands shows that at least four separate disease types occur in southern Germany. All of them lead to drastic needle losses (mainly from older age classes) and to transparency of the crowns. The sets of plausible stress factors associated with each of these disease types differ pronouncedly. There are some diseases in which pollutants and acid precipitation are playing a decisive role. Others are mainly determined by natural stress factors. All these different disease types of Norway spruce seem to be synchronized by one common trigger factor. Since diseases occur on all types of parent rock and soil and in areas where the pollution load varies considerably, the general trigger is unlikely to be a pollution- or a soil-induced stress. Regarding the large scale occurrence of disease phenomena there is more observational and even experimental evidence that weather stress acts as synchronizing factor. Principally either drought, frost, or frost shock events could induce the more or less simultaneous outbreak of different diseases. Searching for extreme weather situations all over central Europe during the period in question (1981-1984) leads to the conclusion, that frost shock events are presumably responsible for the synchronizing effect (Rehfuess 1985, 1986).

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Forest Decline in Germany

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Three questions are to be answered from a personal perspective. In my case they are discussed from the point of view of a forest botanist and pathologist. In order to find a joint base of discussion, please let me start with a number of definitions and characterizations of what we call "Waldsterben" or "neuartige Waldschaden", "forest decline" or "forest damage":

Two different kinds of basic philosophies can be distinguished at the moment:

- Waldsterben is explained as a disease of forest ecosystems
- It is a number of single well-known tree diseases, which simultaneously occur at the same locations by chance.

I prefer the first way of thinking and the following considerations are based on this supposition. Beyond that, a number of peculiarities are found to be typical for the Waldsterben-syndrome, and they are not in harmony with the behaviour of common diseases:

- Waldsterben is a new phenomenon, which appeared suddenly
- It spreads rapidly
  - -geographically (almost over the entire northern hemisphere within 8 years)
  - -biologically (most tree species in Europe are affected, also several shrubs and herbs)
- It is not restricted to
  - -certain geological conditions
  - -climate
  - -soil conditions
  - -methods of forest management (silvicultural methods)
- It is explained with air pollution effects, although "classical pollutants" cannot be the primary causes.

From a pathological point of view it has to be added, that Waldsterben obviously belongs to the range of complex diseases, where more than one pathogenic effect has to occur simultaneously or sequentially. This means we have to consider primary and secondary causes.

Out of these items, out of many additional observations, from research data and literature studies, we have developed a working hypothesis which is summarized in a few sentences. Permanent exposure to low concentrations of air pollution, composed of an unknown number of phytotoxic compounds and transported over long distances leads to reduced vigor of trees and also affects other members of the ecosystem. It's manifested in lower production or lower availability of carbohydrates and secondary plant substances. This again increases the predisposition to climatic extremes and pathological events.

The development and the reproduction ability of the fine root system is affected, the mycorrhization and the nutrition of the tree disturbed. The longer these influences last, the more pronounced is the transparency of crowns and the deterioration of fine roots.

This hypothesis is able to explain the majority of symptoms in many species:

- It makes it understandable that primary and secondary symptoms occur in many cases
- It explains why it is useless to search for a still unknown pathogen which is able to attack dozens of different conifer and broadleaf species on both sides of the Atlantic
- It shows that we need not find climatic extremes, which occurred in southern Italy, central Sweden and on Mt. Mitchell at the same time
- It explains why local differences in symptom expression and disease severity can occur.

There is one disadvantage, however: it fails to present one single cause responsible for the whole syndrome. That's the reason why neither the public, nor the politicians, nor many of my colleagues like this hypothesis.

As a matter of fact - the hypothesis is neither spectacular nor sophisticated. It's just plain good old pathology.

But one fact is new:
The causes are man-made. And they hit a biological system that has not been confronted with them before.

To sum it up:
We assume that hundreds of toxic compounds, one by one or in combination, synergistic or not, burden an ecosystem on thousands of unknown reaction points, and this for dozens of years. Please, just for a minute and only theoretically accept this assumption. And then try to establish a research program to prove it. Pretty soon you will see big, big obstacles.

1. Ecosystems cannot be pressed into artificial test systems like chambers or phytotrons.
2. Field experiments with entire ecosystems are likewise impractible.

3. The composition of ambient air pollution is only known for a handful of components like SO_2 or 0_3. Besides numerous volatile exudates from foliage, however, thousands of anthropogenic components are present. Since they change with time and location, the situation is hardly reproducable and therefore not to be used for experimental purposes. Experimental results with single components are interesting but of little relevance with respect to the causes of Waldesterben.

4. Waldsterben normally starts in old trees. Until now it has not yet reached younger age classes. This fact makes realistic experiments almost impossible.

5. Under these assumptions even Koch's postulates are not applicable, at least not at the moment, because (a) a single, clearly defined causal agent does not exist; (b) a multifactorial ecosystem as a host never reacts in a predictable way.

Under these circumstances it is little surprise to me that Waldsterben research has not been very successful in the past. In addition to these more general aspects, the history of Waldsterben research has some peculiarities of its own, which from my point of view have inevitably led to false and inefficient activities.

- Forest decline, there is no doubt about it, has much to do with trees and forests. Consequently foresters, more than others are able to see it, to feel it, to judge it. At least in our country, they are fairly under-represented on the boards of research funding and planning.

- Forest decline is also a disease. Therefore the rules of pathology have a special and direct meaning. These rules tell us, that all research in disease etiology has to start with an intense study of symptoms. This golden experience has been ignored by Waldsterben-programs in more than one country. It's often an open question whether researchers are talking about the same phenomenon. As an example, a number of hypotheses are based on very special criteria in one species only, restricted to special regions.

- Other hypotheses do not even mention a symptom.

- Secondary symptoms are often interpreted as primary ones. Without the advice of experienced pathologists things sometimes run in the wrong direction.

- Up to now we cannot be sure whether or not forest decline in the United States and Waldsterben in Central Europe is the same phenomenon. It's high time to prove it. How else can it be done than with a tool named symptomatology?

We are all aware, and it is deeply acknowledged, that Waldsterben research started with remarkable activities in monitoring wet and dry deposition. We had dozens of projects on the effect of acid rain on soil chemistry, on leaf surfaces and on nutrient uptake. We also learned quite a bit about the detrimental effects of ozone on the cytology and physiology of leaves. But we seldom focussed these investigations precisely on cases which, for sure, belong to the Waldsterben-syndrome. So I wish you would keep this sentence in mind: Take symptomatology seriously and do not take the second step before the first.

My second and even more basic concern:

Waldsterben probably is the most serious and complicated threat forests were ever exposed to. Many biotic and abiotic parts of forest ecosystems are affected. Under these conditions a well-prepared, far-reaching national and international research strategy, is of central importance. What is practiced in reality is kind of jumping from one favourite component to the next: SO_2 - Acid Rain - Ozone - frost - photooxidants - organic compounds. If we will ever succeed in solving this problem - then by chance. What I wish to stress is: Research strategy has first rank, made by professionals, not by politicians and not by administrators. And this strategy has to be transferred into an international system of coordination. Immediately, if you ask me. Otherwise, Waldsterben research most probably will remain what it presently looks like: Molecule Brownian motion - very active but without direction and progress.

Forest Decline in the Federal Republic of Germany

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Abstract

Forest decline in the Federal Republic of Germany started mainly with Norway spruce in Southern Germany in 1980, and 1982 elsewhere. First symptoms of decline of silver fir were already detectable as early as 1976. Between 1985 and 1987 there was a considerable increase in decline of deciduous trees, especially of European beech. Unlike coniferous trees, the symptomatology and causality of the decline of deciduous trees are still very unclear.

The obvious, most important symptom of decline of Norway spruce is needle chlorosis combined with magnesium deficiency. According to the current state of knowledge, the combinatory effect of poor nutrient status in the soil, caused by geology and acidic deposition, on the one hand, and ozone and acidic fog exposure on the other is the most probable explanation of this novel form of forest decline.

Development and Spatial Distribution of Novel Forest Decline

Within Europe, West Germany is among the countries most affected in recent years by forest damage. All inventories show damage concentrated mostly in southern Germany, south of the Main River (Figure 1). The neighbouring parts of surrounding countries, especially countries to the south like Austria, Switzerland, and France, are also damaged.

Several different species of trees (coniferous and deciduous) are involved. It appears that silver fir *(Abies alba)* first showed apparent symptoms of decline in the mid-1970's, followed by Norway spruce *(Picea abies)* in 1980 in southern Germany and elsewhere in 1982, and some deciduous species such as European beech *(Fagus sylvatica)* and oak *(Quercus* sp.) in 1984 and 1985. With respect to the severity of symptoms and distribution of damage, Norway spruce seems to be the most important. Although more severely damaged, silver fir stands are concentrated in relatively small areas, especially at higher altitudes of the southern German subalpine mountains, so that this type appears to be less important overall.

In Norway spruce, the main symptoms are needle chlorosis, which increases with elevation of the stand, and thinning of the crown, which occurs more at lower elevations and in the plain. With respect to specificity, intensity, and distribution, needle chlorosis in the higher elevations of the subalpine mountains is considered as the really relevant type of damage of Norway spruce. Moreover, the greatest amount of scientific information is available for this type of damage.

Needle chlorosis can be clearly associated with deficiencies of nutrients in the tree, especially deficiencies of magnesium (Figure 2), calcium (see Figure 3), zinc, potassium, and manganese. The supply of other nutrients, especially nitrogen and phosphorus, is, on the whole, sufficient. At some sites where damage is especially severe and which are far from industrial and urban centres, even the concentration of sulfur is significantly lower in yellow needles than in green needles, reaching the range of deficiency of this essential element. This is an important observation for causality in implicating leaching rather than sulfur toxicity as a factor. Only needles exposed to the sun turn yellow.

Older trees are affected more by chlorosis than younger ones. Stands with trees of varying ages and varying types with a rough canopy are more affected than even-aged and uniform stands with a closed canopy.

As already explained, it is most striking that the intensity of needle chlorosis is very much dependent on elevation (Figure 4). Furthermore the damage is not concentrated in the, with respect to sulfur dioxide, highly polluted areas of Rhine and Ruhr but in the remote areas of the Black Forest, the Bavarian Forest and other subalpine mountains. So any causal factor which is brought into discussion has to fit this temporal and spatial pattern.

It has to be added in this connection that there is a clear preference for needle chlorosis on magnesium deficient, acidic soils. On the other side, however, forest decline is not strictly limited to a specific bedrock. At least the dependency on altitude is much stronger than on any soil condition or bedrock situation. So the soil is considered to be an important accompanying factor in the causation of forest decline but not a decisive one.

Poor soil conditions, caused by bedrock and land management, also existed in the past. But forest decline has never reached such dimensions in space and time like now. The discussion has to concentrate on the crucial point why this phenomenon happened just now and why it happened just in the existing spatial variation.

One of the first descriptions of the phenomenon of novel forest decline and attempts to explain it were undertaken by PRINZ et al. 1982. Since that time much literature has been published. For further details, and under a rather subjective view, the following references are given (Prinz et al. 1985, Prinz et al. 1987, FBW 1986, Prinz 1987, Krause 1987, Krause 1988).

Evidence for and Against the Role of Atmospheric Pollutants

Each attempt to explain the cause of forest decline has to start with the phenomenological aspect. Furthermore it has to consider

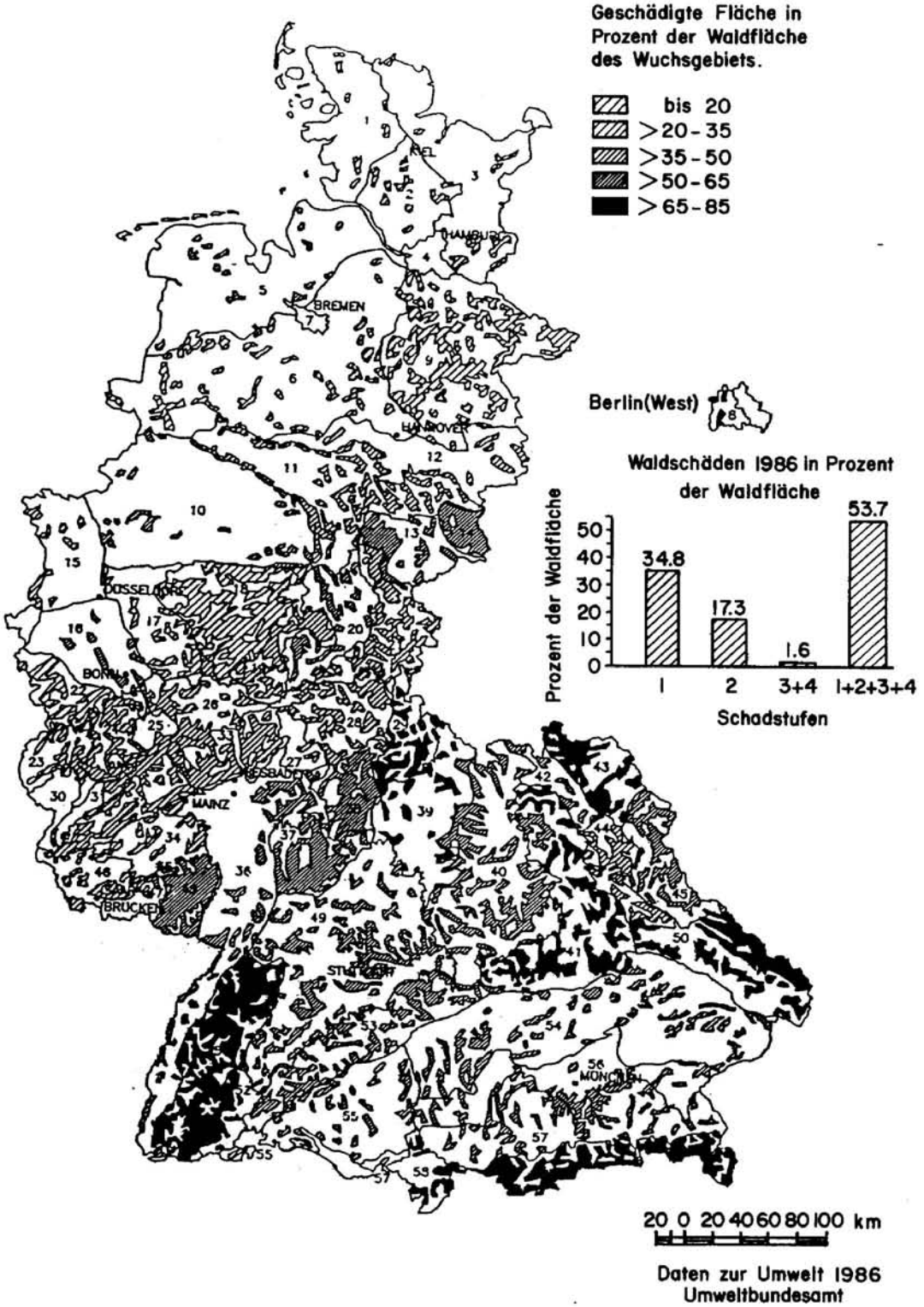

Figure 1.--Distribution of forest decline (all damage classes of all tree species) in the Federal Republic of Germany in 1986. The damage areas are presented as a percent of the forest area within individual growing districts No. 1 to 53 (BML 1986).

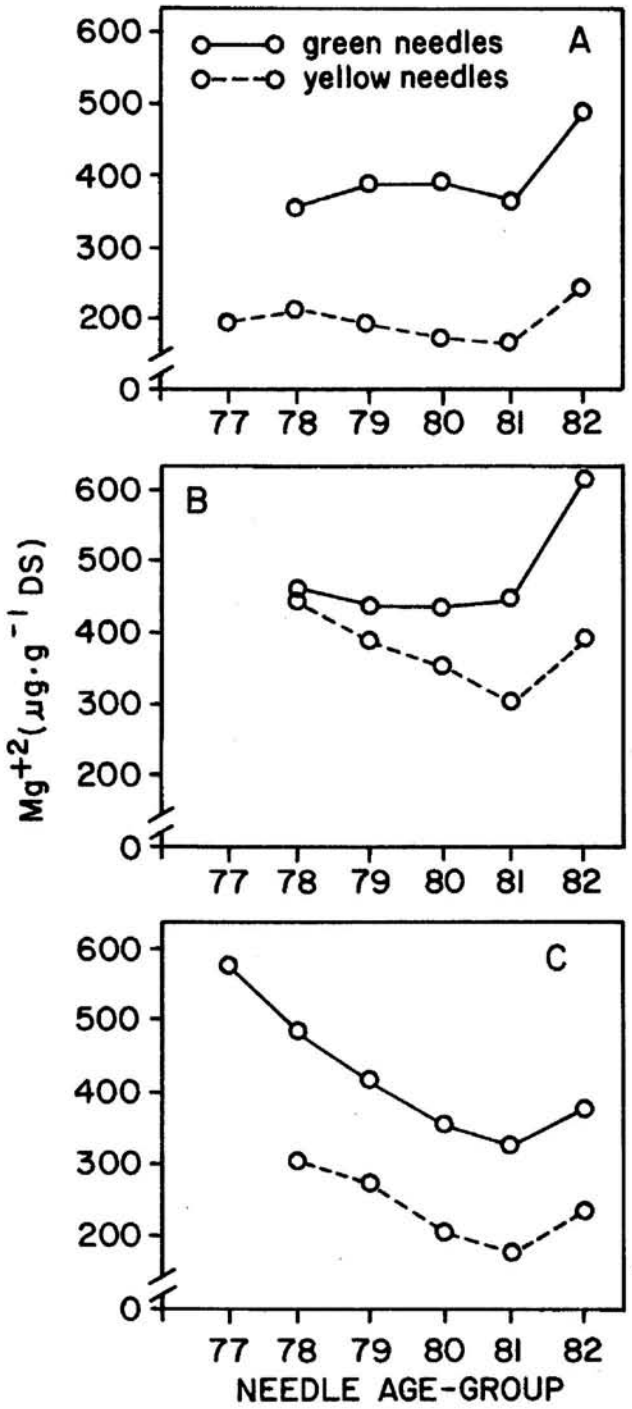

Figure 2.--Concentration of magnesium in needles of Norway spruce with different degree of discoloration. Samples were taken from three different stands in Baden-Wurttemberg (A) und North Rhine Westphalia (B and C) (Prinz et al. 1982).

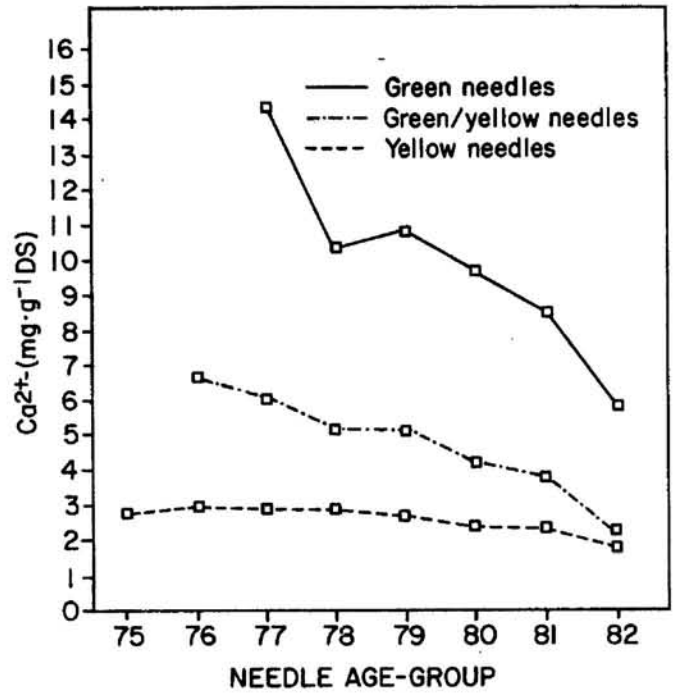

Figure 3.--Concentration of calcium in needles of Norway spruce with different degree of discoloration from a stand in Baden-Wurttembertg (Prinz et al. 1982).

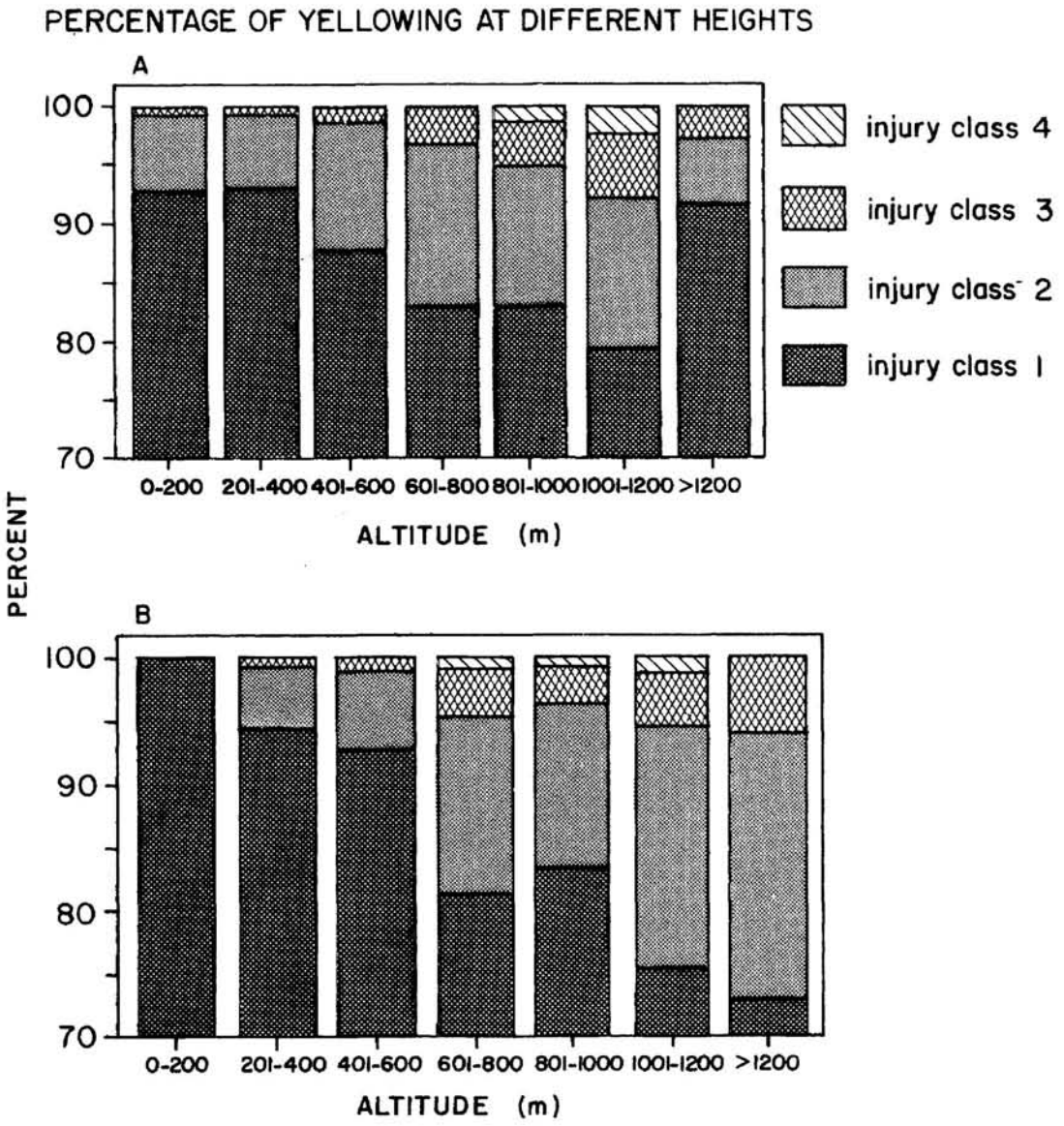

Figure 4.--Percentage of stands of Norway Spruce with discoloured needles dependent on elevation. The situations in the states of Baden-Wurttemberg a) and Bavaria b) are presented as two prominent examples. The steps 1 to 4 mean 0% - 10%, 11% - 25%, 26% - 60%, and 61% - 100% discolouration (FBW 1986).

that plants react to a lot of different factors at one time. Unfortunately sufficient information is only available for Norway spruce and silver fir. Because of its limited distribution, however, Silver fir is of minor importance.

As already explained, the typical symptom of the decline of Norway spruce is yellowing of older needles, combined with deficiency of cationic nutrients, especially magnesium. Magnesium deficiency and chlorosis start synchronously in the previous years' needles with the budding of new needles in springtime. A second step is observable in late autumn. The preference of damage to mixed stands with rough canopies has already been mentioned.

Histologically, the phloem seems to be especially affected. The assimilation rate is reduced mainly by loss of chlorophyll and not so much by malfunction of the remaining chloroplasts.

The change of environment during the last decades as possible causes for the described phenomenon concerns the following factors:

Climate. Dry, warm summers with long periods of sunshine in 1975, 1976, 1980, 1982, modified by regional influences. In North Rhine-Westphalia, for example, also the summer in 1983 was dry, warm and sunny.

Air pollution. Decrease in emissions of sulfur dioxide and most other pollutants, but increase in nitrogen oxides emission. Increase in ambient nitrate deposition and photooxidants. Perhaps also increase in ammonia deposition. At least during the last 20 years no further increase in rain acidity. The only component with a clear relationship to spatial distribution of chlorosis of spruce is ozone. This component clearly increases in concentration with increasing distance from source areas and with increasing altitude. Also of importance is acidic fog with different composition than rain in the higher elevations.

Soil. Obvious loss of buffer capacity and nutrients, with the exception of nitrogen, during the last decades, due to harvest of biomass and acidic deposition. It must be mentioned, however, that no real time-series analysis exists for soil acidification. More data result from reexaminations of the soil immediately after damage had been discovered, i.e. in dry warm summers after 1980. This is of importance because strong, climatically induced variation of soil pH is well known.

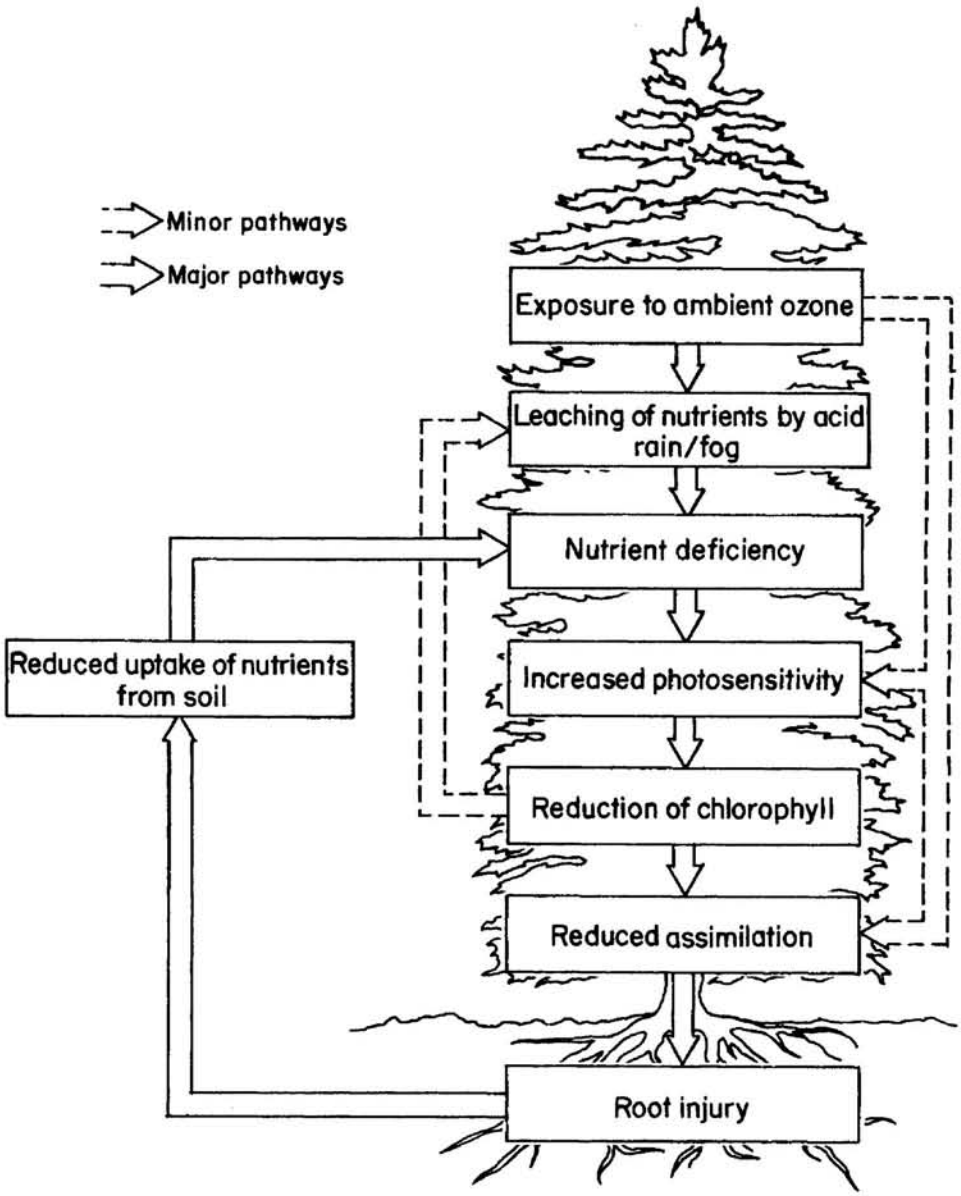

Figure 5.--Possible impact of ozone and acidic fog or rain on conifer forests (Prinz et al. 1985).

In agreement with the second report of the Forschungsbeirat "Waldschaden/Luftverunreinigungen" (FBW 1986) the following assumption seems at the moment to be the most probable explanation of chlorosis of spruce. For other tree species other hypotheses may be more valid, including the influence on deciduous trees of "wet" summers after "dry" summers combined with the attack of parasites.

Causes for the temporal development:

- upward trend of ozone concentration during the last decades
- continuous loss of nutrients in soil by acidic deposition.

Causes for spatial distribution:

- increase of ozone concentration (as a daily average) with increasing altitude;
- geogenic differences in nutrient supply.

Cause for short term appearance (and recovery):

- climate as a triggering or synchronizing factor.

The crucial point in the chain of effects seems to be the impact of ozone on the cell membrane system, the loss of nutrients by leaching, the interaction of the soil and the root system with the impact of ozone on the above ground part of the tree (Figure 5.)

Evidence for this assumption includes:

- Reproduction of the light effect on nutrient deficient trees in the experiment.
- Enhanced leaching after ozone exposure, proven in experiments (Prinz et al. 1985) as well as in natural stands (Fabig et al. 1987). Significant increase of leaching if trees grow on poor soil and are already damaged, which was proven in experiments (Prinz et al. 1985) and in natural stands (Kaupenjohann et al. 1987).
- Effect of ozone on root system by way of nitrate accumulation (Krause, unpubl. data) as well as change in cytokinin and phenolic substances (Schwartzenberg and Hahn 1987, Strack 1987).
- The effect of aluminium on uptake of nutrients is also proven. On the other side no single relationship between intensity of damage and aluminium content in soil or needle exists, although this has to be expected in principal. The observation that in fertilizer experiments not calcium but magnesium provided the greatest initial effect on the recovery of trees suffering from chlorosis leads in the same direction. This means that chlorosis is not a simple reaction to soil pH but more a reaction to insufficient magnesium supply.

Evidence against this assumption includes:

- Episodes of forest decline have always existed. On the other hand, no episode in historical time developed in such a systematic way and was so widely distributed.
- The whole chain of effects has not yet been reproduced. This is especially true for the symptom of needle chlorosis. Here, one has to consider, however, that young trees used in experiments, are also "healthy" in nature, in contrast to the older trees. Furthermore, there is no doubt as the novel type of forest decline is a long lasting process with its own dynamics. In agreement with several other studies, spruce trees fumigated with ozone in experiements at the LIS (Krause and Höckel 1988) showed an initial increase in nutrients. But, nutrient levels decreased, compared to controls, after exposure for 1½ years in the Egge Mountains. It also has to be taken into consideration that ozone concentrations are well in the range of possible damage, apart from chlorosis of spruce, as shown experiments with Austrian Pine and beech (Prinz et al. 1985). Ozone-like damage was observed for the first time this autumn (1987) on white pine exposed in the Egge Mountains in eastern North Rhine Westphalia.
- Nutrient deficiency symptoms are quite normal and therefore without specific sign of decline even on extremely poor soils. This is only partly true since trees can adapt to quite different soil conditions when accustomed to this situation from very early youth.

Needs for further investigations

It is not possible to go into much detail here. The general concept of the research programme in the state of North Rhine-Westphalia (see Köth and Prinz, this proceedings) has the following three integrated stages:

- experiments in exposure chambers with controlled treatments with air pollutants,
- experiments in open top chambers within a damaged stand with application of natural and filtered air as well as with natural and "purified" rain,
- highly sophisticated observations with morphological, histological, physiological, biochemical and genetechnological methods in naturally exposed trees within a damaged and a control stand.

This concept has the following rationale. If only controlled experiments are executed, the question always remains open whether these results are comparable with natural conditions under quantitative as well as interactive aspects. So for example, the temporal pattern of concentration of air pollution in the field will never be replicated in a really realistic manner in the experiment. Also the more or less complex interaction with climate and soil can never be reproduced in full detail. On the other side, the observations in the natural stand very rarely provide conclusions about the factors causing damage with the exemption that the reactions observed in the plants of the natural stand are extremely specific.

The open top chambers are useful links within this integrated concept. If one gains the same principle results in all three stages

than one can be fairly sure that the clue to the problem of forest decline has been found.

One has to confess that much valuable work has been done meanwhile on coniferous trees. Only a very limited section of the current state of knowledge could be given here. One of the main important questions still to be investigated is the influence of air pollutants, especially of ozone on the crown of the tree with secondary effects on the root system. At the same time the interactive effect between direct damage by air pollutants and soil conditions should be studied. On the whole, there is still an immense gap of knowledge with respect to deciduous trees. Future investigations will certainly focus especially on this aspect.

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Outline of Results from "Early Diagnosis of Forest Decline" Survey Carried Out in Europe in 1986

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Abstract

In 1986 a group of institutions carried out a survey of 14 sites spread across a transect of Europe from the Black Forest area of W. Germany to the North of Scotland. Samples gathered from Norway spruce, Scots pine and beech trees were subjected to an array of possible diagnostic indicators of forest decline. Some of these tests, especially with Norway spruce needle samples, showed a clear discrimination between sites. The data from the Scottish sites were often at one end of the range and the results from W. German sites at the other. These differences could be attributed to genotype, soil type, climate, etc. and are not necessarily pollutant induced. However, some of the tests were capable of making a discrimination based on injury when site effects were removed by logistic regression.

Over the past two decades, enhanced combustion of fossil fuels for power generation and transport has caused the emissions of oxides of nitrogen to increase whereas sulphur dioxide emissions have decreased slightly as the result of desulfurization and other control measures. As a result, tropospheric concentrations of ozone have also increased, particularly in rural areas. Predictably, these pollutants have been linked to the causes of recent forest decline in Central Europe but there is wide disagreement over which air pollutant (if any) is primarily responsible. Possible interactions between various atmospheric pollutants and other environmental stresses on plants further complicate the question. Analysis of tree ring growth patterns tend to indicate that this problem of forest decline started over 20 years ago. Intensive research activity has so far failed to isolate potential pathogens that could induce the phenomenon. Moreover, several different tree species from different genera are affected and it is very unusual for a particular pathogen to attack more than one genus.

National forest surveys based on visual appearance of trees have documented the extent to which different species in different areas of Europe have been affected, but, apart from the yellowing of needles associated with certain magnesium-deficient sites, a biochemical/physiological assessment of the numbers of affected and unaffected trees in forests, which can also be simulated by controlled fumigations with suspected atmospheric pollutants in the laboratory, has been lacking. In 1986, a survey of three species (Norway spruce, Scots pine and beech) at 14 sites across Europe from the Black Forest to North Scotland, known to have a wide range of pollution climates (Table 1), was undertaken (Cape et al. 1987, see also acknowledgments). Most of the samples collected were subjected to a wide range of 28 possible tests (Table 2) in the hope that such studies would provide nonvisual quantitative indicators of tree health and supply hints concerning the possible causes of forest decline.

Part of the survey team based at the Natural Environment Research Council Institute of Terrestrial Ecology (NERC-ITE) in Scotland was concerned with tests which provided information on changes of needle surfaces as well as with overseeing the analyses of major nutrients. Large site differences for Norway spruce (but not Scots pine) were shown in the amounts of surface waxes on present year (1986), previous year (1985) and 2-year-old needles (1984). All UK sites had smaller amounts of wax than continental sites. Similar differences were shown with the Hartel (1953) test but we believe that the response of this test to air pollution is more complex than thought hitherto. Large site differences were also shown by measurements of the contact angle formed with droplets of pure water were placed on sample needle surfaces. Consistently smaller values were found on older spruce needles gathered from UK and Dutch sites than those from W. German sites (Figure 1). Absolute values for Scots pine were less useful but the year-to-year changes showed a marked geographical pattern.

Changes in ultrastructure, gas exchanges, and modulated fluorescence were monitored by Dr S Fink, Freiburg University, Dr PH Freer-Smith, Ulster University (now UK Forestry Commission), and the Lancaster University group, respectively. All showed encouraging results which obviously require further development, but timing difficulties or the complexities of the techniques prevented their full participation in the whole survey. Lack of time also prevented the full use of measurements of levels of free radical scavengers such as α-tocopherol, glutathione and ascorbate by the Lancaster University group.

Initial measurements of pH of whole-needle homogenates and the titration of these were both acid or alkali to determine buffer capacities were also undertaken by the Lancaster University group. Large site differences were shown with determinations of leaf pH with less acidic values being shown by UK sites. However, buffering capacity of 2-year-old Norway spruce needles did not differ in any consistent way between sites. In current-year needles (1986), alkaline buffering (pH 8-10) was significantly reduced at W. German and Dutch sites but no significant site-related trend in acid buffering (pH 3-5) was apparent.

The same group also measured ethylene and ethane emission rates from small branches from each of the trees at the different sites as well as the levels of individual pigments in 2-year-old needles. Rates of ethylene emission from individually damaged Norway

Table 1.--Summary of sampling site locations and their relative long term atmospheric pollutant climates (Cape et al. 1987)

Site code	Location	Number of trees sampled[a]	Pollution climate[b]		
			O_3	SO_2/NO_2	Acidity
	W. Germany				
D1	Kalbelescheuer (Black Forest)	12/-/8	+ + +	+	+ +
D2	Haldenhof (Black Forest)	8/4/6			
D3	Langebramke Sud (Harz)[c]	8/-/-	+ +	+	+ + +
D4	Langebramke Nord (Harz)[c]	8/-/-			
D7	Fichtelberg (E. Bavaria)	8/8/8	+ + +	+ + +	+ + +
D8	Selb (E. Bavaria)	8/8/8	+ + +	+ + +	+ + +
	Netherlands				
N1	Kootwijk (Gelderland)	6/6/6	+ +	+ +	+ + +
N2	Rips (Limburg)	6/6/6	+ +	+ + +	+ + +
	UK				
E1	Ashford (S.E. England)	8/8/8	+ +	+ +	+ +
E2	Winchester (S. England)	8/8/8	+ +	+ +	+ +
S1	Glenbranter (W. Scotland)	8/8/8	+	+	+ +
S2	Darnaway (N.E. Scotland)	8/8/8	+	+	+

[a] Norway spruce/Scots pine/beech.
[b] + = light; + + = medium; + + + = heavy.
[c] 8 Scots pine sampled at Celle (D5) and 8 beech at Witzenhausen (D6) nearby.

spruce and Scots pine trees varied greatly, but generally there were lower emissions from Norway spruce samples gathered at Scottish sites than those from the Netherlands or W. Germany (Figure 2). The emissions for Scots pine appeared to be related more to tree age. Analysis of pigments (both chlorophylls and carotenoids) by spectrophotometry and HPLC of pigment extracts from needles, frozen by immersion in liquid N_2 in the field, showed low violaxanthin to antheraxanthin ratios in 2-year-old Norway spruce needles and low violaxanthin to lutein ratios in Scots pine needles from UK sites when compared to analyses of those sample extracts from Dutch and W. German sites (Figure 3).

Stepwise discriminant analysis of all the results for 2-year-old Norway spruce needles indicated that 14 of the 42 variables measured by the survey team were capable of marking a significant (>5%) contribution to the discrimination between sites (Table 3). When these were used in a simple average linkage cluster analysis, a clear discrimination between geographically adjacent sites was achieved (Figure 4). There was also a separation along a transect from Scotland to S. Germany with some similarities between sites in England, the Netherlands and the Harz region of W. Germany. If the 14 variables identified by stepwise discriminant analysis (Table 3) were used in a canonical discriminant analysis, then it was possible to rank the sites in terms of the first three canonical variables (Table 4). When these were related to the pollution climates (Table 1) of the sites then the first canonical variable was found to correlate significantly ($p<0.01$) with only mean rainfall pH and ozone, while the second

Table 2.--Diagnostic tests used in 1986 survey and collaborational responsibilities (asterisk indicates percent of dry weight).

1. Histological examination (Freiburg)

2. Water droplet contact angle measurements (NERC-ITE)

3. Hartel test (NERC-ITE)

4. Cuticular waxes (NERC-ITE)
   a. surface wax*
   b. insoluble surface material*

5. Needle composition (NERC-ITE)
   a. nitrogen*
   b. sulfur*
   c. calcium*
   d. magnesium*
   e. potassium*

6. Modulated leaf fluorescence (Lancaster)

7. Hydrocarbon emissions (Lancaster)
   a. ethylene
   b. ethane
   c. higher hydrocarbons

8. pH (Lancaster)
   a. initial leaf/needle homogenate pH
   b. acid buffer capacities
   c. alkaline buffer capacities

9. Pigment ratios (Lancaster)
   a. chlorophyll a to b
   b. total chlorophylls to carotenoids
   c. β-carotene to chlorophyll a
   d. β-carotene to xanthophylls
   e. violaxanthin to antheraxanthin
   f. violaxanthin to lutein

10. Levels of free radical scavengers (Lancaster)
    a. glutathione
    b. ascorbate
    c. α-tocopherol and metabolites

11. Physiological measurements (Ulster)
    a. shoot/water relations
    b. CO_2 exchange

12. Basic parameters and bases of expression (all)
    a. fresh weight
    b. dry weight
    c. various ratios based on a. and b. above
    d. visual injury classification on CEC system

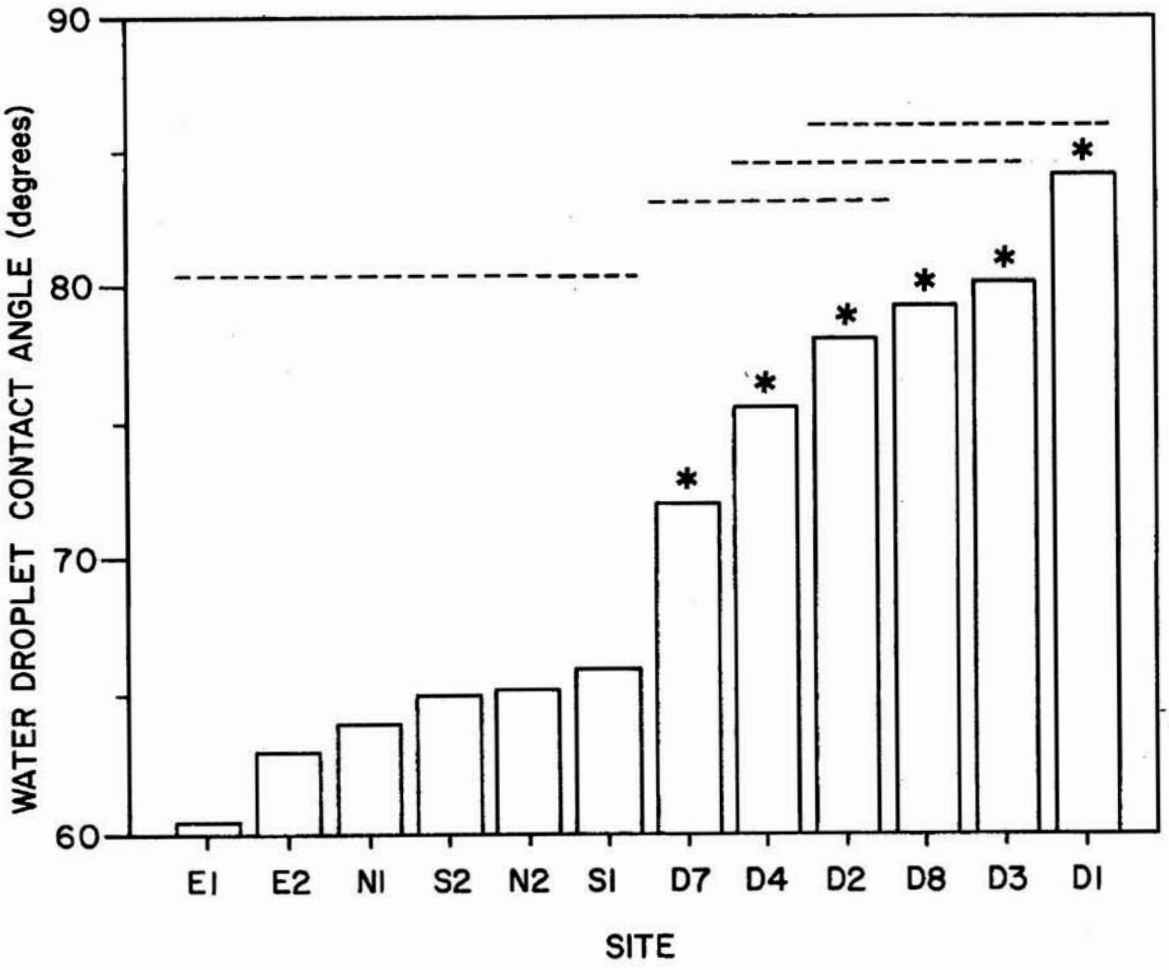

Figure 1.--Water droplet contact angles of 2-year-old Norway spruce needles gathered at different sites. Sites under the same horizontal bar are not significantly different from each other ($p > 0.05$) while an asterisk indicates sites differing significantly from site S2 ($P < 0.05$).

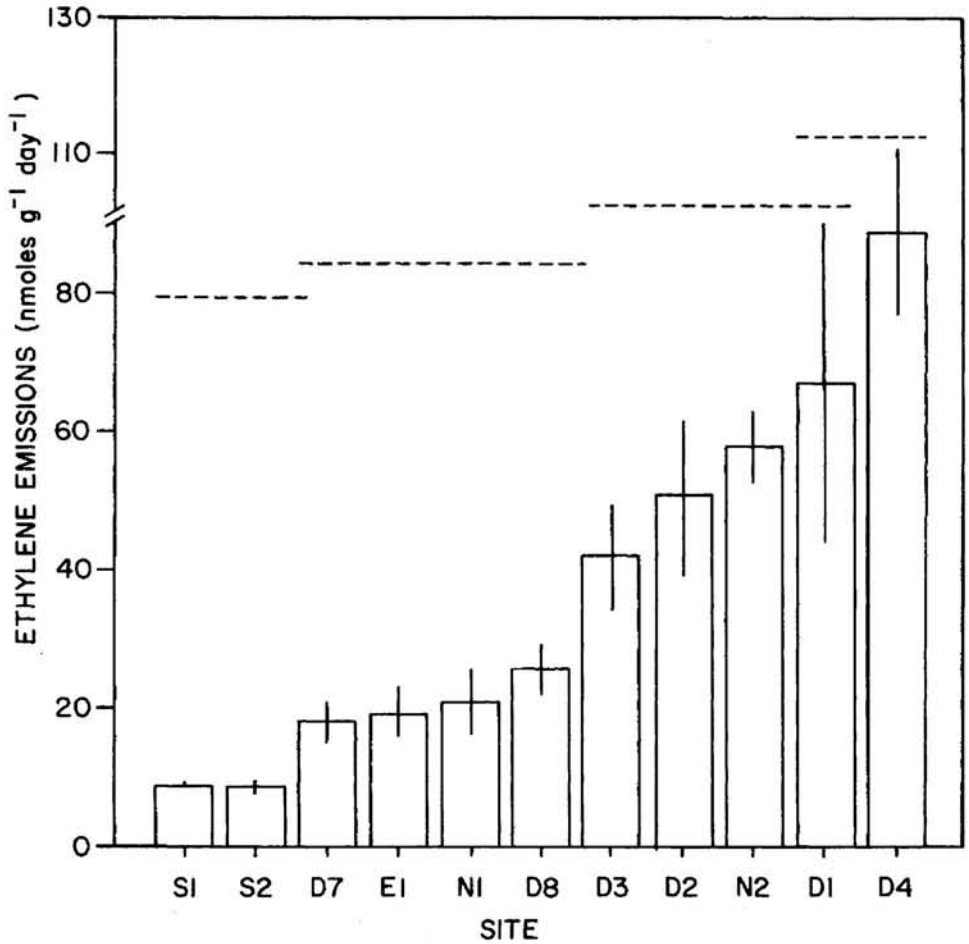

Figure 2.--Rates of ethylene emissions from Norway spruce needles gathered at different sites. Each result indicates the mean and standard error of at least 54 samples (3 replicates each from 3 needle ages of at least 6 trees) while sites under the same horizontal bar are not significantly different according to Duncan's multiple range test.

canonical variable correlated weakly ($p > 0.06$) with deposited acidity and the third ($p < 0.07$) with primary pollutant gases. The site ranking produced for the first canonical variable (Table 4) was very similar to the clustering produced by the average linkage method (Figure 4).

As will be observed in Figures 1-3, Duncan's Multiple Range Test was applied throughout most of the tests to identify similar sites and this is denoted by the dashed horizontal lines above the bars while asterisks are used to denote sites significantly different from S2 in Scotland. However, correlations between different tests have also been undertaken. Figure 5, for example, illustrates the strong correlation between rates of ethylene emissions from and the ratios of violaxanthin to antheraxanthin in 2-year-old Norway spruce needles at different sites. Equally interesting and significant relationships between these two tests and needle contact angles or dry weight differences between current and 2-year-old needles were found.

During this 1986 survey, wherever possible, samples of needles were taken equally from trees showing both damage or no obvious damage when the CEC standard classification of forest decline symptoms (Bauer 1984) were applied. Logistic regression analysis was applied to the respective classifications of trees from which samples were taken for tests with the intention of removing site effects. From such analyses three parameters were identified free from site effects from which it was possible to define the probability of tree injury. Moreover, these could be combined together to further strengthen the possibility of being able to use diagnostic indicators free from subjective visual classifications as a means of documenting the extent of forest decline in the field. These particular three parameters were the dry weight differences between present and 2-year-old needles, the rates of ethylene

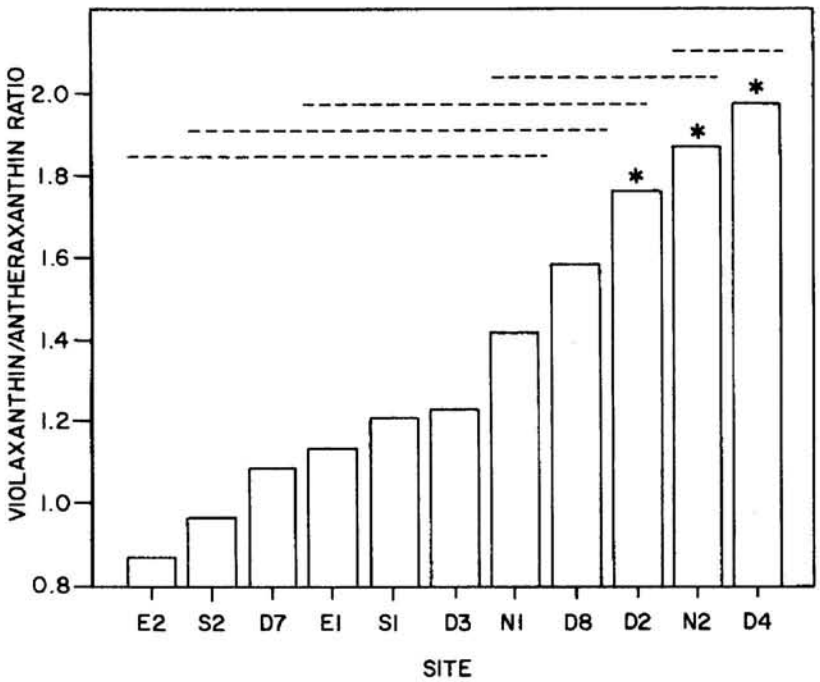

Figure 3.--Pigment ratios from 2-year-old Norway spruce needles gathered at different sites showing violaxanthin/antheraxanthin ratios. Sites under the same horizontal bar are not significantly different from each other ($P > 0.05$) while an asterisk indicates sites differing significantly from site S2 ($P < 0.05$).

Table 3.--Discriminant analysis for 2-year-old Norway spruce needles showing those variables making a significant (>5%) contribution

Variable	partial r^2	F-static	probability (F)
Needle content of calcium	0.79	20.9	0.0001
Needle content of sulphur	0.75	17.1	0.0001
Needle content of nitrogen	0.73	15.3	0.0001
Tissue homogerate pH	0.65	10.0	0.0001
Water droplet contact angle	0.62	8.8	0.0001
Needle content of magnesium	0.60	7.9	0.0001
Dust as percent of dry wt	0.55	6.5	0.0001
Violaxanthin:antheraxanthin	0.51	5.2	0.0001
Chlorophyll:xanthophyll	0.46	4.2	0.0002
Chlorophyll a:b	0.62	8.0	0.0001
Needle content of potassium	0.43	3.6	0.0007
Violaxanthin:lutein	0.41	3.3	0.0019
α-tocopherol	0.38	2.8	0.0062
Dry wt as percent of fresh wt	0.37	2.6	0.0094

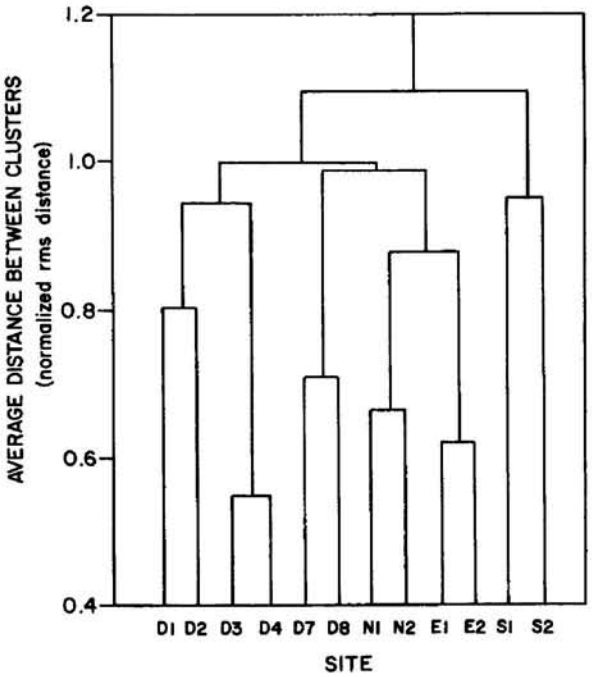

Figure 4.--Average linkage cluster analysis of sites using the 14 variable defined by the discriminant analysis (Table 3).

Table 4.--Site means for the first three canonical variables using 14 discriminant variables shown in Table 3 for 2-year-old needles of Norway spruce

Canonical variable					
1		2		3	
Site	Mean	Site	Mean	Site	Mean
S1	6.2	D8	4.1	N2	4.4
S2	4.2	D7	4.0	N1	2.5
E2	3.7	E1	1.1	S1	1.6
E1	2.8	S1	1.0	D1	1.4
D8	0.7	D3	-0.2	D8	1.2
N1	-0.9	D2	-0.5	E2	0.4
N2	-1.3	D4	-0.8	D7	-0.2
D3	-2.3	N1	-1.1	E1	-0.9
D2	-2.6	N2	-1.5	D4	-1.9
D1	-3.0	E2	-1.5	D2	-1.9
D4	-3.2	S2	-2.1	D3	-2.1
D7	-3.4	D1	-4.0	S2	-2.9

emission, and the ratios of violaxanthin to antheraxanthin. The results of a logistic regression analysis of an analysis combining all these three are shown in Figure 6.

Taken individually, these three tests would tend to imply that injury or decline is brought about by different factors. Growth (or lack of it) in the case of dry weight differences, general environmental stress of undefined cause by enhanced ethylene emissions, and photo-oxidant damage in the case of altered epoxidation of the two xanthophylls. When combined together they appear to cover the different components of forest decline and serve to emphasise how much more likely it is that the phenomenon is brought about by several interacting stresses--one of which is probably ozone.

One of the major benefits of the 1986 study was the very close collaboration in the field among the participating institutions especially NERC-ITE and Lancaster University. This meant that a very wide range of techniques could be applied to the same plant material and a much more complete picture has been gained than could have been obtained by the application of individual tests in isolation.

In order for any of these tests (or any other) to be of value as diagnostic tests, they must now be studied in greater detail under controlled conditions. The criteria for their successful development are:

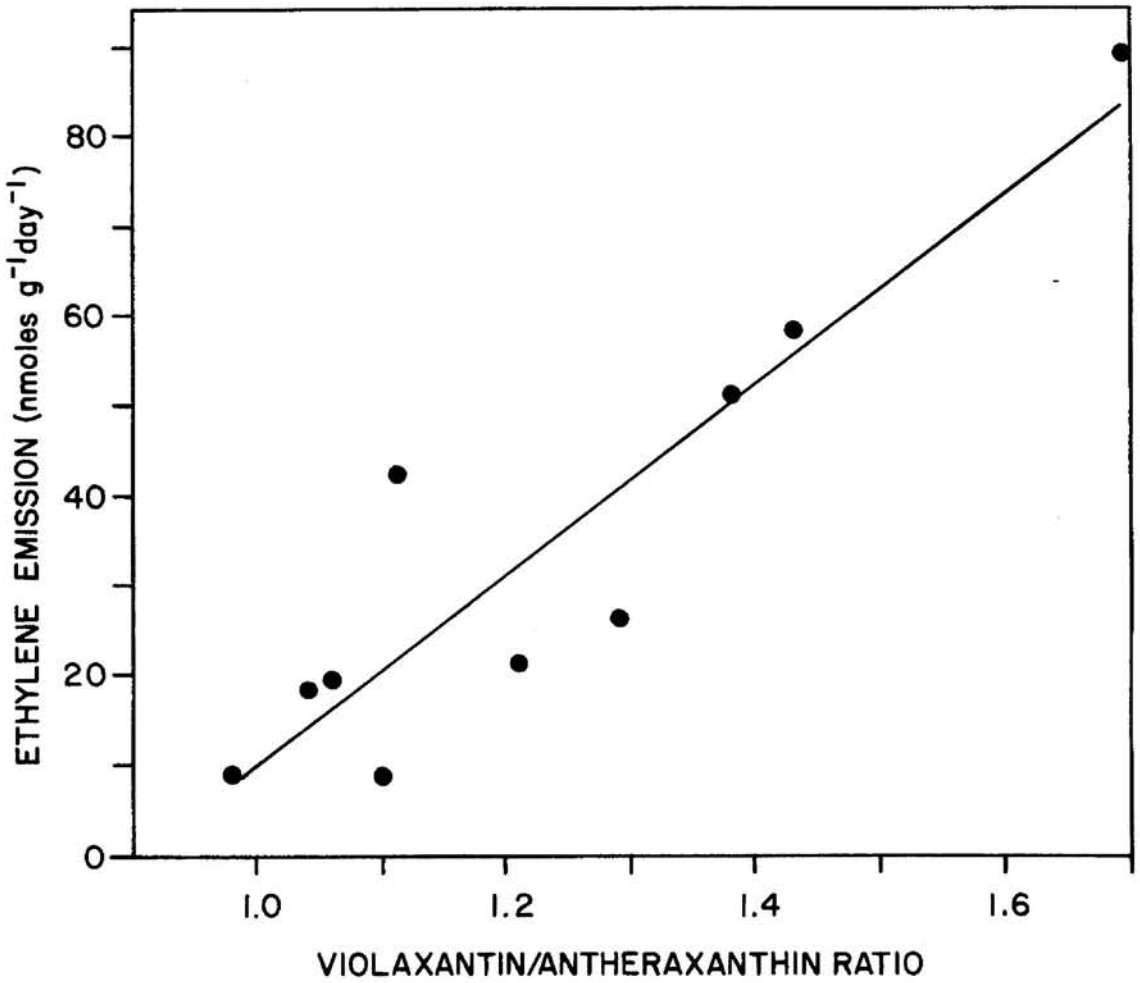

Figure 5.--Correlation of rates of ethylene emissions from Norway spruce needles collected at different sites to their respective mean ratios of violaxanthin to antheraxanthin. Each point is the mean of at least 6 trees and the slope of the fitted line: r is 0.873 ($P<0.01$).

(a) Small variation between genotypes,

(b) Small (or controllable) variation with conditions (e.g. weather),

(c) Small (or predictable) variation with leaf/needle age,

(d) Small (or predictable) variation with tree age,

(e) Specific response to individual pollutants.

In addition, the influences of other stresses (e.g., frost, drought or nutrient deficiency) should be recognized, although these may interact with pollutant stresses.

Plans are already well advanced to grow young trees and rooted older shoots in controlled environments for use in further development. Ultimately, the refined tests will need to be reexamined by more extensive surveys in the field which we hope will take place in 1990 or 1991, but funding for this is still required. However, we marked each of the trees from which samples were taken at the different forest sites and it would be very interesting to gain further results in 1990 or 1991 from the same trees as used in 1986.

Acknowledgments

We are grateful for financial support which came from the European community, the UK Natural Environment Research Council, the UK Department of the Environment and now also from the NAPAP programme but we must acknowledge a host of others who formed part of the team: I.S. Paterson (ITE), J. Wolfenden (Lanc), H. Mehlhorn (Lanc), P.H. Freer-Smith, S.

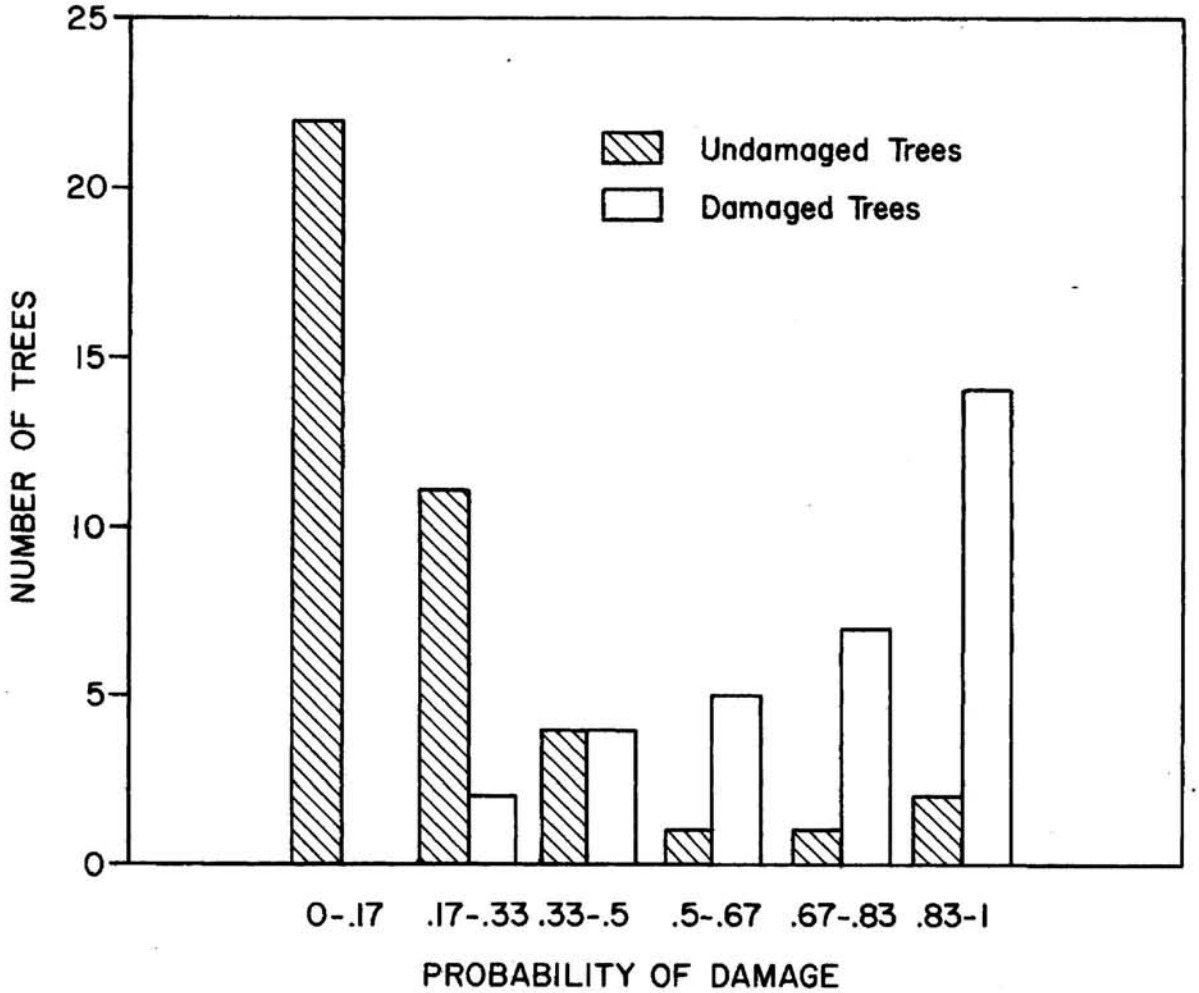

Figure 6.--Numbers of Norway spruce trees that fitted into classes of probability of injury calculated by multiple logistic regression analysis of the logarithms of the dry weight differences from present year to 2-year-old needles plus the violaxanthin to antheraxanthin ratios from 2-year-old needles as well as their emissions of ethylene. The overall value of p was less than 0.01.

Fink (Freiburg); T. Vogt (ITE), J. Bacigalupo (ITE), D.C. Robinson (Lanc) who provided technical support; I.A. Nicholson (ITE), F.T. Last (ITE), K. Percy (Canada), R.B. Wilson (DOE), who assisted with planning; W.D. McIlveen (Ontario), D. Threlfall (Hull) who provided additional help and W.M.J. den Boer, H.J. Schreuder, R.A. Prins, C.H. Gast (Netherlands): B. Ulrich, E. Matzner, O. Benecke (Gottingen): E.D. Schulze, R. Owen, K. Werk, U. Schurr (Bayreuth): W.O. Binns, J. Innes, I. Embry, M.H. Webb, B. Redfern, R.E. Selmes, J. Stannard (UK Forest Commission): M.J. Chapman, V. Thompson (Darnaway Estate, Scotland), who made available site facilities and helped us a great deal.

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Evaluation of Tree Mortality in the Spruce-Fir Forest of the Southeastern United States

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Abstract

*An aerial photographic and ground evaluation was made by the USDA Forest Service in the spruce (**Picea rubens** Sarg.) and Fraser fir (**Abies fraseri** [Pursh] Poir) type during 1985. The purpose of the evaluation was to delineate on maps the entire spurce-fir type and to classify and map tree mortality and/or decline. This information, which was entered into a geographical information system, and the 100 percent aerial photographic coverage will serve as baseline data for determining future trends on the status of spruce-fir in the Southeast. Results of the evaluation showed 65,752 acres (26,609 hectares) of spruce-fir in the southern Appalachians. Overall tree mortality was 8 percent for red spruce and 67 percent for Fraser fir.*

Introduction

Concern about mortality in the spruce-fir forest of the southeastern United States indicated an immediate need to conduct a survey to map the extent and severity of the damage. The forest type is comprised of red spruce (*Picea rubens* Sarg.), which occurs from North Carolina to Nova Scotia, and Fraser fir (*Abies fraseri* [Pursh] Poir.), which occurs only in North Carolina, Tennessee, and Virginia.

Because of the geography and topography of the region, spruce-fir forests in the South occur as a series of island-like stands at high elevations. The southern Appalachian spruce-fir is believed to be threatened by an exotic insect pest, the balsam woolly adelgid (*Adelges piceae* Ratz.), by atmospheric deposition of pollutants, and possibly by other agents. This forest type represents an extremely valuable resource in the South because of its unique natural beauty, its importance for recreation, and its importance as a seed source for Christmas trees and nursery industry. It is considered by many to be a threatened species type because of its marked decline in area.

In addition to the threat of the balsam woolly adelgid, the spruce-fir type may be particularly vulnerable to atmospheric deposition of pollutants. These high-elevation forest types probably receive more deposition because of the higher precipitation and cloud immersion than lower elevations. The complicated nature of the spruce-fir forest mortality and the difficulty in establishing a cause and effect relationship indicated a more pressing need for establishing baseline data on the current status of the spruce-fir type and its relationship to previously recorded geographic information which may be analyzed through the utilization of a geographic information system (GIS).

Objectives

1. Locate and delineate on maps all red spruce and Fraser fir in the southern Appalachians.
2. Classify all red spruce and Fraser fir mortality (percent of dead standing trees) visible on aerial photographic coverage in the states of Tennessee, North Carolina, and Virginia.
3. Using a combination of aerial photographic sampling and ground checks, estimate losses within the spruce-fir type.
4. Acquire large scale aerial photography of previously established research plots.
5. Develop and implement a geographic data base on the extent and intensity of mortality in the spruce-fir type in North Carolina, Tennessee, and Virginia.
6. Provide for comparisons between the extent and intensity of mortality in relation to other geographic information through the computer analysis, storage, and display of spacial (geographic) information.

Methods

Aerial Photographic Acquisition

Color infrared aerial photography at a scale of 1:12,000 of the entire spruce-fir type was acquired in stereo during the summer (leaf-on season) of 1984. An Aero Commander 680-F, equipped with an RC-10 camera and a geographic coordinate referenced navigation system, was used to acquire the photography. In the winter of 1985, true color positive transparencies were acquired in stereo during the leaf-off season over the entire spruce-fir range at a scale of 1:12,000. This photography was used to modify the previously identified boundaries and mortality strata for more specific and detailed evaluations. Underflights were made of previously established research plots at a scale of 1:4,000. All photography was indexed on USGS 1:24,000 scale topo sheets, and the photography and maps were available to other investigators.

Photo Interpretation

Boundaries of the spruce-fir were delineated by skilled aerial photographic interpreters directly on the aerial photographic transparencies using Bausch and Lomb 240 zoom stereoscopes mounted on MIM 4 Richards light tables. For this project, the spruce-fir type was defined as any area where spruce or fir was discernible on the aerial photographs. The boundaries of the type and mortality classes were then transferred to 1:24,000-scale USGS topo maps. Within the spruce-fir type, the following

categories of mortality were recognized: (1) light to moderate--less than 30 percent of the standing dominant and codominant trees dead, (2) heavy--30 to 70 percent standing dominant and codominant trees, and (3) severe--more than 70 percent of the standing dominant and codominant trees dead.

Stratification and Selection of Sample Plots

During the photo interpretation, individual areas were sampled within the three mortality classes. Each mortality class was randomly sampled in proportion to the area of spruce-fir type affected. Two hundred and thirty-two 1/5-acre plots were selected on Mt. Mitchell, Roan Mountain, Blue Ridge Parkway, and Great Smoky Mountains National Park. Randomly selected 1/5-acre plots were viewed in stereo to determine the number of dead spruce and fir trees, and the total number of spruce and fir trees visible in the plots.

Ground Survey

A total of 132 of the 1/5-acre photo plots was randomly selected as plots for the ground phase of the evaluation. Ground crews located the center of the photo plots on the ground and marked them with a metal stake. General information, such as slope, aspect, and the presence of balsam woolly adelgid, was collected. Starting at the center of the plot, a cluster of five sampling plots were established, with the center stake serving as the first point and the other four systematically arranged in a procedure similar to that used by the Southeastern Forest Experiment Station, Forest Inventory and Analysis work unit, as described in their field instruction book. Data were taken at each point in a variable size plot established by a prism with a basal-area factor of 37.5. A fixed-radius plot of 6.8 feet was also established at each point in the cluster. There were two sets of data taken at each point in the cluster on two separate data sheets. The following data were taken on each tree for the variable size sampling points: (1) species, (2) d.b.h. (5 inches or greater), (3) condition, (4) total height, (5) crown position, and (6) destructive agents. On the 6.8-foot radius plots, the following data were taken on each tree 1 inch d.b.h. or greater: (1) species, (2) d.b.h., (3) condition, (4) destructive agents, and (5) crown position.

Map Digitizing and Data Entry

Maps were reviewed before data entry to verify proper attribute placement and polygon closure, as well as edge mapping adjacent quad sheets. The boundaries of the spruce-fir type, with the interior areas classified by mortality, were digitized from 27 quad sheets. The MOSS family of software was used as the GIS for data entry, analysis, and display of the data. The GIS is a set of software for encoding, transformatting, analyzing, and displaying map and other geographic-based information. The system includes three components: (1) the Analytical Mapping System (AMS) for digital data entry; (2) Map Overlay and Statistical System (MOSS) and Map Analysis and Processing Systems (MAPS) for data processing, analysis, and display; and (3) Cartographic Output System (COS) for plotting and producing maps. This software was installed on a MV 4000 Data General minicomputer with over 800 megabytes on line disk storage capacity along with a high-density tape drive. The system also includes two large-format digitizing stations with graphic terminals, color graphic display stations, image display station, and text terminals. An eight-pen plotter provides map output products.

Primary data themes, i.e., those data layers which would be found for all topo maps containing spruce-fir type, were created as follows: (1) spruce-fir type boundaries, (2) spruce-fir mortality classification, (3) topography, (4) transportation, (5) ownership, and (6) drainage. Secondary data themes which included information over portions of the spruce-fir type were: (1) study plot locations, (2) photo index, (3) disturbance history, (4) balsam woolly adelgid protection boundaries, (5) balsam woolly adelgid mortality history, (6) balds, (7) spruce-fir forest type (with hardwood component) for the Great Smoky Mountains National Park, (8) railroad right-of-ways for previous logging activities, (9) 1960 mortality map for Mt. Mitchell, and (10) other data themes as they become available.

Results and Discussion

Data were analyzed by region of spruce-fir type in the Southeast as follows: (1) Great Smoky Mountains National Park, (2) Blue Ridge Parkway, (3) Roan Mountain, (4) Grandfather Mountain, (5) Mt. Rogers/White Top Mountain, and (6) Mt. Mitchell. Data were also compiled to summarize conditions throughout the Southeast. At this time, distribution of the spruce-fir and mortality in relation to elevation has been the primary focus of investigations.

Maps displaying the distribution and stratification of mortality in relation to all primary data themes were produced with legends indicating the total number of acres of spruce-fir type classified by mortality. An analysis of the data for spruce-fir mortality by region will include the following GIS analysis: (1) mortality classification expressed in number of acres and percent of area by geographic region (Table 1), and (2) acres of mortality stratified by elevation expressed as a percent of total area by region (Table 2). Spruce-fir mortality data analysis, based solely on ground truth, will include: (1) percent of spruce and fir mortality classified by elevation for each region (Table 3), and (2) percent of the stand component for spruce and fir classified by elevation for each region (Table 4).

At this point, severe mortality appears to occupy a greater proportion of the area at higher elevations as opposed to lower elevations. These higher elevation stands also contain a much greater percentage of Fraser fir. Fraser fir mortality, as observed in this study, is very consistent with reports of published balsam woolly adelgid activity. A very strong agreement between ground sample points and aerial sample points was found, indicating that future surveys could rely on photography with only a minimum of ground surveys.

Table 1.--Spruce-fir forest in the Southeast, classified by mortality

Geographic area	Light mortality No. acres	Light mortality %	Heavy mortality No. acres	Heavy mortality %	Severe mortality No. acres	Severe mortality %	Total No. acres
Great Smoky Mountains National Park	35,759	73	2,692	6	10,365	21	48,816
Mt. Mitchell	5,409	75	289	4	1,514	21	7,212
Roan Mountain	256	17	583	38	698	45	1,537
Mt. Rogers/White Top Mountain	1,582	100	0	0	0	0	1,582
Grandfather Mountain	659	71	124	13	145	16	928
Blue Ridge Parkway	2,058	37	550	10	2,989	53	5,597
Total	45,723	70	4,238	6	15,711	24	65,672

Table 2.--Spruce-fir mortality in the Southeast, stratified by elevation

L = light mortality; H = heavy; S = severe

	Mortality (% of Area)											
	4600 ft			4600-5200 ft			5200-5800 ft			5800-6400 ft		
Geographic area	L	H	S	L	H	S	L	H	S	L	H	S
Greak Smoky Mountains National Park	7	0	0	39	2	0	26	3	15	1	1	5
Mt. Mitchell	4	0	0	22	0	0	29	1	2	19	3	16
Blue Ridge Parkway	1	0	0	6	1	1	26	8	34	5	1	18
Roan Mountain	0	0	0	1	1	0	10	16	24	5	22	21
Grandfather Mountain	7	0	0	28	1	1	35	12	12	1	0	1
Mt. Rogers/White Top Mountain	2	0	0	54	0	0	44	0	0		NA	
Spruce-Fir Type in the Southeast	7	0	0	34	1	1	25	3	13	4	2	9

It should be noted that this survey was a one point in time analysis of mortality within the spruce-fir type and certainly not a measure of mortality over a period of time. Also, it is a measure of mortality of trees 5 inches or greater and does not include reproduction. It is known that a spruce or fir tree may stand for up to 20 years and still may be visible on aerial photographs. Further investigations will be necessary to develop a stronger cause and effect relationship to account for mortality observed during this survey.

In general, the spruce-fir type in the Southeast occupies 65,752 acres. Seventy-four percent of this forest type was found to occur on the Great Smoky Mountains National Park, followed by Mt. Mitchell at 11 percent, Blue Ridge Parkway at 10 percent, Roan Mountain at 2 percent, Mt. Rogers/White Top at 2 percent, and Grandfather Mountain at 1 percent.

Within the spruce-fir type, 70 percent of the total area was classified as light to moderate mortality (less than 30 percent standing dead trees); heavy mortality occupied 6 percent of the total area (30 to 70 percent dead), and 24 percent of the total area was classified as severe mortality (more than 70 percent dead). Overall tree mortality for the entire type was 8 percent for red spruce and 67 percent for Fraser fir.

Table 3.--Results of ground truth for spruce-fir mortality, by elevation stratum

N = number of trees sampled

Geographic area	4200-5400 ft				5400-6000 ft				6000-6500 ft				Overall	
	Spruce		Fir		Spruce		Fir		Spruce		Fir		Spruce	
	N	%[a]	N	%	N	%	N	%	N	%	N	%	N	%
Mt. Mitchell	102	10	4	100	83	13	57	23	18	39	54	72	203	14
Roan Mountain	17	6	27	67	83	1	181	50	16	13	129	30	116	3
Blue Ridge Parkway	12	0[b]	14	0[b]	128	5	160	93	5	0[b]	3	0[b]	145	5
Great Smoky Mountains National Park	105	13	44	100	147	6	120	88	25	4	14	86	277	9

[a] Percent of sample trees dead.
[b] Insufficient sample size.

Table 4.--Spruce-fir forest type stand component in percent, by elevation stratum for ground samples
(S = red spruce; F = Fraser fir)

Geographic area	4200-5400 ft			5400-6000 ft			6000-6500 ft			Overall	
	S	F	Other	S	F	Other	S	F	Other	S	F
Mt. Mitchell	58	2	40	35	24	41	22	66	12	41	2
Roan Mountain	19	31	50	27	59	14	11	87	2	21	6
Blue Ridge Parkway	21	24	55[a]	33	42	25	63	38	0	32	3
Great Smoky Mountains National Park	52	22	26	43	36	21	64	36	0	48	

[a] Insufficient sample size.