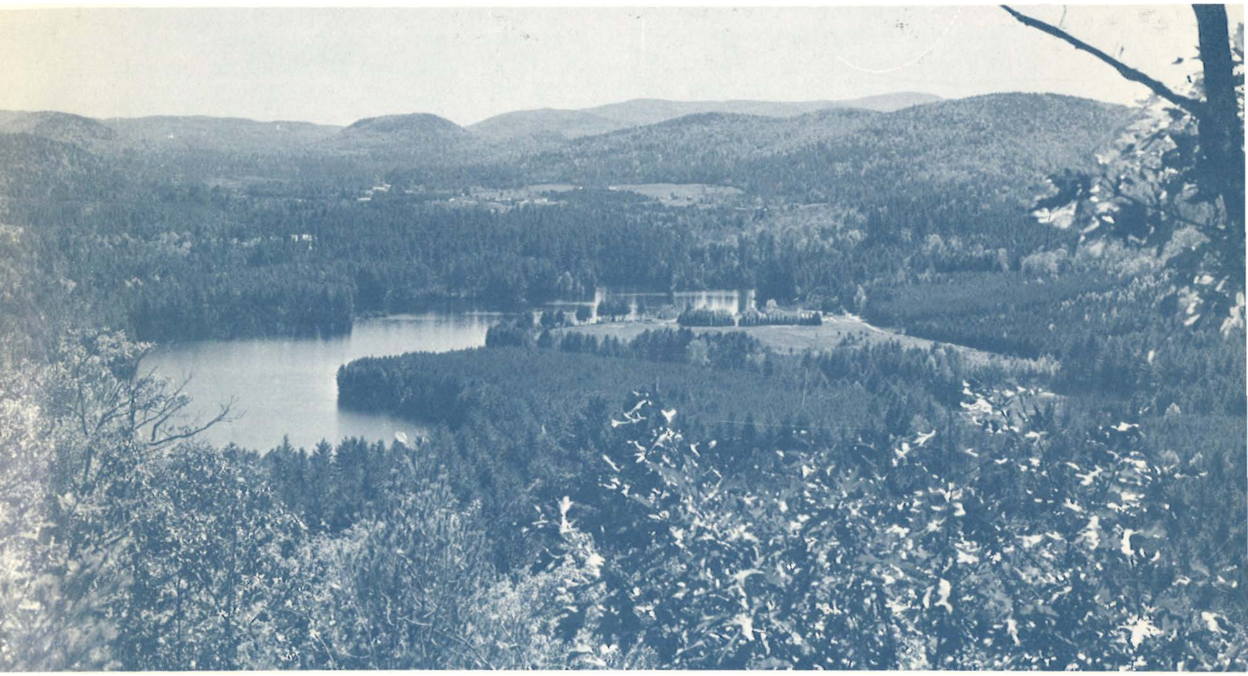
FOREST FERTILIZATION

Symposium Proceedings



PLANNED AND PRESENTED by

the Northeastern Forest Soils Conference

SPONSORED by

the Canadian Forestry Service and
the USDA Forest Service, Northeastern
Forest Experiment Station

HOSTED by

the State University of New York College
of Environmental Science and Forestry

USDA FOREST SERVICE GENERAL TECHNICAL REPORT NE-3
1973

FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
NORTHEASTERN FOREST EXPERIMENT STATION
6816 MARKET STREET, UPPER DARBY, PA. 19082
WARREN T. DOOLITTLE, DIRECTOR

FOREWORD

FOREST FERTILIZATION is a cultural practice becoming available to forest land managers for use in meeting management objectives. Like other cultural practices, it involves an investment in the site, it may result in an array of side effects in the ecosystem, and it must fit logically into long-range management plans.

It has long been known that if nutrient elements are critically deficient on a site for particular plant species, and the rest of the physical environment properties are adequate, the addition of such elements will improve the growth and development of these plants. What has limited forest-fertilization practice in the past is economic feasibility, the interactions within the environment, and more recently the environmental impacts of this practice.

We need to know the differences in nutrient element demands by different tree species at different densities of stocking and different stages of development. We need to know the availability of nutrient elements on a site in relation to the total physical environment and biota. And we need to be able to properly diagnose which element is low or limiting for a given site and species, and how much of the element is required for optimum effectiveness. We need to know how to predict the magnitude of growth and other responses that can be expected from given treatments for different sites and species, and the values to management of these responses compared to the investments in fertilization practices.

Some of this information is known, for some regions, sites, and tree species. However, in the northeastern United States and eastern Canada, relatively little information is available, and relatively few forest-fertilization programs are in action. And within our region, it appears that the information for eastern Canada may, in some respects, surpass that information available in the northeastern United States.

There are many reasons for the apparent lack of this cultural practice in our region: the variety of land-use objectives, landownership patterns, markets, and current concerns of environmental quality in the megalopolis region. Though information about the use of fertilizers to increase wood-fiber production in our region is inadequate, there is even less information about fertilizer programs for non-wood production uses of land in eastern Canada and northeastern United States; for example, recreational site development. Regardless of land-use, healthy, vigorous vegetation is a general common concern. In many places, a carefully designed forest-fertilization program may be worth considering.

When the Northeastern Forest Soils Conference decided in 1970 to form a Committee on Forest Fertilization, it drew together an expression of interest in this cultural practice in the region. This regional Symposium is an outgrowth of the interest expressed.

This Symposium is presented by the Northeastern Forest Soils Conference, with support and financial backing by the USDA Forest Service and the Canadian Forestry Service, and with the cooperation of the State University of New York College of Environmental Sciences and Forestry. We hope a step ahead has been taken in organizing existing information on this subject and in expressing the potential value of this cultural practice in our region.

–ALBERT L. LEAF and RAYMOND E. LEONARD

Dr. Leaf is Chairman, Committee on Forest Fertilization, Northeast Forest Soils Conference, and Professor of Forest Soil Science and Chairman of the Forest Resources Council of the State University of New York College of Environmental Science and Forestry, Syracuse, N. Y. Dr. Leonard is Research Forester, Northeastern Forest Experiment Station, Forest Service, USDA, Durham, N. H.

FOREST FERTILIZATION
Symposium Proceedings

THIS SYMPOSIUM
ON FOREST FERTILIZATION IN AN ENVIRONMENTAL SETTING IN THE NORTHEASTERN UNITED STATES AND EASTERN CANADA

was held at the Charles Lathrop Pack Demonstration Forest on the Warrensburg Campus of the State University of New York College of Environmental Science and Forestry, 22-25 August 1972.

PLANNED AND PRESENTED by
the Northeastern Forest Soils Conference

SPONSORED by
the Canadian Forestry Service, Department of the Environment, and the Northeastern Forest Experiment Station, USDA Forest Service

HOSTED by
The State University of New York College of Environmental Science and Forestry

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COVER PHOTO: View of Charles Lathrop Pack Demonstration Forest, site of pioneering forest fertilization research in the United States and host to the Forest Fertilization Symposium.

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Northeastern Forest Experiment Station
USDA Forest Service
6816 Market Street
Upper Darby, Pa. 19082

Information Branch
Canadian Forestry Service
Department of the Environment
Ottawa, Canada

State University of New York College
of Environmental and Resource
Management, Syracuse Campus,
Syracuse, N. Y. 13210

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https://doi.org/10.2737/NE-GTR-3

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ON BEHALF OF THE U.S. FOREST SERVICE

by WARREN T. DOOLITTLE, *Director, Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Upper Darby, Pa.*

ALL OF US are deeply indebted to the sponsors of this Symposium, and particularly to the Northeastern Forest Soils Conference and the State University of New York College of Environmental Science and Forestry. I know Al Leaf worked very hard on this program on behalf of both the Conference and the College, and I am particularly pleased to have the Canadian Forestry Service join with the U. S. Forest Service, the Conference, and the College in planning, sponsoring, and carrying out this affair.

It seems especially fitting that this Symposium is being held here at Pack Forest. Pack Forest is a sort of cradle of fertilization here in the United States. It was here, some 20 years ago, that Sven Heiberg and Don White were finding out that severe deficiencies in certain nutrient elements drastically reduced the growth and development of red pine and other species. Of particular concern was potassium, which was a major limiting factor on abandoned farm lands that had been planted to trees.

Since then, much other fertilizer and nutrient research has been conducted here and in other places across the continent. Much has been learned about nutrient deficiencies and the interrelationship of nutrients, plants, soil, and water.

More recently, researchers have begun to look at some of the side effects of fertilizers and nutrients as they relate to level of application and forest treatment or management—particularly timber removal and fertilization. We will hear more about these side effects later in the program.

Though most of us are probably interested primarily in fertilization as a means of increasing tree growth and wood production, I am glad to see that we are also going to be looking at the positive and negative values as fertilization relates to special forest crops, recreation, wildlife habitat, water production, revegetation of disturbed land areas, and insect and disease control.

As you know, critics of forestry today are very quick to use our own research against us, especially where negative values from certain practices have been reported. A good example has been the results of nutrient cycle studies at the Hubbard Brook Experimental Forest in New Hampshire. The loss of nutrients from a cutover and chemically treated watershed was repeatedly picked up and reported as what happens after clearcutting of New England hardwood stands. Furthermore, these results were projected nationwide to show the effects of clearcutting.

More recent studies at Hubbard Brook have shown results of nutrient losses following conventional timber cutting methods. While the loss of nutrients is still higher than we would like to see, we now have something more realistic to work with, and prompt regeneration promises to further minimize these losses.

I cite this example of a side effect for two reasons. First of all, we need to know what is happening when we cut, fertilize, or otherwise treat our forest stands. Such knowledge may cause us to change or correct certain management techniques. In harvesting timber on certain soils or in revegetation efforts following fire or surface mining, we may find it necessary and desirable to add fertilizer to replace or renew certain nutrients.

And second, we need to be alert to the implications of some of our research. By this I mean that we need to report our results in such a way that they will be interpreted correctly. This means using proper terms and labels; it also means discussing the results fully and not allowing partial or leading implications that may contribute to erroneous conclusions by others.

Much research has been accomplished on the use of fertilizers and the basics of nutrient deficiencies. Much still needs to be done in relating fertilizer levels to specific species, soils, and management objectives. Much of the job remaining is a job for research, but an important part of the task involves the classification and relation of tree performance to soils and nutrient levels. We also need to know the many possible side effects of fertilizers for these soils and trees. In fact, the number of combinations of possible treatments, species, soils, and side effects is frightening; this task will surely require a careful setting of priorities and selection of tasks. Gentlemen, you have your work cut out for you.

ON BEHALF OF THE CANADIAN FORESTRY SERVICE

by PETER J. RENNIE, *Program Coordinator, Soils, Program Coordination Branch, Canadian Forestry Service, Department of the Environment, Ottawa.*

IT IS UNFORTUNATE these days that the predominant may never be as newsworthy as the trivial. The normal is displaced by the bizarre. And the solid achievements resulting from regular, informal, and matter-of-fact exchanges tend to be forgotten. This is nowhere truer than in United States-Canadian relations, and in forestry it might almost be regarded as strange to examine the countless exchanges between our two countries or to begin to quantify the value of such exchanges.

Nevertheless, I believe it is sometimes necessary to remind ourselves of the intimacy of our relationships, and they have nowhere been more genuine than in the meetings of the Northeastern Forest Soils Conference. Informal and enjoyable scientific excursions have been held for many years in both our countries in the Northeast. These have done much to develop personal friendships and to foster a mutual awareness and understanding of one another's problems in forestry and soil science.

When I first heard of the proposal to mount a formal regional symposium whose theme was to give emphasis to forest fertilization in an environmental context, I was confident that the solid base of contacts built up over the years would contribute much to such a symposium's success.

But there were other reasons why we in Canada should wish to support this Symposium and why the Canadian Forestry Service of the Federal Department of the Environment responded immediately and positively to the invitation to join in co-sponsorship. Interest in forest fertilization in Canada has escalated rapidly within the past few years. As elsewhere, programs as yet are largely research and development, rather than operational; but numerous different agencies are active. There is industry itself; there has been industry in collaboration with the Pulp and Paper Research Institute of Canada; there are the forest services of certain of the provincial governments; there are the universities; and there is the Federal Canadian Forestry Service.

I do not wish to bore you with statistics, but collectively these agencies are devoting over 30 professional man-years and one million dollars annually to forest fertilization and closely related mineral nutrition. Moreover, programs range from over 250 field trials to numerous complementary studies covering adult forest, nursery nutrition, and special situations such as fertilization to secure dominance in overdense stands, to improve Christmas trees, and so forth.

Finally, those of us who have approached forest fertilization from the traditional nutrition side have for some time been slotting our studies into a somewhat wider context, where the nature of the reactions of our fertlizer materials with the inanimate and vital components of the ecosystem have been receiving attention for the purpose of increasing the efficiency of fertilization. The logical extension of this development is concern for even wider environmental issues. To give you an example, the Canadian Forestry Service is now one element of a much more comprehensive federal department in which the interests of water management, environmental protection, fisheries, wildlife, and land inventory find greater scope for collaborative endeavour. It is not surprising, therefore, that several joint studies have commenced in which the environmental impact of forest-management practices, including of course fertilization, is the center of focus. In fact, the days of seeking a mere growth-response are over: we seek a reliable, economic, and environmentally safe technology.

Because these aspirations are very much those of the United States Forest Service, it is most apposite that we should join forces to sponsor this novel Symposium, for I am not aware of the nutritional and environmental themes being previously fused to form the basis of a forest-fertilization meeting. Knowing the content of the formal contributions that are about to be presented, I have every belief that our Symposium is in the van of progress and will serve as the forerunner of others similarly conceived.

I am sure that all Canadians from all agencies formally contributing and participating in our Symposium will appreciate the co-sponsorship of the United States Forest Service, expressed through Dr. Warren T. Doolittle, director of the Northeastern Forest Experiment Station, which has made this Symposium possible. We are privileged to enjoy the hospitality and pleasant surroundings of the Charles Lathrop Pack Forest, thanks to Dr. E. E. Palmer, president of the State University of New York College of Environmental Science and Forestry.

Again, I think it is appropriate that Americans and Canadians should be meeting in this historic Hudson-Champlain Valley, which over the years has been a lifeline of such significance in the development of contacts and relationships between our two countries. I notice, of course, that we are a stone's-throw from Saratoga National Park, but anticipate that the cut-and-thrust of two centuries ago will be echoed merely in the quality of our discussion sessions.

Finally, a special word of appreciation must go to Professor A. L. Leaf, as chairman of the Forest Fertilization Committee of the Conference, for successfully doing those many organizational tasks to ensure the success of our meeting.

In closing, may I say that we Canadians are aware how the pioneering work on potassium nutrition here in the Pack Forest two decades ago sparked interest, effort, and progress far outside its original context. I am sure this Symposium will constitute a similar catalyst.

ON BEHALF OF THE STATE UNIVERSITY OF NEW YORK COLLEGE OF ENVIRONMENTAL SCIENCE AND FORESTRY

by CHARLES C. LARSON, *Professor and Dean, School of Environmental and Resource Management, State University of New York College of Environmental Science and Forestry, Syracuse, N. Y.*

THE STATE UNIVERSITY College of Environmental Science and Forestry is honored to serve as host to this Symposium on Forest Fertilization. I take this opportunity to express our appreciation to the Northeastern Forest Soils Conference and to the co-sponsoring organizations—the Canadian Forestry Service and the U. S. Forest Service—for having given us the opportunity to serve in this capacity.

It is a privilege and great pleasure, indeed, to welcome you in behalf of the College to our Warrensburg Campus, perhaps better known to most of you as the Charles Lathrop Pack Demonstration Forest. Established in 1927 through the generosity of the late Charles Lathrop Pack, this campus embraces an area of some 2,400 acres. It is one of five field campuses that the College operates in support of its instructional, research, and public service programs.

The other four field campuses are located at Newcomb, Wanakena, Cranberry Lake, and Tully, New York. The *Newcomb Campus* is the site of the Archer and Anna Huntington Wildlife Forest and the Adirondack Ecological Center. The *Wanakena Campus* is the home of the Ranger School Forest Technician Program, which is being upgraded to a 2-year associate of applied science degree program beginning this year. The *Cranberry Lake Campus* includes another Charles Lathrop Pack Demonstration Forest and the Cranberry Lake Biological Station. The *Tully Campus*, situated south of Syracuse, consists of the Svend Olaf Heiberg Memorial Forest and a Genetic Field Station.

The Campus at Warrensburg serves as the permanent site of the College's summer session in field forestry. This is a 5-week, 6-semester-hour program, emphasizing the field application of forestry principles. It is offered to students in the resource management and forest biology curriculums.

Apart from serving as a major base for field instruction in forestry, the Pack Forest has been for many years the center of much of our field research effort in forestry. Research currently under way on the property involves both College-based and Forest-based projects. Included among the former are investigations in forest soils, fertilization, solar-energy relations with vegetative cover types, tree improvement, the effects of air pollution on the growth of white pine, and pathology studies involving a variety of tree species.

Among the Forest-based research projects currently in progress are long-term studies of white pine growth, the relation of white-pine weevil damage to red heart rot in white pine, lumber grade recovery in white pine and hemlock, high pruning in white pine, the development of specialty uses for low-grade timber products, new techniques in the stabilization of wood products, and the conversion of bark to humus by composting.

The Forest continues, as always, to serve as a demonstration of white pine silviculture and as a major attraction for students, professionals, and others interested in the management of this species.

Forest fertilization research conducted by our College to date has been centered largely at Warrensburg. Following acquisition of the property in 1927, there was a 5-year period of active tree planting on the abandoned agricultural lands of the area. For the most part, these lands had deep sandy soils of low productivity.

About 5 or 6 years after planting, the trees on these areas, mostly red pine, exhibited a significant reduction in growth rate. In an effort to correct this situation, the late Svend Heiberg, then professor of silviculture at the College, initiated a series of trial applications of organic matter, followed by addition of fertilizer salts.

The first application of commercial fertilizers in Pack Forest plantations was made in the spring of 1937, which may be taken as marking the beginning of forest fertilization research at this institution. Since that time the research efforts by faculty and graduate students have documented the particular nutrient element deficiencies, including potash deficiency, and the rate of fertilizer application for near-maximum response in coniferous tree growth on these depleted sandy soils.

During the last decade, research has emphasized developing a better understanding of the physiological-ecological bases of the growth response, of the role of fertilizers in the forest ecosystem, of the effects of stand manipulation, and of the relation of fertilizers to the total physical environment.

From its initiation through 1964, the research in forest fertilization was carried on under the leadership of Professor Heiberg. Since then, Dr. Albert Leaf has provided immediate direction of the research in this sphere.

Support for our forest-fertilization research has derived from both State and outside sources. During the decade of 1959-69, over $100,000 was contributed to the program by the National Science Foundation. Significant contributions to the research have also been made by the U. S. Forest Service.

Our College, like professional forestry organizations everywhere, has been striving for some time to adjust its overall program of instruction, research, and public service to better accommodate the growing concerns of our society for forest-based goods and services and for environmental quality in general.

At the heart of such adjustment, of course, is change—change in programs, in priorities, in organization structure. The process of effecting change in academia is at best an exceedingly slow and difficult task. To accomplish it with reasonable dispatch and success during a period of rapidly expanding academic workloads and declining budgets is well nigh impossible, and certainly a challenge.

Established as a State-supported institution at Syracuse in 1911, the College has enjoyed the advantages, and suffered some of the disadvantages, of developing its program independently of a college of agriculture, the traditional mother institution for professional forestry education in America. Blessed with broadly-conceived enabling legislation, its own governing board of trustees and a wide degree of independence, the College from its very beginning developed a comprehensive approach to professional forestry and, accordingly, a diverse program of instruction, research, and public service.

To better reflect the broad scope of its programs and competence in relation to forest land resources and their associated environments, the name of the College was recently changed by legislative action to "State University of New York

College of Environmental Science and Forestry."

The inclusion of "Environmental Science" in the new name was to emphasize, better than does the term "Forestry" alone for most people, the fact that this College is qualified by virtue of program, mission, and capability to contribute in a major way toward helping to solve many of the environmental problems of our day.

In conjunction with the name change, the enabling legislation for the College was revised to reflect this environmental capability, as well as to incorporate other changes that have occurred in New York State's educational system since the orignal legislation for the College was adopted.

The College is presided over by a President (Dr. Edward E. Palmer), assisted by four Vice Presidents representing Academic Affairs, Research, Student Affairs, and Administration. Its current organizational structure embraces, in addition to the five field campuses previously mentioned, four academic schools and three research institutes: The School of Biology, Chemistry and Ecology; the School of Environmental and Resource Engineering; the School of Environmental and Resource Management; the School of Landscape Architecture; the Applied Forestry Research Institute; the Empire State Paper Research Institute; and the State University Polymer Research Center.

In addition to the three research institutes, the U. S. Forest Service maintains at the College a Cooperative Research Unit that serves to supplement and further strengthen our overall research capability.

The School of Environmental and Resource Management, over which I have the privilege of presiding at present, has responsibility for the professional forestry curriculum of the College. This School has been undergoing rather substantial change during the past year.

I extend to each of you a hearty welcome on behalf of the administration, faculty, and students of the State University of New York College of Environmental Science and Forestry. We wish you a most pleasant and productive conference.

ON BEHALF OF THE NORTHEAST FOREST SOILS CONFERENCE

by WALTER H. LYFORD, *Secretary-Historian of NEFSC and Soil Scientist, Harvard Forest, Harvard University, Petersham, Mass.*

THE NORTHEAST FOREST Soils Conference (NEFSC), through its Committee on Forest Fertilization, is privileged to present this Forest Fertilization Symposium.

The NEFSC started at the Harvard Forest in 1939 with a meeting of a few foresters and soil scientists interested primarily in forest soils, their classification and mapping, productivity and management. Except for a few years during World War II, yearly field-trip meetings have been held in the summer. In the early 1950's, Canadians joined the group, and since then the meetings have been held both in eastern Canada and northeastern United States; for example, in 1971 we met in New Brunswick, in 1972 in West Virginia.

This group is really not an organization. It has a mailing list of about 200 individuals, but there are no membership dues, bylaws, or officers (except for a permanent secretary-historian whose duty is to act as a repository for the records). The chairman of each year's 1 ½- to 2-day field-trip meeting is a forest soil man in the host state or province, and he arranges the field trip for that year. As soon as the field trip is over, he sends the mailing list and any extra funds or debts to the man who will run the field trip the next year.

On these field trips several sites are visited, and the soil and forest on these sites are examined and discussed in detail. Generally 60 to 80 commercial foresters, university faculty, extension foresters, and employees of state or province forestry organizations, Canadian Forestry Service, U. S. Forest Service, and Soil Conservation Service attend.

Generally one or two informal committees are formed each year to examine and report on some matters of current interest. These committees are autonomous and no attempt is made to achieve long-term goals or end up with published reports. However in the past decade publications have resulted from committee work. For example, the Site Classification Committee (E. L. Stone, chairman) in 1961 produced PLANTING SITES IN THE NORTHEAST, published by the Northeastern Forestry Experimental Station, Upper Darby, Pa. and the Forest Nursery Soil Improvement Committee (R. A. Farrington, chairman) in 1965 produced PROCEEDINGS OF NURSERY SOIL IMPROVEMENT SESSIONS, published by the State University College of Forestry at Syracuse University, Syracuse, N. Y.

MODERATOR'S STATEMENT

by EDWIN H. WHITE, *Symposium Moderator and Assistant Professor, Department of Forestry, University of Kentucky, Lexington, Ky.*

FOREST fertilization is fast coming of age as a silvicultural tool in many parts of North America. This is evidenced by the increasing intensity of both research activities and economical field applications of fertilizers to correct known nutrient-limiting tree growth in forest stands. The major responses of southern pines to phosphorus applications on the poorly-drained flatwood soils of the southeastern Coastal Plain and the nitrogen responses demonstrated in the Pacific Northwest are excellent examples of commercial applications of fertilizers to forest stands.

Several industrial-university cooperative research programs have been established to elucidate both the basic and applied problems associated with forest fertilization. Notable among these are the Cooperative Research In Forest Fertilization program (CRIFF) at the University of Florida and the North Carolina State University Forest Fertilization Cooperative.

Several meetings, beginning with the Duke University symposium on mineral nutrition of trees in 1958, and including the TVA Symposium on *Forest Fertilization . . . Theory and Practice* in 1967 and the Third North American Forest Soils Conference in 1968, focused major attention on tree growth and mineral nutrition. However, even as the demand for wood products from the forest is increasing, so also is there pressure to preserve or improve the quality of the environment. Applications of fertilizers to forest stands affect much more than wood production, including the water, wildlife, and recreation aspects of a forest ecosystem. In eastern North America the most important forest resource in the near future may well be quality water.

The papers of this Forest Fertilization Symposium reflect the growing awareness by forest researchers of the total ecosystem approach to forest-fertilization problems and potentials in eastern North America.

REGIONAL OBJECTIVES IN FOREST FERTILIZATION: CURRENT AND POTENTIAL

by EARL L. STONE, *Charles Lathrop Pack Professor of Forest Soils, Department of Agronomy, Cornell University, Ithaca, N. Y.*

ABSTRACT. A region defined by a 1,500-km. diameter (465-mile radius) circle around Warrensburg, N. Y., contains a variety of climates, vegetation types, and economies. With but a small fraction of the land area, this region contains between one-fourth and one-third of the total population of North America north of Mexico. The vast and varied impacts of this great population impose an increasing degree of regional concern with uses and values of forest land. Nine regional objectives for use of this land are discussed.

I TAKE IT that my task today is to state our interests in holding this conference, and to remind ourselves of various facts and hypotheses that make up the background for our discussions. The following speakers may build upon this groundwork or, on the other hand, may amend, reshape, or destroy it.

My assigned title somehow implies that we are dealing with a defined geographic region and, moreover, that the objectives appropriate to it are in some way unique or different from those applicable to other regions. At first glance, neither of these assumptions seemed self-evident to me. To begin with, probably no two of us would draw the same geographic or ecological boundaries around our region. And I suspect that every other region would claim some substantial interest in each of the objectives we shall list.

OUR REGION

But to focus our attention and to free us from the tyranny of existing boundaries I have arbitrarily created a circular region, 1500 km. in diameter, and centered on our meeting site here at Pack Forest (fig. 1). The borders of this region are wholly free of bias, though perhaps inconvenient at points and likely to be distressing to administrators who properly must think in terms of states, provinces, and counties. But any one who wishes to modify the borders is welcome to replace some of the inordinately large area of ocean with presently excluded portions of New Brunswick, Ontario, or West Virginia or to exchange Virginia pine for more black spruce or balsam.

Our idealized region is some 465 miles in radius—a day's drive wherever roads permit. And so the first characteristic of

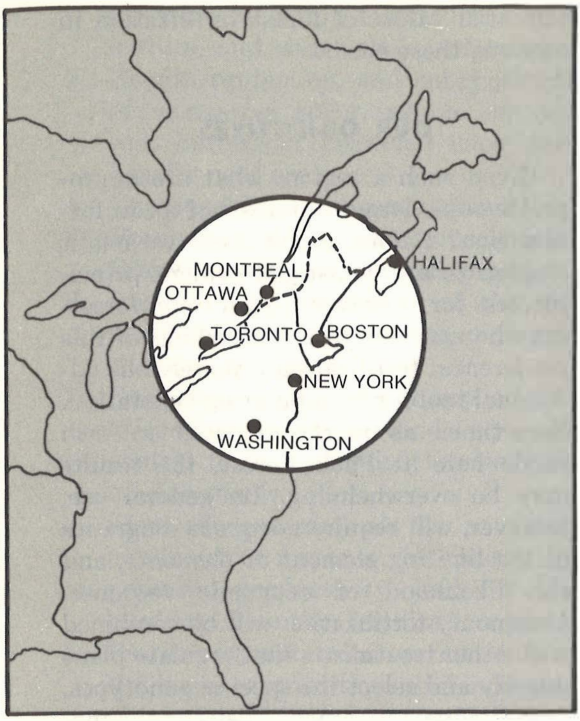


Figure 1.—The circle delimits an idealized region of 1,500-km. diameter, centered on the Pack Demonstration Forest near Warrensburg, New York.

our region is proximity, and an opportunity, whether or not we exercise it, for first-hand acquaintance with the entire range of ecological and economic conditions that we will discuss in these 3 days.

The second obvious characteristic of our region is population density and, perhaps less obviously, its distribution. No matter how we modify the boundaries of the region, it will contain more than 60 million people, somewhere between a quarter and a third of the total population of North America north of Mexico. And this number is not entirely concentrated between Boston and Richmond. Only the absence of roads in the north isolates any part of the region by more than a day's car travel for some millions of people.

I have no intention of reciting projections about further increases in this population or its consuming habits, mobility, and use of leisure time in the future. Or again, about its adjustments to shortages of water and energy or excesses of traffic and pollution. But it is certain that this population's demands for wood products, water, and outdoor recreation will continue to expand. It is certain also that few parts of the region are sufficiently remote to escape drastic increases in the value of forest land and much greater demands upon its various goods and services.

For example, I find that New York has 1.5 million licensed hunters and fishermen, one for every 20 acres of the State, including downtown Manhattan. Scarce wonder that some overflow into adjacent states and provinces. And, though population demands for wood products (*Slinn 1972*) will continue to be served in large part by imports from other regions, rising world demands will eventually, perhaps soon, make timber resources within the region relatively more valuable than they are today. I leave the details of this vision to your favorite soothsayer or economist. But regardless of what assumptions and projections we may make, the varied impacts of this population are so vast and so far-reaching they are imposing a kind of unity on the surrounding region.

So proximity to the pressures of great urban centers creates this region if nothing else does. Otherwise the forester, ecologist, or climatologist might easily object to its extent and limits (*Lull 1968*). For example, there are large variations in length and warmth of the growing season, as well as in depth and duration of snow cover. These, of course, affect the distribution of plant and animal species, forest growth rates, transportation, and certainly the scope of outdoor recreation. In many years the water-skiing season of southern Pennsylvania will overlap the snowmobiling season of central Quebec.

And though the botanical ranges of

some tree species extend widely, it is true that no species is economically significant across the entire region. An overall view of broad forest types, however, shows no convenient lines for subdivision. The center of the region is dominated by birch-beech-maple types, defined broadly as these species together with admixtures of other hardwoods, white pine, and hemlock or spruce. These both penetrate and intergrade with the oak and oak-hardwood types of the South and the great spruce-fir forests of the North. Within each of these three groups, there are pine types of economic significance.

The economic significance of the timber industries is very large in the northern third of the region, intermediate in the south, and least in an east-west central band where the impacts of settlement on present land use have been most concentrated. Nevertheless, even New York State, with its large urban centers, abandoned farmlands, and Forest Preserves, has 47 percent of its area classified as commercial forest land. As we well know, much of the region's forest, except in the mountains and the north, owes its present character to its settlement history, including agricultural clearing and abandonment, plus one to three centuries of forest exploitation and, too often, fire. Thus relatively young or cut-over forests are abundant throughout the southern three-fourths of the region, and commonly land ownership is fragmented and ownership objectives diffused. There are also many vexing questions about the extent to which the original cover of present forest has been altered, and the degree to which inherent fertility and moisture retention of soils may have suffered from these impacts. All these features concern us when we consider forest fertilization.

But plainly, province and state boundaries provide no useful division of present forest conditions, or future needs. Nor does any state or province by itself contain sufficient expertise to examine the potential values of forest fertilization in meeting these needs.

OUR OBJECTIVES

Given such a region, what are appropriate objectives or interests of forest fertilization? Before listing these we might emphasize an almost self-evident principle, less for ourselves than for non-foresters who may read the proceedings of this conference: fertilization is merely one additional tool for manipulating vegetation. Sometimes, as on the depleted outwash sands here at Pack Forest, the results may be overwhelming. Its general use, however, will require adequate diagnoses of the limiting element or elements, and the likelihood of economic response. Commonly fertilization will be combined with other treatments that regulate plant density and select the species, genotypes, or individuals to benefit. Neither the materials nor application are cheap, so indiscriminate use over large areas is not a serious possibility except, perhaps, in occasional overenthusiastic shotgun trials.

Thus forest fertilization is best viewed as an important addition to the new and traditional tools of the silviculturalist—tools such as regeneration techniques, stand-density regulation, mechanized site preparation, fire, herbicides, drainage, and genetic improvement. Though such tools may be applied one at a time, the aim is to combine them in production systems, and the real measure of their value is their effect in combination. In addition, of course, fertilization has a place in revegetating exposed soils.

Our objectives overlap those of a regional silviculture, broadly conceived. I have listed nine objectives, though some are not mutually exclusive and others might easily be divided. Nor does the order of listing imply any priority:

1. Production of more and more useful wood.
2. Greater opportunities for rapid estab-

lishment of young forest, intensified culture, and wider choice of species.

3. Repair, protection, and enhancement of vegetative cover, as on exposed soil, burned or degraded sites, and heavily used areas.
4. Improved food and cover for wildlife.
5. Production of specialty crops such as Christmas trees and maple products.
6. Increased understanding of the opportunities and limitations of forest sites and species.
7. Knowledge of the fate of applied fertilizers, and the methodology and control to insure against undesirable off-site effects.
8. More efficient methods for assessing likelihood of response, for classifying potential productivity, and for the conduct of routine fertilization trials.
9. Better regional collaboration among the many organizations and individuals concerned with forest fertilization.

Objectives 1 to 5 include the major interests in forest fertilization as a realistic management tool. I fear it is easy to either over-rate or under-rate its potential in particular instances, and that we shall need some patience with both before we determine satisfactory prescriptions for use.

In the past, foresters have been quite aware of differences in the economic yields of forest land, and of the association of yield with physiography, forest type, and stand condition. Moreover, they have been comfortable with a fairly sophisticated concept of site quality as the integrated result of all effective environmental variables acting over a long period of time. I think it is true, however, that they have given relatively little attention to either the action of specific limiting factors or the interaction between environmental factors and genotype except in planted forests. Nor have they had reason to do so.

In contrast, forest fertilization is based on the assumption that growth rate or quality is limited by very specific factors —plant-available nutrients that can be positively identified and then added to the site in straightforward fashion. The effect should be increased yields of some particular product—timber, Christmas trees, wildlife food, or soil cover. This expectation derives from the emphasis on fertilizer use in agriculture, coupled with numerous reports of fertilizer response by native tree species.

But the conditions of growth in well-stocked natural forests differ in many respects from those in fields or orchards. First, the native species and genotypes we deal with have been selected, not for responsiveness to man's culture, but by evolutionary pressures acting through their capacity to reproduce, to endure and compete. Usually forests are overfull; a tree crown expands at the expense of its neighbors; and the mere presence of a species or genotype of some age is evidence of ability to compete successfully within prevailing local conditions—including the chemical environment.

Second, some large fractions of the nutrients absorbed each year are returned to the soil for eventual re-use. In some northern forests, however, perhaps over a larger area than we now appreciate, nitrogen may be shunted to long-term storage in organic residues. And third, only a fraction of the total wood produced is harvested from untended stands or those cut at long intervals. The remainder is lost by competition among overabundant stems, by other sources of mortality and cull, and in unwanted species or sizes.

Thus the opportunities to increase growth by nutrient additions, to measure such increases precisely, and then to translate increases and costs into terms of economic choice will often be quite a different matter than in agriculture. There the large gains attributed to fertilizer use actually result from the interactions of nutrient supply with other technological inputs, beginning with genotypes selected for responsiveness, control of plant density, and careful site preparation.

The conditions of fertilizer use in agriculture are approached most closely, of course, in forest plantations. But plantation establishment is a science of its own, requiring more comment than we can give it here. We note only that the new awareness of the fertility requirements of many desirable species, joined with techniques of herbicide use, intensive site preparation, and fertilization, offers a broad new range of possibilities for establishing new stands. We can consider planting species and sites that formerly were difficult or impossible; now they are only costly. Thus we have new options for production of specialty crops, for some special purposes such as vegetation for recreation or soil stabilization, and perhaps for timber. And surely the experience here in combining fertilization with other physical inputs will in some degree influence the approach to natural regeneration and tending of young stands.

Objective 6 is basic to the rest. I do not know the exact number of native tree species within our regional boundaries, but without looking too hard at the southward margins I count some 35 to 40 of widespread commercial importance. We could find about half this number within a several-mile radius of our meeting site. Some related species are similar in wood properties but not necessarily in ecology. And to this number we might add a few others with paramount scenic or wildlife values.

Now, plainly, it is not feasible to begin studying the fertility responses of some 30 to 50 species, from seedlings to maturity. We must either concentrate on a few, or find means of generalizing, or both. We have accumulated considerable knowledge about the characteristics of these species and their adaptations to such things as climate, soil, fire, and pests. But we have relatively little exact information about their nutrient requirements or the degree to which growth rates and competition among species are regulated by nutrient supply.

Approached in this way, forest fertilization is a powerful technique for experimental ecology—or silvics, if you prefer. It is one of the few ways that an investigator can intervene in a large forest ecosystem without large expense or massive disturbance. With skill and good fortune he can observe growth behavior over a range of soil fertility levels without greatly altering other soil or climatic factors. It is also a means of assessing soil potential, inasmuch as marked positive responses demonstrate that neither local climate nor soil physical variables are the immediate constraints on growth. On the other hand, negative responses are sometimes equivocal and too often are buried without critical evaluation.

SOME EXAMPLES

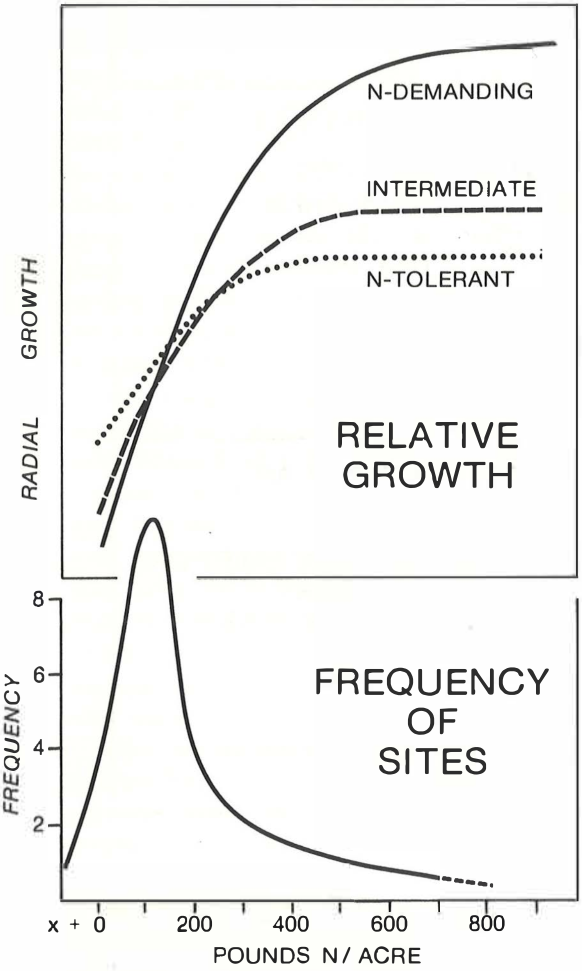
I think we have not given sufficient attention to the silvicultural implications of our limited fertilization studies thus far, and the ways these might be augmented. Let me illustrate with a group of examples, from hardwood forest, on sites that have had various degrees of disturbance.

Some 30 years ago Mitchell and Chandler (*1939*) examined the response of several hardwood species to added N. Among other things, they determined how the N content of foliage increased with treatment level, and so created a scale relating foliar concentration to the total supply available from soil and fertilizer. They then generalized their results by grouping species into three classes according to their relative response to increasing supply (fig. 2). N-tolerant species such as red and white oak, red maple, and aspen grew poorly at the lowest levels and responded markedly as supply increased, up to a point. But their capacity for response to high levels of N supply was limited in contrast with the

Figure 2.—Above: generalized nitrogen response curves of hardwood species. X + 0 indicates the available nitrogen-supplying capacity of an untreated plot bearing trees with the lowest foliar nitrogen concentration.

Below: frequency distribution of 47 unfertilized hardwood stands assessed by the foliar content of red oak.

Both figures are from Mitchell and Chandler (*1939*). See also Mitchell (*1972*).



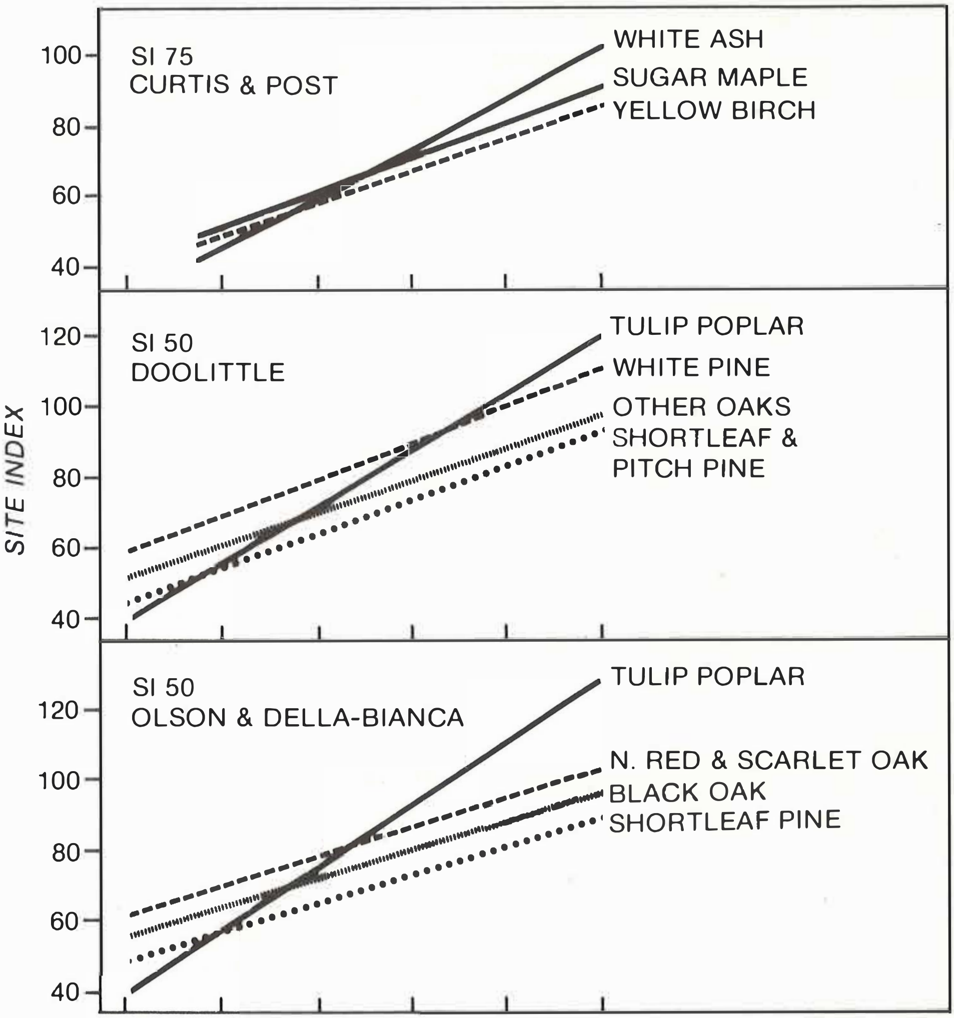
N-demanding species—white ash, basswood, and tulip poplar. Other things being equal, N-tolerant species were superior competitors on low-N sites, and N-demanding on those with abundant available N.

These patterns accord with common observation. But they also agree in rather striking fashion with results from three comparisons of species growing in mixture over a wide range of site qualities (fig. 3). In none of these was N status considered. The results showed that the different growth rates of individual species on any one site tend to continue in roughly parallel fashion over the entire range of site qualities sampled. Note, however, that the sampling requirements probably excluded excessively dry, wet, and infertile sites. But white ash and tulip poplar—the N-demanding species studied by Mitchell and Chandler—are exceptions. They grow much less well than their N-intermediate or N-tolerant associates on the poorest sites, and they respond more vigorously to improved site quality.

But how commonly can we expect to find native hardwood stands on low-N sites? Regretfully, we must again turn back to Mitchell and Chandler, a third of a century ago, for any attempt at a survey within this region. Using their foliar-analysis technique to characterize available-N status, they sampled 36 unfertilized sites on which red oak was present, chiefly within a 200-mile semi-circle of our meeting site. The sample was small and certainly non-random, but the results are instructive (fig. 2). Only a small number of sites provided sufficient N for optimal growth of red oak, and fewer for the N-demanding species.

We may take the results of these several figures as suggestive rather than definitive of widespread regional conditions. But two points stand out: First, that species are far from uniform; they differ greatly in capacity to respond to improved site quality. Second, that available soil N may be a major determinant of site quality in many native upland hardwood stands, and requires at least the same consideration that we have long given to soil physical properties. Though both points require a better foundation, both plainly bear on the management of

Figure 3.—Comparative site indices of species growing together. The abscissa is dimensionless. Redrawn from studies by Curtis and Post (*1962*), Doolittle (*1956*), and Olson and Della-Bianca (*1959*).



sites and species, whether or not fertilization is employed.

Objective 8 takes on significance when we examine the experimental details of existing fertilization trials. These represent an astonishing variety of initial premises, experimental designs, plot sizes, replication, season of application, methods of measurements, and treatment of raw data. If soil or foliar analyses were obtained, they were obtained by any of several sampling and analytical procedures.

We understand the reasons for this diversity. It was sometimes useful and in any case inevitable in the past. But what of the future? I believe that agriculture's experience with soil-fertility research has several lessons for us.

First, there is no substitute for field experimentation. The shrewdest technical judgments and the most realistic models can do no more than extend the results obtained by experiment.

Second, it is a never-ending process, or at least as continuous as the changing technology. At this moment we need more precise results, with more treatments and species, and for longer times, at many more locations. But it is certain that in the near future we will wish to test new fertilizers with additional species or genotypes, and especially in combination with other silvicultural treatments.

Third, field testing is costly. My colleagues' field experiments with corn in easily accessible locations throughout New York have averaged about $100 per single small plot for labor, materials, equipment rental, travel, and computer time, quite apart from the scientist's salary. Multiply this value by suitable numbers of rates, varieties, spacings, replicates, and locations for the costs of 1 year's data for one crop, still to be summarized and interpreted.

Our own N-fertilization study in second-growth hardwoods averaged 13 man-hours field time per single 1/10- to 1/4-acre plot, for location, installation, and treatment, apart from travel and office computation. This is a measure of first cost. Now we are making our first remeasurements and discovering the limitations of our initial perceptions and design. Every investigator could relate similar tales.

But case histories are not widely useful guides for the future. Our regional interests are how—and how rapidly—we can evaluate our collective experimental successes and failures—together with those from other regions—and so derive generally applicable designs and measurement procedures that will yield more and better information for the very considerable sums that we are now investing in forest-fertilization research.

And we might add—that will yield greater interchangeability of information. For the fourth and harshest lesson from agriculture is that we should make strenuous efforts now, before it is too late, to prevent further entrenchment of local experimental and analytical procedures that change abruptly at state or province boundaries and could forever after inhibit interchange of specific data and full cooperation.

Response to these and similar lessons seems a worthy regional objective. In fact, without such effort we are unlikely to achieve other objectives fully or economically. Our resources are small in comparison with the needs we foresee.

This brings me to the last objective on my list. Southern U.S. and the West Coast of the U.S. and British Columbia offer us examples of highly effective cooperation in forest-fertilization investigations by industry, universities, and public agencies. In the next 2 days, we will hear more about the cooperative effort in eastern Canada. It is unlikely that our region will ever be united by a common funding source. Yet our conference here reflects a similar recognition of common problems too large and diverse for any small group to solve, and of the need to exchange information. In these 3 days we will make only a beginning at this exchange. Yet is a magnificent beginning and I suggest that we build upon it.

By this I mean more than planning for some future conference. Why not definite mechanisms for more rapid communication among all workers within the area? Why not efforts to standardize or coordinate the multiplicity of analytical procedures? Why not encouragement to specific agencies or task forces to attack region-wide problems such as those of efficient experimental design and technique? And with such things why not a much greater degree of technical consultation and collaboration among individuals and agencies than we have had in the past, perhaps leading to joint action or shared responsibilities in situations of mutual interest?

I suggest this conference consider formation of a central coordinating committee or, better, a regional forest-fertilization council with the aim of furthering cooperation within and across state and provincial borders.

REFERENCES

Curtis, Robert O., and Boyd W. Post.
1962. COMPARATIVE SITE INDICES FOR NORTHERN HARDWOODS IN THE GREEN MOUNTAINS OF VERMONT. USDA Forest Serv. NE. Forest Exp. Sta. Pap. 171. 6 p., illus.

Doolittle, Warren T.
1958. SITE INDEX COMPARISON FOR SEVERAL FOREST SPECIES IN THE SOUTHERN APPALACHIANS. Soil Sci. Soc. Amer. Proc. 22:455-458.

Lull, Howard W.
1968. A FOREST ATLAS OF THE NORTHEAST. USDA Forest Serv. NE. Forest Exp. Sta. 46 p., illus.

Mitchell, Harold L.
1972. EFFECT OF NITROGEN FERTILIZER ON THE GROWTH RATE AND CERTAIN WOOD QUALITY CHARACTERISTICS OF SAWLOG SIZE RED OAK, YELLOW-POPLAR, AND WHITE ASH. Symp. Effect Growth Acceleration on Properties of Wood Proc.: J-1-15. USDA Forest Serv. Forest Prod. Lab., Madison, Wis.

Mitchell, H. L., and R. F. Chandler, Jr.
1939. THE NITROGEN NUTRITION AND GROWTH OF CERTAIN DECIDUOUS TREES OF NORTHEASTERN UNITED STATES. Black Rock Forest Bull. 11. 94 p.

Olson, David F., Jr., and Lino Della-Bianca.
1959. SITE INDEX COMPARISONS FOR SEVERAL TREE SPECIES IN THE VIRGINIA-CAROLINA PIEDMONT. USDA Forest Serv. SE. Forest Exp. Sta. Pap. 104. 9 p.

Slinn, Ronald J.
1972. PULP AND PAPER DEMANDS OF AN URBANIZED SOCIETY. J. Forest. 70:275-279.

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GENERAL ENVIRONMENTAL AND BIOLOGICAL CONCERNS IN RELATION TO FOREST FERTILIZATION

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ABSTRACT. Forest fertilization, unlike agricultural fertilization, adds nutrients to relatively stable natural ecosystems in which there is an annual recycling of nutrients through humus decomposition. Not only can the new nutrient additions have direct effects on tree and other plant growth; but because the primary productivity is changed, all the consumers and decomposers in the ecosystem can also be modified. The authors outline the probable magnitude and direction of these changes, which, because of the complexity of food chains and organism interactions, may be both immediate and long-term and both local and wide-spread.

WE WILL attempt to give an overview of the effects of fertilization in established forests and plantations, with particular emphasis on N applications to northern temperate forests. The effects on nursery soils are not considered. Trends in forest fertilization have been reviewed recently by Bengston (*1971*). Much of the earlier European work on environmental effects of forest fertilization has been reviewed by Baule and Fricker (*1970*).

The topic is broad, and many aspects are poorly understood. Forest fertilization involves the periodic application of organic and inorganic fertilizers to relatively intact and stable forest ecosystems. Our knowledge of the dynamics of forest ecosystems, particularly the natural patterns of nutrient uptake and turnover and the relationships between primary producers, consumers, and decomposers, is poor; and our knowledge of the effects of artificial manipulation of nutrient relationships is even poorer.

Consequently caution is required in the use of chemical fertilizers. Why caution? Much attention has been given to the effects of insecticide and herbicide use in forests, particularly with reference to their persistence, dispersal to other environments, effects on nontarget organisms, and accumulation in food chains (*Rudd 1964*). In contrast with these materials, the commonly used N, P, and K fertilizers have well-known and comparatively safe chemical properties. On the basis of our understanding of their agronomic uses, it might be assumed that their use in forests will be comparatively safe.

Up to the present, most of the concern about their use has centered around possible leaching losses of N (*TVA 1969*) and the toxic effects due to ingestion by forest animals (*Friburg 1971*). Overrein (*1970*), after examining the environmental effects of forest fertilization in Norway, concluded that, though harmful effects do not seem to have been caused up to now, widespread increases in forest fertilization could result in damage. It is possible, however, that the effects may be much more profound, long-lasting, and more potentially serious than would appear at first glance.

In agriculture, fertilizers are usually added to tilled mineral soils for a single-season effect in relatively large and frequent doses. In contrast, use in forests usually involves a modest application every 3 to 10 years to the surface of an intact forest floor over an undisturbed soil profile in an ecosystem in a relatively steady-state condition. The aim is to increase the productivity of the primary producers, trees, for as many years as possible by augmenting the natural supply of available nutrients.

We do not usually know the primary productivity of the site, nor do we understand the factors that control the natural supply of nutrients to stands of forest trees. We do not even have a soil-chemical analysis technique for forest soils that will enable us to relate fertilizer response by trees to the added N, P, or K.

Consequently our use of fertilizers in forests is still largely empirical and clumsy. It is clear, however, that when fertilizers are used, a large number of changes take place both within and outside the forest. These changes may be drastic and persistent, because the primary productivity—and all food chains and tropic levels related to it (*Woodwell 1970*)—are all changed, often for many years, in some instances very radically. Not only are individuals changed, but the dynamics of the community are changed. Data on these changes are so sketchy and so limited to special situations that the best that can be done is to review what is known and speculate about the rest.

What makes the use of fertilizers in the forest seem alarming is that any current analysis of their effects must be based on so much speculation. The degree of caution and concern depends on a professional and scientific judgment as to whether the primary productivity in any individual forest ecosystem can be changed by chemical means without in turn producing some change that is either undesirable for humans or for the long-term integrity, stability, and productivity of the forest.

CONSEQUENCES OF FERTILIZER PRODUCTION

Beaton and Tisdale (*1969*) have estimated that 2,000,000 acres of forest could be fertilized annually in North America, and that this would require 87,000 tons of N, 39,000 tons of P_2O_5, and 24,000 tons of K_2O. Current (1970) total fertilizer use in the U.S. is: N, 7.5 million tons; P_2O_5, 4.3 million tons; and K_2O, 4.3 million tons (*Harre 1971*). North American fertilizer companies faced with recent over-production, particularly of N, are promoting forest fertilization both by lowering fertilizer cost and by supporting research.

In contrast, some ecologically oriented people view the growth of the fertilizer industry with some alarm (*Commoner 1968*). Except for occasional use to aid in rapid revegetation of burned or disturbed areas (*Hakala et al. 1971*), the only motive for forest fertilization is increased profit from forest products. This profitability is now possible in certain locations because of the improved demand-price situation, increased land prices, and decreased fertilizer prices (*Bengston 1971*). It is outside the scope of this paper to consider all the environmental consequences of increased fertilizer production. Only two points will be considered: research and energy.

Forest-fertilization *research* has required and will require considerable expenditures of money, materials, and energy. It has become a separate scientific discipline, and in terms of human ecology it could be considered a minor industry supporting the livelihoods of a few hundred people in North America—government, industry, and universities. Because of the long-term nature of experiments, sustained inputs of money, materials, and energy resources will be required to provide the scientific basis that will allow full use of this new silvicultural tool.

Energy is needed to manufacture fertilizers. Nicol (*1967*) estimated that the energy contained in 5 tons of coal is needed to make 1 ton of N fertilizer. One Canadian plant uses 35,000 SCF (standard cubic feet) of natural gas for every ton of ammonia produced. Natural gas is both the raw material and energy source for ammonium and urea fertilizers currently used here in forest fertilization. For the same plant, 176 kilowatt-hours of electricity are also needed per ton of ammonia. (Sloan, D. Can. Indus. Ltd. Cent. Res. Lab., McMasterville, P. Q., personal communication, 1972).

One may ask whether it is desirable to use energy on this scale to produce wood. If some of the more dire predictions about energy resources come true—for example, that 80 percent of U. S. fossil fuels will be exhausted within the next 100 years (*Hubbert 1969*)—then the price of energy may well increase much faster than the price of the wood produced through conversion of fossil fuels into ammonium fertilizers. The development of a new technology that enables us to develop fertilizers from a nonrenewable resource, natural gas, has created the possibility of boosting the productivity of a renewable resource, trees. The economics of the technology involved and the future reserves of energy and P and K raw materials must be considered in evaluating the long-term prospects for forest fertilization.

A rough calculation of energy conversion shows that 35,000 SCF of gas at 1,000 B.t.u./SCF and density 0.61 contains 21 million B.t.u. A ton of ammonia converted to urea (34:60) and spread at 400 pounds/acre on 5 acres of spruce forest growing at 40 cubic feet per acre per year may produce an extra 600 cubic feet of wood in 10 years. At 200,000 B.t.u. per cubic foot, this extra wood contains 120 million B.t.u., a six fold energy gain. Alternatively, 21 million B.t.u. of energy have been used to concentrate on 5 acres the growth that would have occurred on 6.5 acres.

Gough and Eastlund (*1971*) have pointed out that, in industrially developed countries, energy sources open the gate to more efficient utilization of the sun's energy. This is only part of the energy story. Energy is required for plant development and maintenance, for advertising, storing, distributing, and applying the fertilizer, and for the research and education that its use necessitates. Indeed, we must include the total amount of energy that has been used to put on, and to transport us to and from, this Symposium!

IMPLICATIONS FOR FOREST MANAGEMENT

Before we deal with specific environmental and biological effects, consider some general effects on the whole forest or landscape that influence management practice.

There are two major types of large-scale fertilization: (1) fertilization at the time of, or soon after, stand establishment, usually using one or more of N, P, and K, as used in peatlands of Scandinavia, British moorlands, in the Lower Coastal Plain of the southeastern United States, and in certain areas of Australia and New Zealand; (2) fertilization of middle-aged and older closed stands, usually using N alone, as used in the Pacific Northwest and on upland soils in Scandinavia (*Bengston 1971*; *Hagner 1971*).

Both types of fertilization increase site quality suddenly, involving initial temporary shocks followed by more gradual biological and silvicultural adjustment. For the first time, the forest land manager has the ability to increase the absolute productivity of a site. All other silvicultural practices merely change the timing and form of the forest crop.

The potential productivity of the forest is greatly increased. Management priorities must be adjusted to allow the concentration of effort on the potentially most productive land. Forest land must be classified for its potential to respond to fertilization, and new growth-rate calculations must be made. Unresponsive and low-potential lands may be released from timber production and made available for recreation and wildlife management, though the tendency of wildlife to prefer browse growing on the most fertile soil can pose problems.

Wood-procurement areas can be reduced by concentrating intensive management practices on accessible, responsive, and productive forest sites. Short rotations, site preparation, more roads, more protection, responsive species and genotypes, and thinning practices must all be reassessed for their relationship to fertilization in increasing productivity in specific forest conditions.

EFFECTS ON LIVING ENVIRONMENT: TARGET ORGANISMS: TREES

Most of the studies of forest fertilization have dealt with effects on tree growth. Less attention has been given to the competitive position of species in mixed stands, increased stand density, shading, and mortality (*Mustanoja and Leaf 1965*). It has been speculated that fertilizer application may increase competition and cause trees to express dominance faster.

This is a factor of some importance, particularly here in the Northeast, where conifer stands are often excessively dense and contain many unmerchantable stems of both conifers and hardwoods. Such stands are not attractive for fertilization because so much of the fertilizer investment goes into unmerchantable stems. This situation has led to establishment of several fertilizer trials involving cleaning or thinning to ensure that only potentially merchantable trees are fertilized. One such trial in black spruce indicated that N fertilization and thinning have given separate and additive beneficial effects (*Weetman 1971*).

With the exception of K responses in old fields (*Stone and Leaf 1967; Fornes et al. 1970*) most fertilizer response in established stands in the Northeast has been associated with the application of N. Since foliar N concentration and chlorophyll concentration are closely related (*Keller 1967*), and there appears to be a generalized N deficiency on podzolic soils, N applications usually result in larger, heavier, and darker green leaves on trees, a feature of great importance in Christmas tree production (*White 1968*). In closed stands, increased shading results; whether or not suppressed trees can respond to the applications may be related to understory light levels (*Brix 1971*) and to the tolerance of the species concerned. Consequently, on such a basis N applications might be expected to increase mortality in stands of intolerant trees, whereas in stands of tolerant species all crown classes may respond equally.

The general relationships among leaf size, nutrient content, and flower and seed production are not clear. Though fertilization has increased seed production (*Armson 1968*), the reasons for the response and its consistency are not well understood. With seed production assured, however, N fertilization may greatly improve conditions for germination and establishment of spruce and fir forests by killing moss vegetation on the forest floor.

The N deficiency in northern forests is associated with the accumulation of organic N reserves, low N mineralization rates, and strong biological competition for N after stand closure (*Romell 1935; Weetman 1962; Heilman 1966*). Higher N mineralization rates in the humus tend to be associated with increasing quantities of herbaceous vegetation and increasing site productivity (*Linteau 1955; Heilman 1966*). After clearcutting, which removes much of the competition for N, there is a rapid release of mineral and other nutrients, the so-called "assart-effect" of Romell (*Romell 1935; Tamm 1964, 1969*), and a vigorous growth of pioneer vegetation. Natural or artificial reproduction of trees with low unit area N demand, growing under such conditions, may not respond to fertilizer applications (*Roberge et al. 1970*). Poisoning of the pioneer vegetation at this stage of development, as was done at Hubbard Brook, N. H., may lead to leaching losses of N (*Likens et al. 1969*).

The uptake of fertilizers by trees is relatively modest, particularly of N, because plants in general are poor competitors against the soil heterotrophic and nitrifying microflora for the assimilation of N (*Jansson 1958*). Studies of ^{15}N-labelled fertilizer uptake by conifers have indicated only a 3- to 23-percent uptake of added N. Thus, relatively little N is added to the above-ground portions of the N cycle. The low uptake figures are no basis for concluding that a large portion of the balance of the added N is lost by leaching; in fact, this does not seem to be the case. Additions of K have been shown in red pine to be recycled and have long-lasting effects. However, N taken up generally has only a temporary effect on growth and is not rapidly recycled, but becomes incorporated into the organic matter, as does added P.

The effects of fertilizer uptake and associated increased production of photosynthate in relation to our understanding of how wood is laid down on trees has been examined by Larson (*1969*). Sudden increases in crown weights increase wind loads and thus modify stem form. Fertilization of young trees can be expected to increase the proportion of less desirable core or juvenile wood in the merchantable stem, to increase crown and branch size, and to delay natural pruning.

The early-wood/late-wood proportions in the annual ring depend largely on the distance from the leaves and tree base to the point at which xylem cells are laid down. Thus trees of differing live-crown ratios can be expected to respond differently to fertilization. In pole stands, moderate fertilization increases both early- and late-wood growth, with relatively little change in wood quality. Forest fertilization may also influence the resistance of trees to drought, frost, smoke, and other pollutants. K applications have resulted in increased frost resistance. (*Baule and Fricker 1970*).

EFFECT ON LIVING ENVIRONMENT: NONTARGET ORGANISMS

The effects of forest fertilization on the organisms associated with the trees depend on:

- Amount and composition of the fertilizer being applied (major nutrients, trace elements, and impurities) and time and uniformity of application.

- Soil properties (size of available and unavailable nutrient pools, pH, and rates of mobilization/immobilization).
- Tree properties (any nutritional imbalance and deficiencies, also tree age, species, crown location, and exposure of foliage, etc.).
- Food and space preferences of the resident organisms.
- Availability of organisms that would be favored by changes in food and space properties resulting from fertilization.

Non-Tree Vegetation

Fertilizer applications tend to be toxic to mosses and stimulating to other vegetation. Particularly where the "assart effect" is not operative, fertilization may greatly increase brush and ground-cover competition. In plantations, stimulation of grass and ericaceous vegetation may be detrimental to tree growth, but may greatly improve its palatability as browse. These difficulties have led to increased use of selective placement and slow-release fertilizer packages in plantation establishment (*White 1968*).

At excessive rates of application, vegetation may be burned. At more moderate rates, ground vegetation similar to that on clearcut conditions (for example, *Epilobium angustifolium*) may develop inside forest stands. At practical levels, N fertilization usually appears to have little effect on ground vegetation in closed stands. P and K fertilization of peats affects the vegetation for a much longer period.

Mycorrhizae, Symbiotic, and Non-Symbiotic N Fixers

As mycorrhizae are usually most active in soils with low N and low pH, fertilization invariably depresses them. This effect is most pronounced at the time of natural inoculation (*Göbl and Platzer 1967*).

As mycorrhizal development is probably determined primarily by the internal nutrient status of the plant (*Hatch 1937*), the application of fertilizers as foliar sprays may be expected to be as damaging to mycorrhizae as when they are applied to soil. The instances where fertilizers have improved or not impaired mycorrhizal development have invariably been on leached sandy soils (*Koberg 1966; Kumar et al. 1968*). The mechanisms involved have been discussed by Harley (*1969*). However, it should be noted that most of the studies on which the above statements are based were carried out in nursery or pot soils, being managed more like agricultural than forest soils. The lower frequency of fertilizer applications in established stands, coupled with the low level of disturbance at time of application, will have the effect of reducing the harmful effects of fertilization on mycorrhizae.

N fixation by symbiotic and nonsymbiotic N fixers in forest soils will undoubtedly be inhibited by N fertilization (*Allos and Bartholemew 1959*; *Delwiche and Wijler 1956*). At present this loss of N is regarded as unimportant because of the low cost of N fertilizer.

Decomposer Microorganisms

Fertilizers have a direct effect on soil microorganisms by altering the pH, C:N ratio, or other nutrient conditions in the soil, and an indirect effect via increased litter fall.

Because of the difficulties in estimating densities of soil microorganisms and distinguishing between active and inactive stages, most studies have been of an indirect nature, concerned with the rates of N mobilization/immobilization and the release of various gases and enzymes.

Studies to examine species changes include those of Corke (*1959*), Reddy and

Knowles (*1965*), Schalin (*1967*), Mai and Fielder (*1968, 1969a, 1969b, 1970*), Kastner and Fielder (*1970*), Peterson (*1970*), and Roberge *et al.* (*1970*). The studies of Roberge and Knowles (*1966, 1967a, 1967b*) have demonstrated increases in ureolytic microorganisms after the application of urea. The significance of most of the other observed changes are hard to assess. More revealing are the studies on the associated changes in N mobilization/immobilization, changes in nutrient release due to a "priming effect", and in rates of nutrient cycling. These processes are usually increased as a result of fertilization (*Parr 1968*), which can consequently be viewed as beneficial, at least in the short term.

The long-term implications of such changes are difficult to assess. In view of the differences between forestry and agricultural operations, it seems unlikely that forest soils will suffer from the reduction in organic matter content that has invariably accompanied the use of fertilizers on agricultural soils. Indeed it is likely that in some locations organic-matter content of the soil will increase because of the increased ability of fertilized trees to capture the sun's energy and fix carbon. The long-lasting effects of fertilization on decomposers are discussed by Franz and Loub (*1959*), who found that the beneficial changes in soil microflora brought about by the application of $CaC0_3$ were still evident 50 years later.

Soil Fauna

Apart from the brief reviews by Mustanoja and Leaf (*1965*) and Baule and Fricker (*1970*) there has been no general review in English of the effects of forest fertilization on soil fauna. There is, however, an extensive Russian study on the general ways of regulating soil fauna in forests (*Lavrov 1968*).

In the same way that soil microbial populations frequently make up a greater biomass than primary producers, so also can soil faunal populations make up a greater biomass than above-ground consumers; and their role in soil has been shown to be more important than their biomass would indicate (*Macfadyen 1961, 1964; Witkamp 1971*). In view of the importance of the soil fauna, it is surprising that there have been so few studies on the effects on them of such management practices as fertilization. Fewer than a dozen comprehensive studies have actually been carried out.

When fertilization increases soil porosity and microbial activity by lowering pH and/or by supplying limiting nutrients, the density, and often the diversity, of the soil fauna increases. Most of the qualitative changes are related to the fertilizer's effect on the balance between bacteria and fungi.

Increases in density have been shown for nematodes, enchytraeids, lumbricids, mites, and Collembola. Studies covering all or most of these groups have usually also demonstrated increases. In most cases the increases have occurred gradually over 4 or 5 years and have persisted for up to another 5 years (*Aaltonen 1940; Franz 1953*). This indicates the need for long-term studies.

The lasting effects of fertilization for trees are probably due largely to the mutually beneficial relationship between the soil microflora and fauna. The microflora provide the fauna with suitable food and the fauna provide the microflora with space by transporting their spores to suitable substrates.

Decreases in density after fertilizer application have been noted for plant parasitic and fungal feeding nematodes (*Bassus 1967, 1968*), cryptostogmatid mites (*Ronde 1957; Franz 1957, 1959; Bassus 1960b; Märkel and Bösner 1960*) and Collembola (*Ronde 1960*). In most of these instances, the fertilizer applied was lime, and the decreases could be correlated with a decrease in density of fungi, the food of most of these animals. However, trace element fertilizers have been shown to drastically reduce cryptostigmatid mite populations in pasture soils, due probably to a direct effect (*Lesin'sh 1970*). With gaseous ammonia, Franz (*1956*) found that all groups were reduced.

These observations have been supported by laboratory studies on the toxicity of ammonia to mites (*Moursi 1962, 1970*). However, Zwolfer (*1957*) and Ronde (*1961*) found that all groups rapidly increased after forest fertilization with NH_3. In the only Canadian study, Behan (*1972*) recorded an initial decrease in density of mites and Collembola, followed by a fairly rapid increase. The decrease was probably due to a direct poisoning effect of the urea fertilizer used, and the increase was due to increased microbial activity. Laboratory studies on effects of fertilization on palatability of leaves to soil arthropods have been carried out by Biwer (*1961*). The complex relationship between the soil fauna and tree health and the ways in which this relationship might be affected by such factors as fertilization have been discussed by Schaerffenberg (*1953*), Zwolfer (*1957*), and Schwenke *et al.* (*1970*).

Effects on Pests and Diseases

If the fertilizer corrects nutritional imbalance and deficiencies in the trees and brings them nearer to their optimum rate of growth, then there will usually be no increase in damage caused to the trees by organisms that feed on them. However, if nutritional imbalance is increased and rate of growth is taken beyond the optimum, then increased attack may be expected. It should be noted that the optimum rate of growth for the trees is likely to differ from the optimum rate of growth that we refer to in our fertilization cost : benefit equations. It would also be noted that damage to the tree is not directly related to the amount of it that is eaten, but rather to the tree's ability to return to an optimum state after being attacked. Unfortunately most studies have been concerned with the extent of attack and density of the attackers rather than the damage done.

Insect and Mite Pests

The literature on the effects of forest fertilization on damage by insect pests has been reviewed in North America most recently by Mustanoja and Leaf (*1965*), Stark (*1965*), Lee (*1968*), Foster (*1968*) and Sharma (*1970*). The extensive German work has been reviewed by Schindler (*1967*) and Merker (*1969*).

For example, Foster (*1968*) noted that fertilization with N has been shown to decrease insect damage by increasing mortality of: (1) those sawfly and moth larvae that chew the foliage of forest trees, and (2) bark beetle larvae; and to increase insect and mite damage by increasing population densities of: (3) twig and shoot boring weevils and moth larvae, and (4) plant sucking bugs, aphids, and mites.

These findings have been explained by relating them to certain effects that fertilizers are known to have on trees and to certain other effects that they may have. These operate by changing the availability of suitable food and space for the pests (see tabulation).

Pests respond by changing their behavior, preferences, tolerance ranges, natality, mortality, longevity, rate of growth, ultimate size, etc. (*Singh 1970*).

The use of fertilizers to reduce insect damage is unlikely to become widespread: first because their controlling effect is usually slight compared to the cost of application; and second, though some pests may decrease, there will always be the danger that others will increase.

On the other hand, it is likely that many fertilization programs will be abandoned because of associated increases in pest damage (*Armson 1968, p. 176*).

Possible effects of fertilizers and their application on insect pests of forest trees

I. Decrease availability of suitable food by:
   a) Reducing percentage sugar in tree.
   b) Direct poisoning effect via food.
   c) Increasing resin and essential oil content of tree and/or by changing the composition of these materials in it.
   d) Accelerating growth and thereby enabling trees to pass through the susceptible stage faster.
   e) Changing osmotic pressure of host sap so it is above or below that of the insect.
   f) Changing amino acid composition of tree.
   g) Increasing lignification of host tissue.

II. Increase availability of suitable food by:
   a) Increasing percentage sugar in tree.
   b) Increasing biomass of tree and accelerating maturation.
   d) Changing osmotic pressure of host sap such that it is nearer to that of pest.
   e) Decreasing cuticle thickness.

III. Decrease availability of suitable space by:
   a) Promoting the release of repellant chemicals from the tree.
   b) Increasing turgor pressure and resin flow such that galleries and tunnels of borers become flooded.
   c) Modifying undergrowth so it can support more parasites and predators of pest.
   d) Contact poisoning effect by fertilizer or its impurities (e.g. biuret in urea).
   e) Physically removing pest when applying fertilizers as foliar sprays.

IV. Increase availability of suitable space by:
   a) Promoting the release of attractant chemicals or by decreasing the release of repellant chemicals from the tree.
   b) Modifying undergrowth so it cannot support sufficient predators and parasites of pest.

Disease Organisms

The effects of fertilizers on diseases of forest trees are no less variable than the effects on insects (*Donaubauer et al. 1967*). Where fertilization corrects deficiencies, disease is usually reduced; and where it creates them, disease often increases (*Mustanoja and Leaf 1965; Foster 1968*). N and N-P-K fertilizers have been found to increase tree susceptibility to a number of fungi, including *Cronartium fusiforme*, certain *Fusarium* spp. and *Verticillium* spp., several rusts, and various fungi of poplars. Increases in diseases of seedlings are particularly common after fertilization. On the other hand, N fertilizers usually decrease attack by *Lophodermium pinastri* (pine needle cast), *Phytophora cinnamomi* (littleleaf disease), *Ceratocystis ulmi* (Dutch elm disease), and *C. fagacearum* (oak wilt). After reviewing 120 studies on the effects of N fertilization on plant diseases, McNew (*1960*) commented that "... about the only conclusion that can be formulated is that excess nitrogen probably should be avoided but every disease has to be considered as a special case"!

Increases in pH after lime or NH_3 application have been found to increase damping-off and attack by *Fomes annosus*, though urea, which can also increase pH, has been used to control development of this fungus on stumps (*Berry 1965*).

K fertilization is usually more successful in reducing disease, especially in cases where N increases it.

Some of the ways in which fertilization can affect disease organisms have been discussed by McNew (*1960*), Sadasivan (*1965*), and Foster (*1968*), though much more work remains to be done before we can obtain a clear picture of the mechanisms involved. For example, fertilizers often increase the density of the undergrowth; this changes the climate above the ground, which in turn is likely to affect the growth and distribution of disease organisms. Very few studies have been carried out to examine these chain-like relationships.

Wildlife

The main findings to date are as follows:

1. Fertile soils support more wildlife (*Wilde 1946; Nagel 1952*).
2. When presented with a choice, wildlife select the most nutritious food (*Arnold 1964; Watson 1970; Dasmann 1971*).
3. Wildlife feed preferentially on browse that has been fertilized, rather in the same way that they feed preferentially on the highly nutritious shrubs that develop after a forest fire (*Dasmann 1964, 1971*).

Where several combinations of fertilizers have been tested, N alone or in combination with P and/or K has increased attack by wildlife more than has P and/or K or lime, the latter often having no effect (*Wood and Lindzey 1966*). Though all the studies cited above refer to mammals, particularly deer, similar findings have been recorded for birds (*Andersson et al. 1970*; *Friburg 1971*; *Miller 1968*; *Miller et al. 1970*; *Moss 1968, 1972*).

We have noted increased feeding by spruce grouse on fertilized black spruce in Quebec.

Friburg (*1971*) has reported on Finnish studies where moose, reindeer, and deer showed no interest in eating P-K or urea fertilizer. When mixed with moss, urea gave reindeer an upset stomach. After fertilizer has been spread in the forest, birds may swallow particles while looking for sand, though fairly large doses would be required to harm them. Some birds spat the fertilizer out and rapidly lost a taste for it.

EFFECT ON NON-LIVING ENVIRONMENT

Air-Gas Composition

Volatalization of added ammonium N has been shown to be appreciable, particularly when urea fertilizer results in increases in pH on dry forest floors (*Volk 1970; Bernier et al. 1972; Watkins et al. 1972*). There is also some evidence of loss of elemental N (*Nommik and Thorin 1971*). It is possible that some of the released ammonia may be picked up by vegetation in the forest. Carbon dioxide concentrations may also be temporarily increased after hydrolysis of added fertilizer by urease to carbamate, which breaks down to ammonia and carbon dioxide.

Water Composition

Losses of nitrate-N from corn fertilization (*Commoner 1971*) and from an unfertilized but herbicide-treated clearcut watershed at Hubbard Brook, N. H. (*Smith et al. 1968; Likens et al. 1969*) have attracted a lot of recent attention and critical comment. In contrast, a recent study showed that leaching losses of urea N fertilizer added to an intact forest ecosystem were very small (*Cole and Gessel 1965*).

Overrein (*1968, 1969*) has studied leaching losses for 12 weeks after applying urea, ammonia, and nitrate at 250 kg. N/ha. Leaching losses in the lysimeter in the acid forest soil were 1.6, 21.5, and 91.8 percent respectively of each form of added N. Nommik and Popovic (*1971*), using ^{15}N-labelled fertilizers on microplots exposed to weathering for 12 months, recovered 76, 63, and 23 percent of added urea, ammonium, and nitrate-N in the soil profiles. Similar ^{15}N labelling and uptake studies on black spruce (*Weetman et al. 1971; Lefebvre 1972*) confirmed that, of the three forms of N fertilizers, urea is the least subject to leaching losses.

Aerial urea fertilization of two forested creeks in Washington, about 2,000 acres in area, caused nitrate-N levels in the creeks to increase to a maximum of 1.32 p.p.m. 1 week after fertilization. Urea concentration increased on the day of application. Nitrate levels were back to prefertilization levels after 4 months (*McCall 1970*).

In Sweden, urea was applied at 250 kg. of urea/ha. around the perimeter of a forest lake; a total of 11 tons of N was applied. In the first summer after treatment only 30 to 40 kg. of N were found in the lake (0.6 mg./1. to 0.9 mg./1.) and in the second summer only 10 to 20 kg. (*Friburg 1971*).

Generally it appears that urea is well retained in the upper portions of the soil, while ammonium nitrate is less well retained. Nitrate-N is barely retained and is washed down into the mineral soil below the depth of rooting. The effects of increased nitrate-N levels in the water have not been demonstrated. Most forest sites can be considered good filters, which allows successful disposal of sewage by irrigation (*Wadleigh 1968*).

For peat sites P and K are generally used. Leaching of K does not present any drawbacks, whereas small increases in P concentration can increase vegetation growth in the water unfavorably. Research to date indicates that soluble P fertilizers can be leached easily, while non-soluble forms are not. Any difference in fertilizer effect between those types has not been observed (*Friburg 1971*).

Soil

Bengston (*1970*) has recently reviewed the effects of N and P additions on the forest floor. Only a small amount of added N is taken up by the trees; much of the balance increases the N cycling within the humus layer. The fate of added N, the changes in size of the N pool, and the "priming effect" of added fertilizer N on the mineralization of native organic N have been studied in acid raw humus soils in particular. These changes are of great practical importance because under these conditions the length and magnitude of the response by the trees is closely related to levels of ammonium-N in the humus layer. N fertilizer additions may increase P, K, Ca, and Mg concentrations in humus leachates (*Beaton et al. 1969*).

The additions of ammonium-N to such soils turns the normally fibrous humus layer into a blacker and greasier condition. The significance of the change in physical state is uncertain; improved seedbed properties and increased water penetration may result. Concern over declining organic matter reserves due to N fertilization in agriculture would not seem to be appropriate on most forest soils that show N responses because many tend to suffer from excess organic-matter accumulations.

N fertilization may increase the solubility of organic matter and lead to increased deposition in the B horizon or even increases in organic matter in drainage water. Ogner (*1972*), who has studied the effects of urea on raw humus, noted that "physical chemical reactions" dominate the humic transformations. The formation of ammonium salts and increased pH leads to increased solubility, leaching of organic matter, and partial collapse of the physical structure. The significance of increases in the amount of non-hydrolyzable organic matter, with a higher N percentage, and losses of humus N compounds, carbohydrate materials, and lipophilic components on long-term soil productivity have yet to be assessed. Deposition of organic-N in the B-horizon may be of some value to future tree growth (*Tamm 1969*).

Phosphatic fertilizers, although little used in this region, have been found to improve soil physical properties and drainage, and to immobilize excess Al and Mn in Piedmont and Coastal Plain soils (*Bengston 1970*).

DISCUSSION AND CONCLUSIONS

As little attention was paid to forest fertilization before 1960, the study of its effects is relatively new in North America. The use of fertilizers in agriculture and forestry is very different, so the temptation to draw close parallels between agronomic and forest effects must be resisted.

The two major effects of forest fertilization of most concern are: (1) risks of general water pollution, and (2) general changes in the biology of forest ecosystems.

There is some reason to believe that, with care in application, the chances of serious groundwater pollution are slim because the forest floor is such a good natural filter.

There is less reason for confidence about changes in the biology of forests. Fertilization makes the forest look more vigorous, but a price may have to be paid in terms of unfavorable changes in the population density and dynamics of the other components of the ecosystem. The need for long-term and fundamental studies of forest systems cannot be ignored. With such a paucity of data, there is a danger that wide publicity of a few examples of unfavorable biological consequences due to fertilization may cause public opinion to inhibit forest-fertilization practice.

REFERENCES

Aaltonen, V. T.
1940. Mrtsämaa. Helsinki. 615 pp.

Abrahamsen C.
1970. Forest fertilization and the soil fauna. Tidsskr. Skogbruk. 78(2): 296-303. Forest Abstr. 31: 692.

Allos, H. F., and W. V. Bartholomew.
1959. Replacement of symbiotic fixation by available nitrogen. Soil Sci. 87: 61-66.

Andersson, O., H. Burgtorf, and C. O. Tamm.
1970. Capercaillie feeding and forest fertilization. Sveriges Skogsvförb. Tidskr. 68 (6): 557-566. Forest Abstr. 32: 4269.

Armson, K. A.
1967. A review of forest fertilization in Canada. Queen's Printer, Ottawa. 175 p.

Arnold, G. W.
1964. Some principles in the investigation of selective grazing. Austral. Soc. Anim. Prod. Proc. 5: 258-271.

Asher, W. C.
1963. Squirrels prefer cones from fertilized trees. USDA Forest Serv. Res. Note. SE-3. 1 p. SE. Forest Exp. Sta.

Bassus, W.
1960a. Die Nematodenfauna des Fichtenroh-humus unter dem Einfluss der Kalkdungung. Nematologica 5: 86-91.

Bassus, W.
1960b. Der Einfluss der Kalkdüngung auf die Fauna des Waldbodens. Arch. Forstw. 9(12): 1065-1081.

Bassus, W.
1967. Der Einfluss von Meliorations und Düngungsmassnahmen auf die Nematodenfauna verschiedener Waldböden. Pedobiologia 7: 280-295.

Bassus, W.
1968. Über Wirkungen von Industrieexhalten auf den Nematodenbesatz im Boden von Kiefernwäldern. Pedobiologia 8 (314): 289-295.

Baule, H., and C. Fricker.
1970. The fertilizer treatment of forest trees. BLV., Munich 259 p. (Transl. by C. L. Whittles.)

Beaton, J. D., J. H. Harapiak, R. C. Speer, and R. T. Gardiner.
1969. Release of plant nutrients from forest soil humus treated with nitrogen and sulphur fertilizers. Can. Soil. Sci. Soc. Meet., Saskatoon.

Beaton, J. D., and S. L. Tisdale.
1969. Potential plant nutrient consumption in North America. Sulphur Inst. Washington, D. C. 64 p.

Behan, V.
1972. The effects of urea on Acarina and other Arthropods in Quebec black spruce (*Picea Mariana* Mill) humus. M. Sc. thesis, McGill Univ., Montreal. 175 p.

Bengston, G. W.
1970. Forest soil improvement through chemical amendments. J. Forest 68: 343-347.

Bengston, G. W.
1971. Trends in forest fertilization. *In* SEARCHING THE SEVENTIES: 72-77. TVA, Muscle Shoals, Ala.

Bernier, B., M. Bazeau, and C. H. Winget.
1972. Gaseous loss of ammonia following urea application in a balsam fir forest. Can. J. Forest Res. 2 (1): 59-62.

Berry, F. H.
1965. Treat stumps to prevent F. annosus in shortleaf pine plantations. USDA Forest Serv. Res. Note CS-34, 4 p. Cent. States Forest Exp. Sta.

Bilger, W.
1968. Die Beeinflussung des Regenwurmbesatzes in Waldböden durch Dungungsmassnahmen. Mitt. Ver. Forst. Standortsk Forstpflzucht 18: 72-75.

Biwer, A.
1961. Quantitative investigations on the importance of woodlice and bacteria for the decomposition of leaf litter, with special reference to the effect of ad-

DITIONS OF MINERAL FERTILIZERS. Ztschr. Angew. Ent. 48 (3/4): 307-328, 377-394. Forest Abstr. 24: 1521.

Bjorkman, E., G. Lundeberg, and H. Nommick.
1967. DISTRIBUTION AND BALANCE OF ^{15}N-LABELLED FERTILIZER NITROGEN APPLIED TO YOUNG PINE TREES (*PINUS SILVESTRIS* L.). Studia Forest. Suecica 48.

Brauns, A.
1955. ANGEWANDTE BODENBIOLOGIE WALDBAULICHE PROBLEME, RAUMFORSCHUNG UND LANDESPLANUNG. Neues Archiv f. Niedersachsen Jg. 1955 (1/3): 1-18.

Brix, H.
1971. EFFECTS OF NITROGEN FERTILIZATION ON PHOTOSYNTHESIS AND RESPIRATION IN DOUGLAS FIR. Forest Sci. 17 407-414.

Carey, A. M., D. L. Dindal, and A. L. Leaf.
1971. RESPONSES OF MICROATHROPOD POPULATIONS TO POTASSIUM. FERTILIZATION AND/OR IRRIGATION (ABSTRACT). Amer. Soc. Agron. Annu. Meeting 1971.

Chopwick, R. E., and K. A. Armson.
1967. *In* A REVIEW OF FOREST FERTILIZATION IN CANADA: 157-158. Study 79, Queen's Printer, Ottawa.

Cole, D. W., and S. P. Gessel.
1965. MOVEMENT OF ELEMENTS THROUGH A FOREST SOIL AS INFLUENCED BY TREE REMOVAL AND FERTILIZER ADDITIONS. *In* FOREST SOIL RELATIONSHIPS OF NORTH AMERICA: 95-104. Oreg. State Univ. Press, Corvallis.

Commoner, B.
1968. NATURE UNBALANCED; HOW MAN INTERFERS WITH THE NITROGEN CYCLE. Sci. & Cit. 10: 9-12.

Commoner, B.
1971. THE CLOSING CIRCLE. Alfred A. Knopf, New York. 362 p.

Corke, C. T.
1959. NITROGEN TRANSFORMATIONS IN ONTARIO FOREST PODZOLS. N. Amer. Forest Soils Conf. Proc. 1: 116-121. East Lansing, Mich.

Dasmann, R. F.
1964. WILDLIFE BIOLOGY. Wiley, New York. 231 p.

Dasmann, W.
1971. IF DEER ARE TO SURVIVE. Stackpole Books, Harrisburg, Pa. 128 p.

Delwiche, C. C., and J. Wijler.
1956. NON-SYMBIOTIC NITROGEN FIXATION IN SOIL. Plant and Soil 7: 113-129.

Donaubauer, E.
1967. ERNAHRUNG UND KRANKHEITSBEFALL BEI FORSTPFLANZEN. 1. BEEINFLUSSUNG DES BEFALLSGRADES. IUFRO Congr. 14 Proc. 5 (24): 400-418. Munich.

Fornes, R. H., J. V. Berglund, and A. L. Leaf.
1970. A COMPARISON OF THE GROWTH AND NUTRITION OF *Picea Abies and Pinus Resinosa* ON A K-DEFICIENT SITE SUBJECT TO K FERTILIZATION. Plant and Soil 33: 345-360.

Forsslund, K. H.
1961. THE LOWER ANIMALS OF THE FOREST SOIL AND THEIR IMPORTANCE FOR VEGETATION. K. Skogs-o. Lantb. Akad. Tidskr. 100 (3/4): 233-256. Stockholm. Forest Abstr. 23: 3089.

Foster, A. A.
1968. DAMAGE TO FORESTS BY FUNGI & INSECTS AS AFFECTED BY FERTILIZERS. *In*: FOREST FERTILIZATION . . . THEORY AND PRACTICE: 42-46. TVA, Muscle Shoals, Ala.

Francé, R. H.
1912. DAS EDAPHON. Vlg. Deut. Mikrolog. Ges. E. V., Munich.

Franz, F.
1959. DAS BIOLOGISCHE GESCHEBEN IM WALDBODEN UND SEINE BEEINFLUSSUNG DURCH DIE KALDUNGUNG. Allg. Forstztg. 70: 178-181.

Franz, F., and W. Loub.
1959. BODENBIOLOGISCHE UNTERSUCHUNGEN AN WALDDÜNGUNGSVERSUCHEN. Centbl. Gesell. Forstw. 76 (3): 129-162.

Franz, H.
1953. DER EINFLUSS VERSCHIEDENER DUNGUNGSMASSNAHMEN AUF DIE BODENFAUNA. Angew. Pflanzensoz. 11: 1-50.

Franz, H.
1956. DIE WALDDÜNGUNG IM LICHTE DER BODENBIOLOGIE. Allg. Forstz. 11: 321-323.

Franz, H.
1957. DIE MODERNE BODENWIRTSCHAFT IM LICHTE DER BODENBIOLOGIE. Mitt. St. Forstverw. Bayerns 29: 29-49.

Franz, H.
1963. BIOZONOTISCHE UND SYNOKOLOGISCHE UNTERSUCHUNGEN ÜBER DIE BODENFAUNA UND IHRE BEZIEHUNGEN ZU MIKRO-UND MAKROFLORA. *In* SOIL ORGANISMS. N. Holland Publ. Co., Amsterdam.

Friburg, R.
1971. GODSLING OCH MILJOVARD. (FERTILIZATION AND THE ENVIRONMENT). Skogen 58 (11): 368-370. (Translation available from G. Weetman).

Gessel, S. P., and G. H. Orians.
1967. RODENT DAMAGE TO FERTILIZED PACIFIC SILVER FIR IN WESTERN WASHINGTON. Ecology 48: 694-697.

Göbl, F., and H. Platzer.
1967. FERTILIZATION & MYCORRHIZA DEVELOPMENT IN YOUNG *PINUS CEMBERA* PLANTS. Mitt. Forstl. Versuchtsanst. 74, 63 p., (Mariabrunn). Forest Abstr. 29: 2205.

Gough, W. C., and B. J. Eastlund.
1971. THE PROSPECTS OF FUSION POWER. Sci. Amer. 22 (2): 50-64.

Hagner, S.
1971. TECHNIQUES IN SILVICULTURAL OPERATIONS. IUFRO Congr. 15 Div. 3: 184-207. Sveriges Skogsvärdförbands Förlag, Stockholm.

Hakala, J. B., R. K. Seemel, R. A. Richey, and J. E. Kurtz.
1971. FIRE EFFECTS AND REHABILITATION METHODS. *In* FIRE AND THE NORTHERN ENVIRONMENT: Pacific N.W. Forest and Range Exp. Sta. 87-100.

Harley, J. L.
1969. THE BIOLOGY OF MYCORRHIZA. Leonard Hill, London. 334 p.

Harre, E. A.
1971. TRENDS IN THE SUPPLY-DEMAND SITUATION. *In* SEARCHING THE SEVENTIES: 9-14. TVA, Muscle Shoals, Ala.

Hatch, A. B.
1937. THE PHYSCIAL BASIS OF MYCOTROPHY IN THE GENUS PINUS. Black Rock Forest Bull. 6. 168 p.

Heiberg, S. O., and D. P. White.
1951. POTASSIUM DEFICIENCY OF REFORESTED

PINE & SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15: 369-376.

Heilman, P. E.
1966. CHANGE IN DISTRIBUTION AND AVAILABILITY OF NITROGEN WITH FOREST SUCCESSION ON NORTH SLOPES IN INTERIOR ALASKA. Ecology 47: 825-831.

Holstener-Jørgensen, H.
1963. A FERTILIZER STUDY IN A PLANTATION OF NORWAY SPRUCE AND JAPANESE LARCH AT KLOSTERHEDEN. Forstl. Forsøgsv. Danm. 28 (2): 69-95 Forest Abstr. 27: 624.

Holstener-Jørgensen, H.
1964. A QUALITATIVE FERTILIZER EXPERIMENT IN A BEECH PLANTATION ON AN OLD PLAIN IN JAEGERSBORG, DYREHAVE. Forstl. Forsøgsv. Danm. 29(1): 25-53. Forest Abstr. 26: 3665.

Hubbert, M. K.
1969. ENERGY RESOURCES. *In* RESOURCES AND MAN: 157-242. W. H. Freeman and Company, San Francisco.

Huhta, V., E. Karppinen, M. Nurminen, and A. Valpas.
1967. EFFECT OF SILVICULTURAL PRACTICES UPON ARTHROPOD, ANNELID & NEMATODE POPULATIONS IN CONIFEROUS FOREST SOIL. Ann. Zool. Fennici. 4: 87-143.

Huhta, V., M. Nurminen, and A. Valpas.
1969. FURTHER NOTES ON THE EFFECT OF SILVICULTURAL PRACTICES UPON THE FAUNA OF CONIFEROUS FOREST SOIL. Ann. Zool. Fennici 6: 327-334.

Hüser, R.
1971. DIE UMSETZUNG VON ^{15}N-DUNGERN IN PROBEN EINER PODZOL-BRAUNERDE UND IHRE AUSNUTZUNG DURCH EINJARHIGE KONIFEREN. Plant and Soil 35: 37-50.

Jansson, S. L.
1958. TRACER STUDIES ON NITROGEN TRANSFORMATION IN SOIL WITH SPECIAL REFERENCE TO MINERALIZATION IMMOBILIZATION RELATIONSHIPS. Ann. Roy. Agr. Coll. Sweden 24: 101-361.

Kästner, C., and H. J. Fiedler.
1970. BODENMIKROBIOLOGISCHE UNTERSUCHUNGEN AUF PSEUDOGLEYSTANDORTEN DES WERMSDORFER WALDES. Arch. Forstw. 19 (9/10): 981-1006.

Keller, T. H.
1967. THE INFLUENCE OF FERTILIZATION ON GAS EXCHANGE OF FOREST TREE SPECIES IN FOREST FERTILIZATION. Colloq. Int. Potash Inst. Proc. 5: 65-79. Berne, Switzerland.

Klebingat, G.
1962. PROBLEMS OF FOREST ECOLOGY, WITH SPECIAL REFERENCE TO SPRUCE GROWING ON MOUNTAINS OF MEDIUM ALTITUDE. Tagunsberichte Deut. Akad. Landw. Wiss. Berlin. 53, 198 p. Forest Abstr. 26: 3521.

Klein, D.
1970. FOOD SELECTION BY NORTH AMERICAN DEER & THEIR RESPONSE TO OVER-UTILIZATION OF PREFERRED PLANT SPECIES. *In* ANIMAL POPULATION IN RELATION TO THEIR FOOD RESOURCES: 25-46. Blackwell, Oxford.

Kleinschmit, R.
1962. UNTERSUCHING VON KALKDUNGUNGSVERSUCHSFLACHEN IM LEHRFORSTAMT ESCHERODE. Forstarchiv. 33 (2): 25-29.

Knowles, R.
1969. MICROORGANISMS AND NITROGEN IN THE RAW HUMUS OF A BLACK SPRUCE FOREST. Trend (Pulp and Pap. Res. Inst. Can.) 15: 13-17.

Knowles, R., and J. Lefebvre.
1971. FIELD, GREENHOUSE AND LABORATORY STUDIES OF TRANSFORMATION AND TRANSLOCATION OF ^{15}N-LABELLED FERTILIZER IN A BOREAL BLACK SPRUCE SYSTEM. FAO/IAEA Symp. Vienna Rep. SM-151/47.

Koberg, H.
1966. FERTILIZERS & MYCORRHIZAE: A POT EXPERIMENT WITH *PINUS SYLVESTRIS.* Forstwiss. Centbl. 85 (11/12): 371-379. Forest. Abstr. 28: 3485.

Kumar, D. et al.
1968. A PRELIMINARY NOTE ON MYCORRHIZAE FORMATION IN CHIR PINE ON SAND AT DIFFERENT N, P, K LEVELS. Indian Forest. 94 (3): 247-250 Forest. Abstr. 29: 5526.

Larson, P. P.
1969. WOOD FORMATION AND THE CONCEPT OF WOOD QUALITY. Yale Univ. School Forest. Bull. 74. 54 p.

Lavrov, M.T.
1968. THE FAUNA OF FOREST SOILS AND WAYS OF REGULATING IT. Izelatelistvo Lesnaja Promystonnost (Moscow) 131 p. Forest. Abstr. 30: 5134.

Lee, Y.
1968. A REVIEW OF RESEARCH LITERATURE ON FOREST FERTILIZATION. Victoria, B. C., Forest. Res. Lab., Inform. Rep. BC-X-18. 40 p.

Lefebvre, J.
1972. GREENHOUSE & LABORATORY STUDIES OF TRANSFORMATION & TRANSLOCATION OF ^{15}N-LABELLED FERTILIZER IN A BOREAL FOREST BLACK SPRUCE (*PICEA MARIANA*) SYSTEM. M. Sc. thesis, McGill Univ., Montreal.

Lesin'sh, K.P.
1970. SENSITIVITY OF ORIBATIDS TO TRACE ELEMENT FERTILIZERS. Izv. Akad. Nauk. Latv. S. S. R. 9: 28-33. Biol. Abstr. 52: 102182.

Likens, G. E., F. H. Bormann, and N. M. Johnson.
1969. NITRIFICATION: IMPORTANCE TO NUTRIENT LOSSES FROM A CUTOVER FORESTED ECOSYSTEM. Science 163: 1205-1206.

Linteau, A.
1955. FOREST SITE CLASSIFICATION OF THE NORTHEASTERN CONIFEROUS SECTION, BOREAL FOREST REGION, QUEBEC. Can. Dep. N. Affairs and Nat. Resources Bull. 118.

Lohwasser, W.
1953. KALKDÜNGUNGSVERSUCHE IM EGGEGEBIRGE UND HUNSRÜCK: ERTRAGSKUNDLICHE UNTERSUCHUNGEN. Forstarchiv 24 (9/10): 213-222.

Macfadyen, A.
1961. METABOLISM OF SOIL INVERTEBRATES IN RELATION TO SOIL FERTILITY. Ann. Appl. Biol. 49: 216-219.

Macfadyen, A.
1964. ENERGY FLOW IN ECOSYSTEMS AND ITS EXPLOITATION BY GRAZING. *In* GRAZING IN TERRESTRIAL & MARINE ENVIRONMENTS: 3-20. Blackwell, Oxford.

Mai, H., and H. J. Fiedler.
1968. SOIL MICROBIOLOGICAL STUDIES IN A FERTILIZER TRIAL ESTABLISHED IN A SPRUCE STAND IN THE EASTERN ERZGEBINGE RANGE.

I. Arch. Forstw. 17 (11): 1141-1153. Forest. Abstr. 30: 3960.

Mai, H., and H. J. Fiedler.
1969a. SOIL MICROBIOLOGICAL STUDIES IN A FERTILIZER TRIAL ESTABLISHED IN A SPRUCE STAND IN THE EASTERN ERZGEBINGE RANGE. II. Arch. Forstw. 18 (2): 155-177. Forest. Abstr. 30: 5678.

Mai, H., and H. J. Fiedler.
1969b. SOIL MICROBIAL STUDIES IN A FERTILIZER TRIAL ESTABLISHED ON SPRUCE RAW HUMUS IN THE THURINGEN WALD. II. Arch. Forstw. 18 (11): 211-224. Forest. Abstr. 31: 4491.

Mai, H., and H. J. Fiedler.
1970. SOIL MICROBIOLOGICAL STUDIES IN A TRIAL OF DIFFERENT FORMS OF NITROGEN. Arch. Forstw. 19 (9/10): 1049-1061 Forest. Abstr. 32: 5992.

Märkel, K., and R. Bösener.
1960. DIE BEDEUTUNG DER BODENTIERWELT FUR DEN ERFOLG VON BESTANDESKALKUNGEN. Forst. u. Jagd 10 (4): 179-181.

Mayer-Krapoll, H.
1963. THE EFFECT OF COMMERICAL FERTILIZERS ON THE MICROFLORA AND FAUNA OF FOREST SOILS. Phosphorsäure Essen. 23 (4): 179-205. Forest. Abstr. 25: 4573.

McCall, M.
1970. THE EFFECTS OF AERIAL FOREST FERTILIZATION ON WATER QUALITY FOR TWO STREAMS IN THE CAPITOL FOREST. Wash. State Dep. Ecol. Olympia. 22 p.

McNew, G. L.
1960. THE NATURE, ORIGIN AND EVOLUTION OF PARASITISM. *In* PLANT PATHOLOGY, AN ADVANCED TREATISE: 2: 19-69. Academic Press, New York.

Mead, D. J.
1971. THE MOVEMENT OF ADDED NITROGEN AND PHOSPHORUS IN A PINE FOREST ECOSYSTEM. Ph.D. thesis, Univ. Fl., Gainesville.

Merker, E.
1969. THE RELIABILITY OF STAND FERTILIZING AS MEANS OF INSECT PEST CONTROL. Wald-Hygiene 8 (1/4): 1-100. Forest. Abstr. 32: 1069.

Miller, G. R.
1968. EVIDENCE FOR SELECTIVE FEEDING ON FERTILIZED PLOTS BY RED GROUSE, HARES & RABBITS. J. Wildlife. Manage. 32: 849-853.

Miller, G. R., A. Watson, and D. Jenkins.
1970. RESPONSES OF RED GROUSE POPULATIONS TO EXPERIMENTAL IMPROVEMENT OF THEIR FOOD. *In* ANIMAL POPULATIONS IN RELATION TO THEIR FOOD RESOURCES: 323-334. Blackwell, Oxford.

Mitchell, H. L., and N. W. Hosley.
1936. DIFFERENTIAL BROWSING BY DEER ON PLOTS VARIOUSLY FERTILIZED. Black Rock Forest Pap. 1 (2): 24-27.

Moss, R.
1968. FOOD SELECTION AND NUTRITION IN PTARMIGAN (*LAGOPUS MUTUS*). *In* COMPARATIVE NUTRITION OF WILD ANIMALS: 207-216. Academic Press, London.

Moss, R.
1972. FOOD SELECTION BY RED GROUSE (*LAGOPUS LAGOPUS SCOTICUS* (LATH.) IN RELATION TO CHEMICAL COMPOSITION. J. Anim. Ecol. 41 (2): 411-428.

Moursi, A. A.
1962. THE LETHAL DOSES OF CO_2, N_2, NH_3 & H_2S FOR SOIL ARTHROPODA. Pedobiologia 2 (1): 9-14.

Moursi, A. A.
1970. TOXICITY OF AMMONIA ON SOIL ARTHROPODAS. Entomol. Soc. Egypt. Econ. Ser. Bull. 4: 241-244.

Mustanoja, K. J., and A. L. Leaf.
1965. FOREST FERTILIZATION RESEARCH 1957-1964. Bot. Rev. 31 (2): 151-246.

Nagel, W. O.
1952. WILDLIFE & THE SOIL. Mo. Conserv. Com., Jefferson City.

Nicol, H.
1967. THE LIMITS OF MAN. Constable and Co., Ltd., London. 283 p.

Nommik, H.
1966. THE UPTAKE AND TRANSLOCATION OF FERTILIZER ^{15}N IN YOUNG TREES OF SCOTS PINE AND NORWAY SPRUCE. Studia Forest. Suecia 35.

Nommik, H., and B. Popovic.
1971. RECOVERY OF VERTICAL DISTRIBUTION OF ^{15}N LABELLED FERTILIZER NITROGEN IN FOREST SOIL. Studia Forest. Suecica 92.

Nommik, H., and J. Thorin.
1971. TRANSFORMATION OF ^{15}N-LABELLED NITRITE AND NITRATE IN FOREST RAW HUMUS. FAO/IAEA Symp. Vienna Rep. 92.

Ogner, G.
1972. THE COMPOSITION OF A FOREST RAW HUMUS AFTER FERTILIZATION WITH UREA. Soil Sci. 113: 440-447.

Oh, J. H., M. B. Jones, W. M. Longhurst, and G. E. Connolly.
1970. DEER BROWSING AND RUMEN MICROBIAL FERMENTATION OF DOUGLAS FIR AS AFFECTED BY FERTILIZATION & GROWTH STAGE. Forest. Sci. 16: 21-27.

Overrein, L. N.
1968. LYSIMETER STUDIES ON TRACER NITROGEN IN FOREST SOIL. I. NITROGEN LOSSES BY LEACHING AND VOLATILIZATION AFTER THE ADDITION OF UREA ^{15}N. Soil Sci. 106: 280-291.

Overrein, L. N.
1969. LYSIMETER STUDIES ON TRACER NITROGEN IN FOREST SOIL. II. COMPARATIVE LOSSES OF NITROGEN THROUGH LEACHING AND VOLATILIZATION AFTER THE ADDITION OF UREA, AMMONIUM AND NITRATE - ^{15}N. Soil Sci. 107: 149-159.

Overrein, L. N.
1970. FOREST FERTILIZATION AND NATURE CONSERVATION. Tidsskr. Skogbr. 78 (2): 287-297. Forest. Abstr. 32: 693.

Parr, J. F.
1968. THE SOIL MICROBIOLOGICAL EQUILIBRIUM; NATURE & DURATION OF CHANGES INDUCED BY CULTURAL PRACTICES. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 28-37. TVA., Muscle Shoals, Ala.

Petersen, P. M.
1970. CHANGES OF THE FUNGUS FLORA AFTER TREATMENT WITH VARIOUS CHEMICALS. Bot. Tidsskr. 65 (3): 264-280.

Reddy, T. K. R., and R. Knowles.
1965. THE FUNGAL FLORA OF A BOREAL FOREST RAW HUMUS. Can. J. Microbiol. 11: 837-843.

Roberge, M. R., and R. Knowles.
1966. MICROBIAL POPULATIONS IN A BLACK

SPRUCE HUMUS FERTILIZED WITH UREA. Pulp and Pap. Res. Inst. Can. Woodland Res. Index 180. 27 p.

Roberge, M. R., and R. Knowles.
1967a. STERILIZATION PAR RADIATIONS GAMMA D'UN HUMUS D'EPINETTE NOIRE (*PICEA MARIANA* (MILL) B.S.P.). Natur. Can. 94: 221-227.

Roberge, M. R. and R. Knowles.
1967b. THE UREOLYTIC MICROFLORA IN A BLACK SPRUCE (*Picea Mariana* MILL) HUMUS. Soil Sci. Soc. Amer. Proc. 31: 76-79.

Roberge, M. R., G. F. Weetman, and R. Knowles.
1970. AN ECOLOGICAL & MICROBIOLOGICAL STUDY OF UREA FERTILIZATION & THINNING IN A BLACK SPRUCE STAND. *In* TREE GROWTH & FOREST SOILS: 73-96. Ore. State Univ. Press, Corvallis.

Romell, L. G.
1935. ECOLOGICAL PROBLEMS OF THE HUMUS LAYER OF THE FOREST. Cornell Univ. Agr. Exp. Sta. Memoir 170. 28 p.

Ronde, G.
1957. STUDIEN ZUR WALDBODENKLEINFAUNA. Forstwiss. Centbl. 76 (3/4): 95-126.

Ronde, G.
1959. WALDBODEN—DÜNGUNG UND KLEINFAUNA. Allg. Forstztschr. 14 (42): 742.

Ronde, G.
1960. WALDBODENDUNGUNG UND LEBENSGEMEINSCHAFT—BODENFAUNA. Ztschur. Angew. Ent. 47: 52-57.

Ronde, G.
1961. BODENZOOLOGISCHE UNTERSUCHUNGEN VON STICKSTOFF-FORMEN-VERGLEICHS-VERSUCHEN IN BADEN—WÜRTTEMBERG. Allg. Forstu. Jagd. Ztg. 132 (12): 303-311.

Ronde, G. et al.
1958. BODENZOOLOGISCHE UNTERSUCHUNGEN VON STICKSTOFF-MELIORATIONSFLÄCHEN IM BAYERISCHEN STAATSFORSTAMT SCHWABACH MITTELFRANKEN. *In* AUSWERTUNG VON DÜNGUNGSUND MELIORATIONSVERSUCHEN IN DER FORSTWIRTSCHAFT 49-128. Ruhr-Stickstoff Ag., Bochum. Forest. Abstr. 21: 475.

Ronde, G.
1969. UNTERSUCHUNGEN DER BODENKLEINFAUNA. *In*: ERGEBNISSE EINES DÜNGUNGS—VERSUCHS ZU 66 JÄHRIGEN FICHTEN AUF EINEN TYPISCHEN STANDORT DES OBEREN BUNTSANDSTEINS IM WÜRTT. SCHWARZWALD. Allg. Forst u. Jag. Ztg. 140 (2): 88-89.

Rudd, R. L.
1964. PESTICIDES AND THE LIVING LANDSCAPE. Univ. Wis. Press, Madison. 320 p.

Sadasivan, T. S.
1965. EFFECT OF MINERAL NUTRIENTS ON MICROORGANISMS & PLANT DISEASE. *In* ECOLOGY OF SOIL—BORNE PLANT PATHOGENS: 460-470. Univ. of Calif. Press, Los Angeles.

Schaerffenberg, B.
1953. BIOLOGISCHE GLEICHGEWICHTSSTÖRUNGEN IM BODEN UND IHRE FOLGEN. Ztschr. Angew. Ent. 35: 136-145.

Schalin, I.
1967. ON THE EFFECT OF NITROGEN FERTILIZATION ON THE BACTERIA & MICROFUNGI IN HUMUS LAYER. Silva Fenn. 1 (3): 1-12.

Schindler, U.
1967. EINFLUSS DER DUNGUNG AUF FORSTINSEKTEN. *In*: FOREST FERTILIZATION. Colloq. Int. Potash Inst. Proc. 5: 321-327. Berne, Switzerland.

Schroder, J., and W. Thalenhorst.
1967. DISTRIBUTION OF BROWSING INJURY ON TWO FERTILIZER-EXPERIMENT PLOTS. Ztschr. Jagdwiss. Hamburg 13 (2), 63-75. Forest Abstr. 29: 2585.

Schwenke, W., W. Bäumler, H. Koschel, M. Matschek, and M. W. Roomi.
1970. DISTRIBUTION, BIOLOGY AND ECOLOGY OF ENCHYTRAEIDAE, LUMBRICIDAE, ORIBATIDAE & COLLEMBOLA IN SOIL UNDER CONIFERS SUSCEPTIBLE TO PESTS. Anz. Schädlingskde Pflschutz 43 (3): 33-41. (G.). Forest Abstr. 31: 5802.

Sharma, M. L.
1970. RESPONSE DES INSECTES PHYTOPHAGES AUX TRAITEMENTS D'AZOTE POTASSE ET PHOSPHORE APPLIQUES AUX PLANTES. Ann. Soc. Ent. Quebec 15 (2): 88-95.

Singh, P.
1970. HOST-PLANT NUTRITION AND COMPOSITION EFFECTS ON AGRICULTURE PESTS. Res. Inst. Can. Dep. Agr. Inform. Bull. 6. 102 p.

Smith, W. H., F. H. Bormann, and G. E. Likens.
1968. RESPONSE OF CHEMOAUTOTROPHIC NITRIFIERS TO FOREST CUTTING. Soil Sci. 106: 471-473.

Sopper, W. E.
1971. DISPOSAL OF MUNICIPAL WASTE WATER THROUGH IRRIGATION. Environ. Pollut. 1: 263-284.

Stark, R. W.
1965. RECENT TRENDS IN FOREST ENTOMOLOGY. Annu. Rev. Ent. 10: 303-324.

Stone, E. L., and A. L. Leaf.
1967. POTASSIUM DEFICIENCY AND RESPONSE IN YOUNG TREES IN EASTERN NORTH AMERICA. Colloq. Int. Potash Inst. Proc. 5: 217-229. Berne, Switzerland.

Tamm. C. O.
1964. DETERMINATION OF NUTRIENT REQUIREMENTS OF FOREST STANDS. Int. Rev. Forest Res. 1: 115-170.

Tamm. C. O.
1969. STUDIES ON NITROGEN MOBILIZATION IN FOREST SOILS. Studia Forest Suecica 75, 39 p.

Tennessee Valley Authority.
1969. EFFECTS OF FERTILIZERS ON WATER QUALITY. TVA Nat. Fert. Develop. Cent., Muscle Shoals, Ala. 107 p.

Volk, G. M.
1970. GASEOUS LOSS OF AMMONIA FROM PRILLED UREA APPILLED TO SLASH PINE. Soil Sci. Soc. Amer. Proc. 34: 573-576.

Waldleigh, C. H.
1968. WASTES IN RELATION TO AGRICULTURE AND FORESTRY. USDA Misc. Pub. 1065, 112 p.

Watkins, S. H., R. F. Strand, D. S. DeBell, and J. Esch, Jr.
1972. FACTORS INFLUENCING AMMONIA LOSS FROM UREA APPLIED TO NORTHWESTERN FOREST SOILS. Soil Sci. Soc. Amer. Proc. 36: 354-357.

Watson, A.
1970. POPULATIONS IN RELATION TO THEIR FOOD RESOURCES. Blackwell, Oxford. 477 p.

Weetman, G. F.
1962. NITROGEN RELATIONS OF A BLACK SPRUCE (*Picea Marianna* MILL) STAND SUB-

JECT TO VARIOUS FERTILIZER AND SOIL TREATMENTS. Pulp and Pap. Res. Inst. Can. Woodland Res. Index. 129. 112 p.

Weetman, G. F.
1971. EFFECTS OF THINNING AND FERTILIZATION ON THE NUTRIENT UPTAKE, GROWTH AND WOOD QUALITY OF UPLAND BLACK SPRUCE. Pulp and Pap. Res. Inst. Can. Woodland. Rep. 32. 18 p.

Weetman, G. F., R. Knowles, and S. Hill.
1972. EFFECTS OF DIFFERENT FORMS OF NITROGEN FERTILIZER ON UPTAKE BY BLACK SPRUCE AND ITS HUMUS AND HUMUS MESOFAUNA. Pulp and Pap. Res. Inst. Can. Woodland. Rep. 39. 20 p.

White, D. P.
1968. PROGRESS AND NEEDS IN TREE NUTRITION RESEARCH IN THE LAKE STATES AND NORTHEAST. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 226-233. TVA, Muscle Shoals, Ala.

Wilde, S. A.
1946. SOIL FERTILITY STANDARDS FOR GAME FOOD PLANTS. J. Wildlife. Manage. 10: 77-81.

Witkamp, M.
1971. SOILS AS COMPONENTS OF ECOSYSTEMS. Annu. Rev. Ecol. Syst. 2: 85-110.

Wood, G. W., and J. S. Lindzey.
1966. EFFECTS OF FOREST FERTILIZATION ON THE CRUDE PROTEIN, CALCIUM AND PHOSPHORUS CONTENT OF DEER FOOD IN A MIXED OAK FOREST. Pa. State Univ. School Forest Resources Res. Brief. 1 (2): 35-37.

Woodwell, G. M.
1970. THE ENERGY CYCLE OF THE BIOSPHERE. *In* THE BIOSPHERE: 25-36. Sci. Amer. Inc., W. H. Freeman and Co., San Francisco.

Zwolfer, W.
1957. EIN JAHRZEHNT FORSTENTOMOLOGISCHER FORSCHUNG. Mitt. Statens Forstverw. Bayern 29: 9-99.

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A MULTIDISCIPLINARY APPROACH TO STAND-MANAGEMENT RESEARCH IN THE FOREST ECOSYSTEM

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ABSTRACT. The potential for effective results is good. The ecosystem in which an individual tree exists is not unmanageable. The resources and range of disciplines required to study it and other individual tree ecosystems intensively can be acquired and deployed without many of the difficulties encountered in studying forest ecosystems. Sampling techniques to provide a link between individual trees and the forest stand in which they exist are now being tested. Tree-growth models, vital to the development of analytical and predictive capacities we need, already exist, though at a low resolution.

MAINTENANCE of a healthy and competitive forest industry in British Columbia is of great importance to local and national economies (*Nagle 1970*). The economic viability of this industry depends in part on the cost of acquiring, harvesting, and processing wood. This cost is rising as logging operations shift to less productive and lower quality stands at higher elevations and in the hinterlands. In spite of large timber reserves, local wood shortages are predicted, particularly in the coastal forest region. These shortages will become more acute if the diversion of forest land from timber-growing to other uses continues at present rates (*Worrell 1967*).

Consequently, it is essential that British Columbia move toward a management program in which attainment of optimum productivity of forest lands is stimulated. The British Columbia Forest Productivity Committee was recently created in recognition of this need, resulting in incentives offered in the form of increased allowable cuts to forest companies that implement certain tree improvement, spacing, thinning, or fertilization practices on public land. In acknowledgment of research needs, the Committee is also undertaking large-scale cooperative fertilization-thinning trials, covering the major soil and climatic regions in coastal British Columbia.

This paper outlines the rationale for the Pacific Forest Research Centre's multidisciplinary research program to assist in the attainment of optimum productivity of forest lands; the status of the program, its inter-related studies, and its expectations.

RATIONALE

Where it was once possible to identify and solve most problems singly, it is now clear that there are growing interdependencies among people, their activities, and the environments in which these activities take place. These interdependencies are becoming critical factors in the implementation of new resource-development programs.

Questions of local and global population growth rates, resource availability and usage, and incidence of wastes or pollutants are no longer unrelated problems. They are realities today that we must learn to deal with. To paraphrase Reichle (*1970*), our challenge to meet increasing wood needs will require optimization of the productivity of managed forest ecosystems with minimal degradation of environmental quality. In the light of only a few of our problems, this is indeed a lofty challenge.

Forest fertilization and thinning are merely two of several general ways of manipulating forest ecosystems. They must be considered in terms of complex chemical, physical, and biological interrelationships if we expect to explain the wide variation of response to such treatments, and if we are to extrapolate research results.

Unexplained variation is seen in the results of many field trials. Although promising, these results have not provided the kind of predictive ability required to improve wood yields, ensure environmental stability over a range of forest types, and recommend management practices or prescriptions.

The complex inter-relationships of factors involved in determining biological productivity are not completely identified, let alone understood. Our knowledge varies from one discipline to another. Sampling techniques, instrumentation, and predictive tools are of variable quality and usefulness and, in general, are inadequate.

In British Columbia, other problems are raised by the extreme variation of local topography, climate, and soils. Almost every conceivable physical feature is represented. Climate ranges from cool, high precipitation coastal regions to hot, arid desert lands. Soils are mainly young and of glacial origin. They have poorly developed profiles and are extremely variable. This wide range of conditions has led to development of a corresponding plethora of plant and animal associations.

How can we achieve a better understanding of basic growth processes and thereby develop effective and environmentally acceptable cultural practices in view of the low state of knowledge, the extreme variability of B.C. forests, and their chemical, physical, and biological complexity? Consideration of all the preceding factors indicates, first, that only a multidisciplinary project team, supported by provincial government and industrial forest cooperators, is likely to produce effective results in reasonable time at a realistic cost.

Second, all questions cannot be answered simultaneously. Initial trials must be flexible to accommodate the establishment of closely related studies in tree physiology, soil chemistry, land classification, soil micro- and macrobiology, climatology, pathology, entomology, and mensuration. The trials must also cover a range of treatments that have some relevance to future management practices and, by changing the forest environment, provide a basis for explaining some of the factors involved in these changes.

Third, extensive effort must be expended on the development, testing, and refinement of sampling techniques, instrumentation, and predictive tools. Existing stand-sampling techniques are not adequate. Unless sample size can be reduced and refined, we cannot afford the expense of studying enough of the pertinent variables at one time. In addition, we cannot find sufficient homogeneous areas of a size in which traditional trials may be carried out.

Also, we need a better means by which growth-limiting factors affecting tree-growth response may be defined. At present, we know that many site, tree, and stand parameters integrate growth factors; but we cannot characterize the specific components and we do not understand their relative importance. Finally, we need a predictive ability with high resolution if we are to assess the many possible management practices in light of great variation and complexity.

The importance of development and refinement of sampling techniques and tree-growth models cannot be overestimated. We must have these research tools in usable form if our multidisciplinary team is to make significant moves beyond the limitations of present investigations.

PRESENT PROGRAM

The objectives of the program in its initial phase are:

- To explain the effects of N fertilization on the quantity and quality of tree growth under different stand-density levels, and to study how climatic and edaphic factors affect N availability and tree response.
- To develop a better definition of growth-limiting factors presently integrated under site and tree or stand condition.
- To build a basis, through the development of sampling and predictive tools, for measurement and interpretation of biological, physical, and environmental factors over a wide range of site, age, density, and species types.

The main organizational mechanism through which our multidisciplinary program is operating is a common study area in a 26-year-old Douglas-fir plantation on a medium- to low-site glacial till, near Shawnigan Lake, British Columbia. According to Krajina (*1965*), this area is included in the biogeoclimatic subzone Madrono-Douglas-fir, which is a part of the coastal Douglas-fir zone.

The climate is Mediterranean subhumid. Mean annual temperature is 49°F. and precipitation 46.2 inches. Average winter snowfall is 34.5 inches. The area is characterized by regular spring or summer droughts of 4 to 8 weeks' duration.

The study imposes fertilization and thinning treatments at several levels, singly and combined, in each of two successive years (fig. 1). It begins with the commonly used N fertilizers urea and ammonium nitrate.

As of 1 April 1972, 36 one-fifth-acre plots, each with a 33-foot buffer zone, were established. Treatments imposed on 18 plots during 1971 and 18 plots during 1972 were:

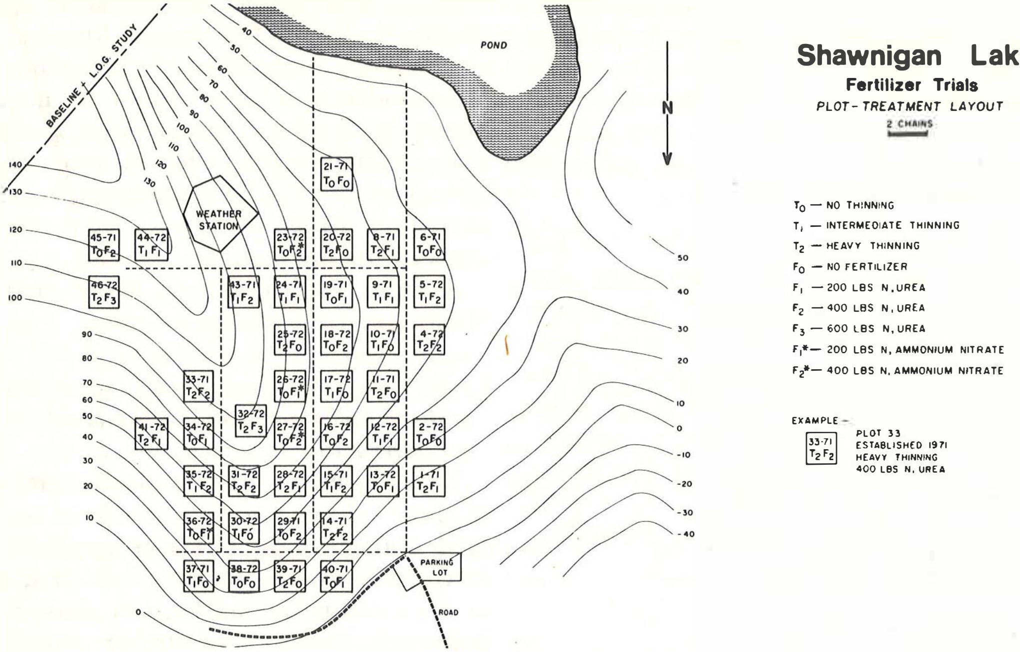
- Three levels of growing space, ranging from unthinned controls to open-grown trees.
- Three levels of N in the form of urea at 0, 200, and 400 pounds N per acre.

Six additional plots were established in 1972 and treated as follows:

- Two plots thinned to an open-grown condition and treated with 600 pounds N per acre in the form of urea.
- Four unthinned plots, two treated with ammonium nitrate at the rate of 200 pounds N per acre, and two at the rate of 400 pounds N per acre, also in the form of ammonium nitrate.

By manipulating several N and stand-density levels, we hope to explain changes in the forest environment in terms of tree growth and tree-growth

Figure 1.—Plot-treatment layout for Shawnigan Lake fertilizer trials.



processes, and from field and laboratory studies to interpret important soil and climatic factors relative to tree growth. The knowledge and experience gained should lead to a better definition of growth-limiting factors which, in quantifiable form, can be utilized in the development of a biologically-based tree-growth model (fig. 2).

The results of the Shawnigan Lake studies and the concurrent development of both a growth model and a more efficient sampling design should lead to studies covering a wider and more comprehensive range of conditions. Consequently, a greater variety of sites and treatments can be selected in future trials, in cooperation with the British Columbia Forest Productivity Committee. Such coverage will enable testing of the knowledge gained at Shawnigan Lake and in the laboratory and will facilitate further development of growth-prediction models.

At present our studies are designed to

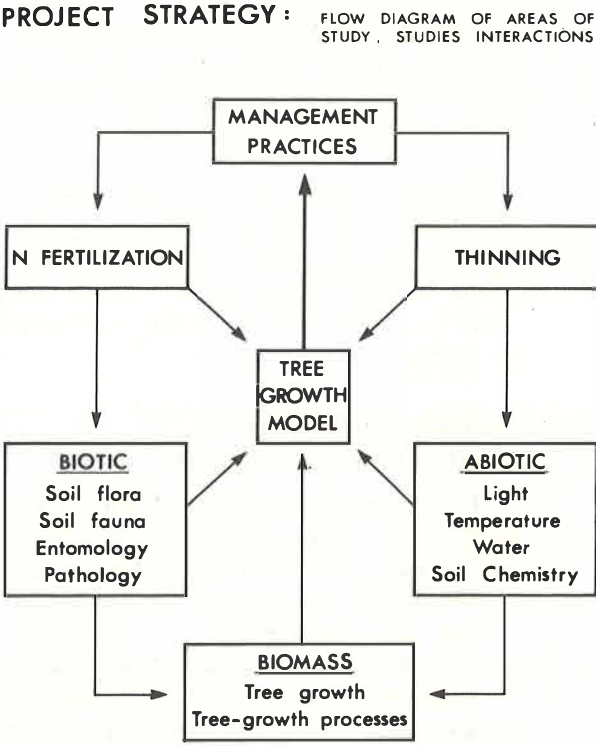


Figure 2.—Flow diagram of areas of study and study interactions.

assess the availability and the utilization of N, and to develop sampling techniques and a tree-growth model. The main Shawnigan Lake studies are described later in more detail.

Availability of Nitrogen

In the first group, studies are directed toward explaining the immediate and long-term effects of applied N treatments on N availability to trees and other vegetation. Studies of immediate N effects are: N uptake, leaching and runoff, volatilization and immobilization by soil, soil flora, and fauna. Studies of the longer term effects of applied N are covered under N cycling: retention, redistribution, and soil storage.

Utilization of Nitrogen

In the second group, the studies are designed to explain and quantify tree growth in terms of physiological processes and conditions resulting from interaction of available N and other growth-limiting factors. Studies of these other growth-limiting factors are: light, air and soil temperature, precipitation and soil water, and other nutrients. In addition to measuring these factors under natural conditions, the studies include investigation of changes under controlled conditions in the laboratory and under field situations through such stand treatments as irrigation and thinning.

Sampling Techniques/ Growth-Model Development

In the final group, studies are to test and refine an individual tree-plot sampling design recently developed by Arney (*1972a*) to investigate and develop means of quantifying growth-limiting factors, which would enable their testing as components in tree-growth models; to test existing tree-growth models such as those of Arney (*1972b*), Bella (*1970*), Lee (*1967*), and Lin (*1969*); to further develop and refine appropriate tree-growth models on the basis of knowledge acquired as a result of the Shawnigan Lake studies and those carried out in the future; and finally, to use the models after initial testing to measure the efficacy of the kind and number of components required to predict accurately tree growth and quality.

A brief description of seven major Shawnigan Lake studies follows:

1. *Pilot fertilization trials of coastal Douglas-fir and western hemlock.* (*C. P. Brett*)

The objectives of this study are to measure volume growth response of managed stands to N fertilizer applied to specified sites and stand conditions; to assist, coordinate, and keep in phase the supportive efforts of researchers working in related projects, and to assist in development, refinement, and testing of individual tree-plot sampling techniques, tools, and tree-growth models.

The main responsibilities within this study have been to establish and maintain the study area (described previously) near Shawnigan Lake, British Columbia, and to facilitate the efforts of associate researchers.

Tree measurements on the 42 plots include location, d.b.h. (to 1/100th inch), height to live crown, crown class, crown quality, and cone-bearing status. Tree heights were taken in conjunction with a tree physiology study on 6 trees per plot, and with a tree-form study on 10 trees per plot. In addition, 144 tree heights on selected plots were measured in conjunction with the individual tree plot design study.

To acquire pre- and post-thinning data for crown mapping and tree-height measurements essential for use in stand growth model utilization (*Mitchell 1969)*, low level 70-mm. fixed-base aerial photographs were taken at appropriate times.

A meteorological station was established on site in April 1970. This station is equipped with a 30-day hygrothermograph, rainfall recorder, snow gage, total precipitation gage, solar radiation recorder, and recording anemometer. Stem analyses were carried out on selected trees before treatment.

2. *Nutrient distribution of a young Douglas-fir ecosystem.* (*B. D. Webber*)

To provide pre-treatment characterization of total above-ground biomass and of nutrient distribution, sampling has been carried out in selected plots on the Shawnigan Lake site.

3. *The physiology of growth of Douglas-fir in relation to nitrogen fertilization and thinning.* (*H. Brix*)

The purpose of this study is to find criteria for prediction of growth responses to stand thinning and N fertilization by providing knowledge of environmental conditions and physiological mechanisms associated with the growth response.

Several team studies are concerned with factors that affect the availability of N to the tree. This study aims at defining stand and environmental conditions that influence the growth response of trees when their N content has been increased. The study, which began in 1967 in the laboratory and at the Greater Victoria watershed, sought to clarify whether fertilization affects stem growth by influencing the amount of leaves produced, the productivity of the leaves, or both (*Brix and Ebell 1969* and *Brix 1971*). In the first case, it is clear that only stands with leaf masses below the optimum will benefit from fertilization. In the latter case, the processes by which productivity of leaves is affected should be known, and interactions with environmental factors such as light, temperature, and water should also be investigated to predict the growth response of a stand to fertilization.

Rates of photosynthesis and respiration have been measured in the laboratory in relation to light intensity and leaf water potential for trees receiving different N regimes. Stand treatments such as irrigation and thinning, with or without fertilization, have further aided in explaining physiological aspects of N fertilization.

4. *The role of soil fauna in tree nutrition and forest fertilization.* (*V. G. Marshall*)

This study is to determine the effects of fertilizers and thinning on natural soil faunal populations, and to elucidate food chains of the dominant animals and ascertain their role in nutrient cycling. The long-range goal is to indicate the possible means of manipulating the soil fauna that favorably influence soil fertility and increase tree growth.

Soil faunal populations are being studied, and measurements of CO_2 evolution, pH, soil temperature, soil moisture, and organic-matter decomposition are being taken. Pilot greenhouse experiments have been initiated to evaluate ^{15}N techniques for a proposed major collaborative study.

5. *Microflora and biotic processes in managed forest land.* (*J. Dangerfield*)

This study seeks to determine the effect of various management practices on the soil microflora and associated biological processes, and the significance of this effect on nutrient availability and forest productivity. The long-range goal is to develop guidelines outlining the combined soil conditions and management practices likely to produce desirable biotic effects.

Thinning and fertilization effects will be evaluated by conducting a specific microfloral characterization, determining the potential of mixed soil flora to perform selected organic and inorganic transformations, and monitoring soil enzyme levels (cellulose, protease, phytase, urease, dehydrogenase). This will provide information for the data pool, to develop a meaningful explanation of these effects on plant productivity.

6. *Nitrogen movement and urea-induced transformations in forest soils.* (*B. D. Webber*)

The study is to characterise the soil N cycle and transformations, and the effect that urea fertilization has upon them.

Lysimetry sampling, after Cole and Gessel (*1968*), has been undertaken at all levels of fertilization both in medium-thinning 1971 plots and unthinned and heavily thinned 1972 plots. There is continuous monitoring of soil temperature, moisture, and pH. Attempts have been made to measure volatilization losses immediately after fertilizer applications in 1971 and 1972.

7. *Treatment responses of individual trees as a basis for prediction of growth and yield of managed stands in coastal B.C. (J. Arney)*

The objectives of this study are to quantify and develop models of the basic components of tree and stand growth, and to provide a basis for predicting stand-volume growth response from one period to another.

Individual tree-volume growth predictions will come from inputs from potential tree growth (present stem volume and crown dimensions) and, initially, from environmental constraints (present age, site index, and degree of surrounding competition). At this stage, the model has a low resolution. A higher resolution is expected in the future as growth-limiting factors are defined more clearly and can be utilized by the model.

Studies of individual trees, however, will have limited meaning to resource managers unless a clear growth and volume relationship is established between trees and forest stands. A promising approach to this problem has been developed by Arney following procedures similar to Keister (*1971*) and Lin. Individual trees have been located on 9 one-fifth-acre plots covering 3 levels of fertilizer application, 5 levels of competition and 2 levels of thinning release. Only 48 trees are required for each fertilization rate, including four replications.

With plot stand tables and stem maps (both required for calculating a competition index for all plot trees), and assuming that individual tree data within each of the five competition levels represent the average for their respective classes, the data can be expanded to a plot basis. This means that one of the 18-plot Shawnigan Lake installations covering 3 levels of fertilization and 3 levels of density replicated only twice could be replaced by a 2- to 3-acre installation in which only 144 trees were measured intensively.

Associated Studies and Consultants

Several other researchers at the Pacific Forest Research Centre are associated with the program through their related studies in forest fertilization and thinning before organization of this program, or through their expertise in a range of disciplines. Lee (*1968, 1970, 1971*) and Carrow (*1971*) have extended their studies to the Shawnigan Lake site to determine the effects of thinning and fertilization on tree form and on black-headed budworm populations, respectively. Diggle (*1971*) has established a long-term thinning study in the same plantation immediately adjacent to the fertilizer-thinning installations.

Other consultants include a pathologist, a soil scientist, a seed and cone entomologist, a meteorologist, an economist, and a biometrician.

CONCLUSION

The approach taken is based on the realization that we are obliged to reach for optimum productivity on forest lands, but there is little hope that we can approach this goal unless we commit ourselves to systematic investigations designed to achieve a growing understanding of biological productivity.

At present, the program reflects a concentration of effort in one place on field trials of limited design. However, this step is seen primarily as a preparation necessary for constructing a firm base before embarking on an adventurous but deliberate path through a maze of biological complexities.

The potential for meaningful results is good. The ecosystem in which an individual tree exists is not of unmanageable proportions. The resources and expertise required to study it and other individual tree-ecosystems intensively can be acquired and deployed without the extreme difficulties encountered in studying forest ecosystems.

Sampling techniques, which can provide a linkage between individual trees and the forest stand in which they exist, have been designed and are now being tested. Finally, tree-growth models, vital to the development of analytical and predictive capacities we need, already exist, albeit at a low resolution.

At present, there is a priority to test, on other sites and age classes, knowledge now being acquired. Other aspects of fertilization to be studied are: other N sources, time of application, other rates, repeated application, and various fertilizer combinations. Other related studies include: the role of mycorrhiza in nutrient uptake, the use of ^{15}N-tagged fertilizers to elucidate applied N pathways, and the affects of proposed intensive management practices on wood quality.

Knowledge and experience gained from closely related studies at the Shawnigan Lake site and in the laboratory—along with the concurrent and integrated development of sampling and predictive tools—are expected to lead to a better definition of future research needs and the increased probability that we can develop the technology to fulfill these needs and, ultimately, to the development of management prescriptions.

REFERENCES

Arney, J. D.
1972a. QUANTIFYING COMPETITIVE STRESS FOR TREE AND STAND GROWTH PREDICTION. In press.

Arney, J. D.
1972b. COMPUTER SIMULATION OF DOUGLAS-FIR TREE AND STAND GROWTH. Oreg. State Univ. School Forest. Ph.D. thesis. 79 p. Corvallis.

Bella, I. E.
1970. SIMULATION OF GROWTH, YIELD AND MANAGEMENT OF ASPEN. Univ. Brit. Columbia Fac. Forest. Ph. D. thesis. 190 p.

Brix, H., and L. F. Ebell.
1969. EFFECTS OF NITROGEN FERTILIZATION ON GROWTH, LEAF AREA, AND PHOTOSYNTHESIS RATE IN DOUGLAS-FIR. Forest Sci. 15: 189-196.

Brix, H.
1971. EFFECTS OF NITROGEN FERTILIZATION ON PHOTOSYNTHESIS AND RESPIRATION IN DOUGLAS-FIR. Forest Sci. 17: 407-414.

Carrow, J. Roderick.
1971. FOLIAR APPLICATION OF NITROGEN TO THE HOST TREE AND ITS EFFECTS ON THE LIFE HISTORY AND POPULATION GROWTH OF THE BALSAM WOOLY APHID ADELGES PICEAE (RATZ.). Can. Forest. Serv. Dep. Environ. Intern. Rep. BC-26. 113 p.

Cole, Dale W., and Stanley P. Gessel.
1968. CEDAR RIVER RESEARCH, A PROGRAM FOR STUDYING THE PATHWAYS, RATES AND PROCESSES OF ELEMENTAL CYCLING IN A FOREST ECOSYSTEM. Univ. Wash. Coll. Forest Resources Inst. Forest Prod. Contrib. 4. 54 p.

Diggle, P. K.
1972. THE LEVELS OF GROWING STOCK COOPERATIVE STUDY IN DOUGLAS-FIR IN BRITISH COLUMBIA. Can. Forest. Serv. Dep. Environ. Inform. Rep. BC-X-66. 52 p.

Keister, T. D.
1971. A MEASURE OF INTRASPECIFIC COMPETITION EXPERIENCED BY AN INDIVIDUAL TREE IN A PLANTED STAND. La. State Univ. Bull. 652. 30 p.

Krajina, V. J.
1965. ECOLOGY OF WESTERN NORTH AMERICA. Univ. Brit. Columbia Dep. Bot. Vol 1, 112 p.

Lee, Y.
1967. STAND MODELS FOR LODGEPOLE PINE AND LIMITS TO THEIR APPLICATION. Univ. Brit. Columbia Fac. Forest. Ph.D. thesis. 332 p.

Lee, Y.
1968. A REVIEW OF RESEARCH LITERATURE ON FOREST FERTILIZATION. Can. Forest. Serv. Dep. Environ. Inform. Rep. BC-X-18. 40 p.

Lee, Y.
1970. FERTILIZING THINNED AND UNTHINNED DOUGLAS-FIR STANDS. Can. Forest. Serv. Dep. Environ. Intern. Rep. BC-21. 19 p.

Lee, Y.
1971. EFFECTS OF UREA FERTILIZATION ON NUTRIENT CONCENTRATION OF NEEDLES AND SOILS IN THINNED AND UNTHINNED DOUGLAS-FIR STAND. Can. Forest. Serv. Dep. Environ. Inform. Rep. BC-X-55. 25 p.

Lin, Jim.
1969. GROWING SPACE INDEX AND STAND SIMULATION OF YOUNG WESTERN HEMLOCK IN OREGON. Duke Univ. School Forest. Ph.D. thesis. 182 p.

Mitchell, Kenneth J.
1969. SIMULATION OF THE GROWTH OF EVEN-AGED STANDS OF WHITE SPRUCE. Yale Univ. School Forest. Bull. 75. 48 p.

Nagle, George S.
1970. ECONOMICS AND PUBLIC POLICY IN THE FORESTRY SECTOR OF BRITISH COLUMBIA. Yale Univ. Fac. Grad. School Ph.D. thesis. 198 p.

Reichle, David E.
1970. TEMPERATE FOREST ECOSYSTEMS, ECOLOGICAL STUDIES 1. Terrest. Prod. (PT) Sect. IBP and Oak Ridge Nat. Lab. 304 p.

Worrell, Albert C.
1967. FOREST RESOURCES, PRIVATE ENTERPRISE, AND THE FUTURE. Ind. Forest. Assoc., Portland, Ore. 70 p.

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ECONOMIC CONSIDERATIONS IN FOREST FERTILIZATION

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ABSTRACT. Forest fertilization is considered in the context of: (1) the process of fertilization and forest production related to economic analyses; (2) recent ideas for economic analyses of forest fertilization; (3) additional thoughts on economic rationalization of forest fertilization; and (4) identification of research targets for forest fertilization. Available data should be considered for use in developing response surface information and fertilization simulation models that can be used to test the relative sensitivity of optional management regimes to changes in fertilizer application and economic climate.

THE GREENING of American forests through fertilizer application was probably a bit fugitive for Charles Reich as he assembled the conceptual apparatus for *The Greening of America* (1970). Nevertheless, and nurtured perhaps by the same process of economic and social evolution, fertilizer application and forest production can probably be characterized as also proceeding through three stages of "consciousness" as in Reich's view of American society.

One point in "consciousness I" might be marked by the publication of ideas on forest manuring in 1844 (*Gessell 1969*). "Consciousness II"—roughly the period between the world wars—was characterized by analyses of the roles of particular macro- and micro-elements such as Ca, P, N, and Mn in tree growth. The post-World War II period may be forest fertilization's "consciousness III", in which relatively large-scale field trials of different kinds, rates, and timing of fertilizer application have been undertaken. Perhaps a "consciousness IV", which will entail use of fertilizers on an operational basis, is near at hand.

Thus far, from consciousness I through III, the major concern has been with understanding the physical and biological processes relating fertilizers to tree and forest growth and productivity. This, in economics jargon, has been analysis of the production process—the relationships of the kinds and levels of inputs or factors of production to output. To this point, however, there has been no major effort to optimize production processes—to determine the maximum-net-return combinations of fertilizers with other factors of forest production—even though there are some papers and publications dealing wholly or in part with questions of the financial worthiness of fertilization. Two reasons for the somewhat minor emphasis on economic analysis in forest fertilization apparently are:

- The biological framework or production process needed to be described first, and this data base is still incomplete.
- Fertilization analysis does not require any new economic tools for analysis, merely the application with circumspection of tried and proven economic concepts.

FERTILIZATION IN FORESTRY PRODUCTION PROCESS

The forestry production system is the sum total of all interactions of all factors constraining as well as contributing to the output of all products of the forest. These include natural factors such as climate and soil, man-made factors such as machines, and man himself. The specific modes in which these factors interact may be called processes, such as the process of photosynthesis or the process of adjusting stand density by thinning. Forest management itself is a process that controls the combinations of factors and processes, intervening in processes where necessary, to produce desired kinds and amounts of products including pulpwood, sawlogs, game browse, and even aesthetics.

Forest fertilization can be viewed as a process that has an almost infinite variety of forms and subprocesses. Equally important are the interactions of the forest fertilization process with other processes in the forest production system. These other processes may be taken as given, or they too may be adjusted by the management process.

Thus, while certain results may be obtained by applying alternative amounts of a specific N-P-K fertilizer formulation to a forest stand—given species, soil moisture, stand age, and density—entirely different results may be obtained from the same amounts of the N-P-K combination when any of these given factors or related processes change. Because the output from a forest production system may be more sensitive to changes in factors or processes other than forest fertilization, determination of the "best" forest-fertilization process to employ must always be made with full consideration of the other processes and factors that also affect the results of fertilizer application.

At this point we need an orderly way to look at forest fertilization for the purpose of developing useful economic guides for fertilizer use. First, we will distinguish between two general classes of forest-production factors and some of the specific factors in each class that have special relevance for forest fertilizer application. These are called, in economics jargon, "fixed" factors and "variable" factors. "Fixed" factors are those that are held at given or constant levels in the production process while output is varied as a result of changes in the levels of other factors. "Variable" factors are those whose amounts are changed to produce changes in the amount of product induced.

Fixed and Variable Factors for Forest Fertilization

Fertilization is a man-induced change in a complex ecosystem. However, it is a relatively small change in numbers of variables in the ecosystem. Thus the number of factors in the forest production system—or ecosystem—which remain fixed or unvaried as a result of man's intervention by fertilization remains relatively very large.

Traditional analyses of forest site quality have not shown the supply of mineral nutrients to be important and have thereby tended to stress the importance of other factors of the forest environment that influence productivity.

Sites chosen for such analyses were those occupied by trees, and mineral nutrients were not obvious limits on tree growth. Furthermore, the various environmental factors determining the moisture regime tend to override the effects of mineral-element supply.

Many factors, therefore, condition the response of forests to fertilizer. Most of these factors are not manipulated or manipulatable by the forest manager. Others, like mineral nutrients, are manipulated or varied. These can be called, respectively, "fixed" and "variable" factors. For purposes of perspective we have listed some of these in table 1. The factors listed are not inclusive, nor is their classification entirely consistent. Nevertheless, it does serve to illustrate the relatively limited scope of intervention options of forest managers in the larger ecological system of the forest. This listing also suggests the need to develop analyses of forest fertilization that are more comprehensive than the throw-some-on-and-see-what-happens type.

The Generalized Functional Relationships

Some of our existing knowledge about forest response to fertilization does have utility for economic evaluation.

We seem to have considerable information about the response of forest growth to alternative rates of application of various fertilizers. A more or less classical single-variable production function results with increasing and decreasing rates of response, which can be evaluated economically to determine the optimum rate of application. Since time is customarily held constant among application-rate alternatives in most of these evaluations (growth response at some common point in time is measured for all treatments), it is only necessary to determine that rate at which the value growth response of one additional unit of fertilizer just equals the added cost of that last unit of fertilizer. At that point marginal cost and marginal revenue are equal and "profit" is maximized.

Table 1.—Environmental factors that interact with fertilizer to affect tree growth

Usually Fixed	Generally changeable	Customarily varied by managers
Climate:	Vegetation density	Stocking
Precipitation	Species	Species
Temperature	Soil:	Stand age
Humidity	Moisture	
Radiation	Nutrients	
Wind	Temperature	
Land form	Micro-organisms	
Elevation	Foliar nutrients	
Soil:	Faunal density:	
Depth	Insects	
Texture	Animals	
Organic content	*Moisture distribution:	
Root distribution	Time	
	Place	
	*Soil nutrients	

*Variation of these factors by managers may be due more to inadvertence than design.

Stratification with respect to other attributes of the forest is usually made to hold these other attributes or factors constant. As a result, it would be possible to determine the optimum rate of application for a variety of forest conditions, to the extent that these conditions fit the attributes held constant. Thus we find that response to alternative rates of application varies directly with respect to such fixed factors as basal area, age, site index, and soil moisture. That is, the response curve for a basal area of 250 square feet per acre of Douglas-fir is higher than that for 190 square feet. Likewise, as site index increases, so does the response level. *Rates* of response, of course, may vary among levels of these fixed factors; and this will mean that when the level of the fixed factor changes, the optimum rate of application will change.

Because of the obviously limited value of single-variable response data, response surfaces representing the interactions of two or more variables are needed. We will simply note here that there is apparently relatively little multivariable response information for forest fertilization. In addition to new studies designed to obtain such data, we would urge that the results of existing studies be examined to determine their suitability for estimating multivariable responses to fertilization.

ECONOMIC RATIONALIZATION OF FOREST FERTILIZATION

We recently inventoried current USDA-funded and state agricultural experiment station research reported to CRIS (the Current Research Information System administered by the USDA Cooperative State Research Service) and found some 56 current projects in all forest regions of the United States dealing wholly or in part with forest fertilization. These included U. S. Forest Service research projects. Not one of the project reports in this inventory mentioned economics analysis as part of the project. Even if we concede the incomplete information base of CRIS reports, it would appear that solid and sustained economics research in forest fertilization has received short shrift, at least by the public forestry research community.

Nevertheless, there are allusions to the economic benefits of forest fertilization in many publications and papers on the subject, and a few articles dealing mainly with its economic aspects. Four of these are discussed below.

A Generalized Financial Model

One criterion that may be used to answer the question, "Does fertilization pay?", is present net worth. This has the general form of:

$$\mathrm{Pnw} = \frac{R^{t}}{(1+i)^{t}} \qquad \begin{matrix} C(1+i)^{t-n} \\ (1+i)^{t} \end{matrix}$$

in which
Pnw = present net worth.
R = revenue
C = cost
t = time of receipt of revenue or harvest
n = time period from present to investment in treatment or occurence of fertilization cost.
i = required rate of return.

Without consideration of other factors, if Pnw $\geq$ 0, it "pays" to fertilize. That is, you will have at least earned or bettered the required rate of return on the investment in or cost of fertilization. At the end of the investment period, t, you will have recovered all investment costs, C, plus an increment equivalent to at least what C would have earned at i invested elsewhere at the same period of time.

Two observations stem from the logic of this equation. First, all other things remaining constant, the higher the required rate of return, the smaller the present net worth. Second, all other things remaining constant, the larger the size of n, the lower the costs and the higher the present net worth. That is, the closer to the time of harvest when the fertilization investment is made, the lower the investment costs. These two observations, coupled with other aspects of the fertilization system, are frequently found in the literature; and their basic relevance is tied to the logic of this economic criterion.

This criterion can be applied to any number of management options, and that option that yields the largest present net worth may be chosen as optimum or the "best". Thus, options which use different kinds, levels, and times of fertilizer applications may be compared with this criterion. In addition, other treatment costs and returns may be added in similar form to the criterion for comparing any number of management options, which include fertilizers as only one subpart. And regularly repeated applications can be evaluated (for example, application of fertilizer 10 years before rotation harvest for each rotation in the future) with a minor modification of the basic equation.

The main point of all this is that the financial model for evaluating fertilizer application, by itself or as part of a larger management system option, is already well known. The main requirement is simply an orderly time-specific accounting for the various cost and return elements in the criterion and some capability for predicting or forecasting the cost-and-return effects of alternative management system options.

Haley (*1967*) has developed a somewhat elaborated version of this general approach and has shown some standard options for discounting costs and revenues given periodicity of fertilizer applications. He also pointed out some additional implications of using compound interest—for example, doubling the frequency of application of fertilizer within a given time period will more than double the financial cost over that period.

The Shadow of Uncertainty

The rational precision and neatness of present net worth calculation has tremendous appeal. Unfortunately—and it is always thus—real-world data do not match the precision of the model in which they are used. This is not to deny the validity of the method, but only to point out the obvious: we do not know with certainty the various attributes of the future that our model requires. We do not know what prices will be; we do not know what costs will be; we do not know the interest rate that should be used from time period to time period; and, most important perhaps, we really do not yet know very precisely the response levels of forests to fertilizer.

We are, in a word, uncertain about the reliability of the data we are still forced to use in the model. More important, we are uncertain about the degree to which we may err in our management prescription, which will stem from our precise calculations; and it is this kind of uncertainty that has the most immediate impact upon decisions to incorporate fertilization in management practices.

Schweitzer[1] has summarized this concern for uncertainty in forestry decision-making with special emphasis on forest fertilization. He notes that we always have imperfect information, but we make decisions anyway. Two general classes of uncertainty mitigation are identified. One of these can be labeled "institutional"; it includes elements that reduce the value or importance of risk and uncertainty associated with relatively minor parts, such as a fertilization regime, of a total system or enterprise. Some managers may include fertilization

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[1] Schweitzer, Dennis L. 1971. Forest fertilization in the Pacific Northwest: a case study in timber production under uncertainty, to be published in Proceedings of the Forest Economics Sub-Group Workshop on Uncertainty in Forestry Investment Decisions Regarding Timber Growing; International Union of Forestry Research Organizations, Gainesville, Fla., 21 March 1971.

as a production option simply to accumulate a level of experience comparable to that of competing managers. In some cases, a fertilization practice may be implemented simply to produce higher and more timely yields for overall production goals and may not be viewed as a profit-center activity by itself.

A second class of uncertainty mitigation involves such strategies as using a conservative bias in forecasting the yield impact of a fertilization practice; adding a safety margin for costs; reducing expected profit margins by some arbitrary factor; and inflating the discount rate to account for risk. Schweitzer pointed out that environmental concerns are now providing additional rationale for safety-margin strategies. Undesirable nutrient impact on water quality is a principal concern in this regard and certain water-side areas are now excluded from fertilizer application.

In summary, a number of uncertainty issues can be raised in the context of forest fertilization. The most important general class seems to be that of forecasting yield effects of fertilization. Another important class is application costs, especially since effective application systems are still in the developmental stages. Finally, we need to identify those management options that are most sensitive to uncertainty strategies regarding fertilizer application. If what we propose to do in our total management system would change little even if our fertilizer subsystem changed greatly or gave wildly varying results, we need not be too concerned about obtaining more certain or more precise information about fertilizer effects.

The Allowable Cut Effect

Schweitzer alluded to a somewhat controversial notion in forest regulation called the "allowable cut effect". The reasoning is simple: if a practice such as fertilization is applied today, and it is estimated to increase allowable cutting levels in the future, present cutting levels may be increased accordingly. If, for example, a technical rotation (one that will yield sawtimber-size trees in a given period of time) is shortened by the fertilization practice, and area regulation is employed, the amount of area cut today can be increased by the amount of increase in area devolving from the calculation for the shorter rotation periods.

Brantseg (*1966*) applied this notion specifically to fertilizer application. On the basis of logic and some limited calculations, Brantseg suggested that the growth increment attributable to fertilization can be harvested from existing harvestable trees elsewhere in the allowable-cut unit as soon as the growth increment is discernible, rather than waiting for today's fertilized trees to reach harvest age or size.

The beneficence of this phenomenon is apparent. The financial yield from increased present harvests can help offset the present costs of fertilization. Ultimately, however, the increased annual yields must cover the time costs associated with the present net investment in fertilization. In addition, and most important, there must be current *harvestable* material in extra amounts equivalent to the increase in current growth. This, in turn, begins to suggest the special care required to evaluate the allowable-cut effect as a means of capturing future benefits in the present.

Generally, the allowable-cut effect appears most relevant for the conversion period in forests with an overabundance of mature or near mature timber. It has no special relevance in forests with an understocking or immature-age-class bias. And in any event, it may be regarded as only a special case in forest practice evaluation. If all annual costs and all annual returns based on all forecast annual yields from a given forest property are accounted for within a fully regulated sustained-yield forest model, the so-called allowable-cut effect should be built into the annual cutting level prescription automatically.

One final note of caution. Intensive forest-management practices may not always lead to shorter rotations. It is easy to demonstrate that thinning may lead to longer biological rotations, because thinning in some stands will increase average annual growth and yield, thus pushing the culmination of mean annual increment farther into the future. Financial rotations may be similarly affected. Fertilization may in some cases increase periodic annual value increment more than it increases the annual cost of forest management and production. In such a case it would pay to move the rotation or final harvest farther into the future to that point where the added value yield just equals the added cost of waiting and treatment.

The Economist's Complaint

In 1967, at the Forest Fertilization Symposium at Gainesville, Fla., Stoltenberg and Phares (*1968*) concluded with what may be termed "the economist's complaint": perhaps more economics would be applied to fertilization *if only the data were adequate!* Adequacy in this instance means unbiased and efficient estimates of the response surfaces for various levels and combinations of fertilizers. These authors and Clutter (*1968*), in a paper at the same symposium, argued for a shift in experimental design to rotatable composite designs that economize on treatment combination and emphasize response surface analyses.

Nevertheless, we believe there is an abundance of data already available that can lend itself to some useful economics analysis. Some of the general single-variable functions delineated earlier may be evaluated in an economics context to provide some assistance to forest managers in deciding on worthwhile fertilizer treatments. What seems to be required is not only more data of a more adequate form, but more sifting and sorting through existing data to utilize it in decision-making.

SOME GENERAL GUIDES

The guides suggested below are mainly logical and procedural in nature. Instead of detailing instances in which fertilization "pays", we offer some suggestions for approaches to answering this question, and we note some circumstances that seem to embody the best chances for profitable fertilizer applications.

The Management Decision Framework

Forest management in North America is still an immature art and relatively unsophisticated. Much management is still merely a matter of scheduling the harvest of existing timber. Even where new and man-cultivated forests have been developed, natural site productivity is utilized. Fertilization can be considered a relatively advanced form of site-productivity modification.

Generally, in our unsophisticated forest-management framework, only two variables (inputs) are controlled by the manager: (1) time and (2) stocking. Most textbook forest management and certainly much current management planning is built around the manipulation of these two variables, either individually but more frequently in combination.

The time variable has several forms: (1) time for regeneration of harvested areas; (2) time between cultural treatments, including thinning and perhaps fertilizer application; (3) time period of the cutting cycle in mixed-age management; and (4) time or age of harvest.

The stocking variable likewise has several forms, including initial stocking levels and after-thinning stocking; and these are measured in several ways including basal area, stems per acre, and volume in trees of designated size or age classes.

We would argue that most current management decisions for forest production can be boiled down to making choices between alternative combinations of some time and stocking attributes of the forest. Other variables of the forest production system, though requiring some decisions prior to this one, will usually be taken as given. Thus, for a given combination of site (and all of its inherent variables) and species, and for a selected set of production systems (logging or other treatment system with its associated costs), the best combination of time of treatment (or intervals between treatments) and the number of trees or stocking levels to which the treatment applies will be sought.

Like the response surface generated from composite rotatable statistical designs, showing the yield interactions of N and P in a fertilizer formulation, response surfaces in timber yields for time and stocking combinations can be generated. Every yield point on the response surface can be evaluated by using present net worth analysis as discussed earlier. That interaction or combination of time and stocking yielding the greatest present net worth would be chosen to guide the forest manager's decisions.

If the foregoing management-decision framework is an accurate portrayal of the manager's concern, when, how, and where are forest-fertilization decisions made? There are two basic ways in which fertilization decisions can be articulated with the time-stocking decision model. One is to take as given a specific fertilizer formulation, rate, and time of application. Given the specific fertilizer regime, the manager's decision is to choose the best combination of time and stocking.

The second basic way to articulate fertilization decisions with the time-stocking decision model is to incorporate some elements of the fertilization regime directly into the model, defining time and stocking attributes in fertilizer-regime terms. For example, a fixed formulation of N-P-K fertilizer may be assumed. Time and rate of application must still be determined to complete the fertilization-regime structure for the given site and species. Instead of using alternative rotation lengths as the time parameter, alternative times of application or lengths of time between applications may be used.

Stocking could be held constant, rate varying with application time; or rate could be expressed in stocking terms and stocking and rate varied with time of application. An expression of this latter possibility might be pounds of the given fertilizer formulation per 100 trees or 100 cubic feet of stocking per acre.

Although the exact functional relationships implied by the above suggestions are not clear, the time-stocking model is suggestive of the kind of response surface information that lends itself readily to the forest-management decision system. Perhaps this will be useful in the design of subsequent analyses of the effect of fertilizer on forest growth and yield.

Priority Possibilities for Fertilizer Payoff

We have not made a systematic—or economic—appraisal of the various opportunities or circumstances in which high payoffs are most likely from forest fertilization. Nevertheless, there seem to be a few generalizations to guide the direction in which we might seek such high payoff opportunities.

First, good sites will likely offer the best opportunities to take advantage of the benefits offered by fertilization. This will be related primarily to favorable soil-moisture conditions. This in turn suggests that irrigation and fertilization practices together should be evaluated because they are strongly supplementary to each other.

Second, high-value species seem likely to offer better payoff opportunities than low-value species. This follows from the realization that application costs are not as responsive to species variation as are value yields. Thus high-value, high-value-response species such as walnut and oak would probably rate higher in fertilizer treatment priority than red pine or aspen.

Third, minimization of fertilizer investment time has financial payoff, which suggests two strategies. One is to apply the fertilizer late in the rotation to minimize investment costs, but not so late as to lose the yield effect of the treatment. Another strategy that may be worthwhile in the future would be to couple fertilization with very short agronomic production cycles where feasible. Such possibilities may exist in future development of very short aspen rotations, and perhaps in the so-called "sycamore silage" type of operation. Both types of development emphasize fiber yield, with little regard for the macrostructure in which fiber yield is packaged.

Finally, application systems and their costs need to be considered in identifying general high-priority possibilities for fertilizer payoff. Getting the fertilizer to the tree in the right amount at the right time without creating secondary problems such as stimulating growth of unwanted vegetation and incurring extra costs such as those of storage during inclement weather is still a major problem. The application system may in some instances be a more important consideration than the ultimate yield impact because of costs or lack of effective controlled distribution of yield impact.

SUMMARY AND CONCLUSIONS

We have not presented the results of original or new research in forest fertilization. Nor have we presented a complete display of economics research in forest fertilization. We have tried instead to present an outside point of view, relating economics concepts to some of the more well-known aspects of forest fertilization. We have also tried to place this discussion in a management-decision context.

We concluded early in our review that the tools for economic analysis of forest fertilization already exist. The needs are therefore those of application, not development. Furthermore, major issues of application are those common to other fields. One of these is simply the need to account for all the yields and costs of alternative fertilization programs in a time-specific manner to apply the tools of financial analysis. Another is the need to measure the incremental effects of the full range of fertilizer-application options so that optimum treatments can be determined. This in turn embodies previous recommendations by others (*Stoltenberg and Phares 1968*) to design fertilizer experiments that will generate response surfaces rather than simple tests of significant differences among a limited range of treatments.

The time and stocking management context that we have suggested is admittedly simple. It is difficult to imagine any management system with only two variables. In this regard we would like to stress that we are not proposing a two-variable management system; but we do believe that these two variables are the major manipulatable variables in forest management and that they do provide a useful core concept around which we may organize what we need to know about forest fertilization.

Finally, we argue that fertilization evaluation out of context seems a somewhat fruitless endeavor. Care needs to be taken to evaluate all factors associated with forest yield where fertilization might also be considered. Other biological factors may overshadow even the most optimistic forecast of fertilizer effects; and the economic environment may militate against the realization of any worthwhile gains. Perhaps the time is at hand when accumulated knowledge will lend itself to fertilizer-simulation models that can be used to test the relative sensitivity of optional management regimes to changes in fertilizer application and economic climate.

REFERENCES

Brantseg, Alf.
1966. THE PROFITABILITY OF FOREST FERTILIZATION. Norsk Skogbruk. 7/8 (translated by Roy S. Larsen). 6 p.

Clutter, Jerome L.
1968. DESIGN AND ANALYSIS OF FOREST FERTILIZATION EXPERIMENTS. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 281-288. TVA, Muscle Shoals, Ala.

Gessell, Stanley P.
1969. INTRODUCTION TO FOREST FERTILIZATION IN NORTH AMERICA. Forest Ind. 96 (10): 26-28.

Haley, David.
1967. THE ECONOMICS OF FOREST FERTILIZATION. Forest. Chron. 42 (4): 390-394.

Reich, Charles A.
1970. THE GREENING OF AMERICA. Random House, New York. 347 p.

Stoltenberg, Carl H., and Robert E. Phares.
1968. ECONOMIC CONSIDERATIONS IN FOREST FERTILIZATION. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 289-293. TVA, Muscle Shoals, Ala.

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FERTILIZER METHODS AND APPLICATIONS TO FORESTRY PRACTICE

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ABSTRACT. Although N and P are the nutrients that most frequently increase tree growth and vigor in forest stands of eastern North America, other elements, including K, S, Ca, and Mg, are also beneficial. Most fertilizer products suitable for use in forestry exert considerable influence on the chemical and physical properties of forest soils, mainly through temporary and permanent changes in soil pH. Solubilization of organic matter, release of plant nutrients, and movement of nutrient cations are all affected by fertilizer-induced alterations in soil reaction. The best opportunity for placing fertilizers is during site preparation for new stands. Aerial applications are often the only practical method of topdressing extensive areas of established stands.

TREES ARE LIVING organisms, and for their maximum development a number of environmental conditions must be favorable. Soil fertility is one of the important factors. If the plant-nutrient status of a soil is suboptimal when the other growth factors are sufficient or nearly so, poor tree growth will result. Forest trees receiving proper nutrition are more likely to be capable of withstanding stress conditions such as drought, disease, insects, etc., just like agricultural crops. There is evidence that P fertilization tends to compensate for soil conditions restricting development of tree roots.

Forest soils are usually low in fertility because soils of better nutrient status and productivity are customarily used for agricultural purposes. Removal of plant nutrients from these rather infertile soils is accelerating through the adoption of intensive management practices, resulting in greater tree vigor and productivity. More complete utilization of the tree crop is also contributing to greater withdrawal of plant nutrients from forest soils. In some areas, uniformed public opinion has recently forced foresters to abandon their long-standing practice of broadcast-burning slash, which aided in the recycling of plant nutrients, and to turn to burning large accumulations of forest wastes at a few specified locations.

Research on the benefits of forest fertilization is relatively new in North America. Fertilizers were included in a few experiments in forests of the South about 40 years ago, and serious research was not started there until some 25 years later (*Bengtson 1968*). Tree-nutrition research has been under way for about 30 years in the Lake States and the Northeast (*White 1968*). Research work on the nutrient needs of forest trees in the Pacific Northwest started around 1950 (*Gessel 1968*).

Commercial fertilization of forests in North America is not widespread (*Beaton and Tisdale 1969*), and most of the fertilized forest land in the United States received treatment within the past 5 years (*Bengtson 1971*). Operational-scale forest fertilization began on Vancouver Island, British Columbia in 1963 (*Beaton and MacRae 1967; MacRae and Beaton 1968*).

The purpose of this paper is to consider the commonly accepted principles of fertilization and their applications to forestry practice.

FERTILIZER PRINCIPLES

The five basic principles for sound use of fertilizers in forestry practice are:

- Identify the nutrients currently limiting growth and those present in marginal amounts.
- Use the most effective fertilizer materials for a given set of conditions.
- Apply proper rates of the required nutrients to avoid excesses and imbalances.
- Fertilize so that nutrients are available when needed most.
- Place fertilizers so that the nutrients being supplied are positionally available.

IDENTIFICATION OF NUTRIENTS LIMITING GROWTH

Soil Testing

Soil testing, either alone or in conjunction with plant analysis, is the most commonly used tool for diagnosing the need for fertilization of agricultural crops. Before either soil testing or plant analysis can be used to formulate fertilizer programs for crop production, background information relating soil-test values and nutrient concentrations in plant tissue to growth and yield must be available. Agriculturists have been involved for many years in making fertilizer recommendations and have collected much of this type of data. Their task of relating growth to plant tissue and soil-test values is considerably easier than that of the forester because they are often working with annual crops.

Use of soil tests for diagnosing the need for fertilization of forest trees has had only limited success. Readily available soluble nutrients are probably less important for development of perennial plants such as trees than they are to growth of short-lived annual crops (*Leaf 1968*). Also, the extractants used to measure nutrients available to annual field crops may not satisfactorily estimate the "available-to-trees" fraction of nutrients in soil. However, the usefulness of soil tests developed for agronomic crops should not be discounted entirely since Pritchett (*1968*) reported that levels of approximately 2 p.p.m. or less of NH_4OAc—extractable P in surface (0 to 20 cm.) soils were insufficient for good growth of slash pine. Increased growth of loblolly and slash pine is expected from fertilizer P additions in the South Carolina Coastal Plain when available soil P is less than 11 kg./ha. (*Wiley et al. 1970*).

Measurement of total and potentially available plant nutrients is probably a more realistic approach to predicting the need for fertilizers. Total N concentrations of less than 0.1 percent in the surface 15 cm. of glaciated soils in northwestern Washington generally indicated inadequate levels of this nutrient for Douglas-fir (*Gessel 1968*). Soils deficient in K for red pine can be distinguished from nondeficient soils by means of a test for the potentially available portion of this nutrient in soil (*Leaf 1968*).

Tissue Testing

Tissue analysis promises to be a useful tool for detecting inadequate levels of plant nutrients in established forest stands. Several comprehensive reviews of plant analysis guidelines for assessing the nutrient status of forest trees have been published recently (*Bengtson et al. 1968; Leaf, in press*).

A few examples of important nutrient status levels follow. Growth response of loblolly pine to N fertilization is expected when the foliar concentration of this nutrient is less than 1.16 percent (*Wells 1968*). Levels below 1.0 percent total N in current year's Douglas-fir foliage sampled in September or October are considered indicative of N deficiency (*Gessel 1968*). Growth of 5- to 8-year-old slash pine on Flatwoods soils can be increased by P fertilization when the concentration of this nutrient in the needles is between 0.09 and 0.10 percent (*Pritchett 1968*). Responses of loblolly pine in the South Carolina Coastal Plain to P fertilization were expected when foliage contained less than 0.11 percent P (*Wiley et al. 1970*). Benefits from K fertilization of red pine are expected when the concentration of this nutrient in current year's near-terminal foliage is between 0.3 and 0.4 percent in October (*Leaf 1968*).

Fertilizer Trials

In the absence of soil tests and tissue analyses that are well correlated with tree growth or forest productivity, fertilizer trials can be conducted to assess the nutrient status of forest soils. Many such trials have been conducted in North America, and the results to date indicate that N and P are the nutrients that most frequently increase tree growth and vigor.

In addition to N and P, dressings of other nutrients–including K, S, Ca, and Mg—have been beneficial for stands of various forest species in eastern North America (table 1). There is evidence that combinations of two or more essential nutrients may result in substantially larger increases than applications of a single nutrient (*Swan 1969a*). Swan (*1969b*) reported that in his 10 years of field experience in eastern Canada, N only treatments were always less effective than N plus K or P.

The need for more than one plant nutrient or "balanced fertility" is not a new concept. Most agronomists are constantly faced with prescribing fertilizer programs involving two or more nutrients. Heavy rates of N, P, or K fertilization often lead to deficiencies of nutrients such as S, Mg, Ca, and the micronutrients. The recent findings of van Lear and Smith (*1972*) that Cu, Mn, and Zn supplements increased the response of slash pine seedlings to applications of N and P certainly indicate that nutrient balance should not be overlooked in forest fertilization.

USE OF MOST EFFECTIVE FERTILIZER MATERIALS

Changes in Soil pH

Although fertilizer properties may be just as important as those of the forest floor and underlying mineral soil, little attention has been given to the selection and use of materials that will produce the most favorable nutritive conditions for tree growth. Most fertilizer materials suitable for use in forestry will exert considerable influence on the chemical and physical properties of forest soils through

Table I.—Some examples of forest response to fertilization in Eastern North America

Location	Species and age of stand	Nutrient resulting in growth response	References
	CONIFEROUS SPECIES		
Northern New York State (Adirondack Region)	Young plantations of red pine, white Pine, Norway spruce, and white spruce	K	Heiberg & White 1951
Northern New York State (Adirondack Region)	Young plantations of red pine	Mg	Stone 1953
Quebec	Plantations of white spruce	K,Mg	Lafond 1958
Quebec	20-year-old plantation of red pine	K,Mg	Gagnon 1965
Maine	White pine plantation	K,NPK	Stratton et al. 1968
Quebec	60-year-old jack pine stand	K,NK	Swan 1969a.
Quebec	White spruce stands	N,NK	Swan 1969a
Ontario	85 year-old black spruce stand	P	Swan 1969a
New Brunswick	40-90-year-old black spruce stands	NP	McFarlane & Krause 1972
Atlantic Coastal Plain	Young plantations of loblolly and slash pine	P	Bengtson 1968; Brendemuehl 1968; Pritchett & Smith 1968; Wiley et al. 1970
Borrow pits in South Carolina	2-year-old slash and loblolly pine seedlings	N,NS	McGregor & Goebel 1968
Atlantic Coastal Plain	Plantations of southern pines following crown closure, approximately 15-20 years old	N,NP	Bengtson 1968; Pritchett & Smith 1968; Pritchett & Hanna 1969
Coastal Plain in Florida	9-18-year-old slash pine plantations	N,NS	Pritchett personal communication 1972
Tennessee Valley	20-75-year-old southern pines	N,NP	Farmer, Bengtson & Curlin, 1970
	HARDWOOD SPECIES		
Michigan	19-year-old tulip-poplar plantation	N,K,NK	White 1968
Michigan	25-year-old black walnut plantation	NPK	White 1969
Ohio	30-year-old yellow-poplar plantation	NPK	Vimmerstedt & Osmond 1968
Massachusetts	Sugar maple trees	N	Mader et al. 1969
Pennsylvania	50-year upland oak (white and scarlet oak)	N,Ca,NCa	Ward & Bowersox 1970
Tennessee (3 locations)	Merchantable upland hardwood stands (northern red oak, white oak, chestnut oak, southern red oak, yellow-poplar, black cherry, hickory, dogwood)	N,NP	Jones & Curlin 1968
North Carolina	Merchantable upland hardwood stands	N,NP	Jones & Curlin 1968
Tennessee Valley	Second-year growth response of cottonwood clones	N	Jones & Curlin 1968
Louisiana	20-year-old stand of sweetgum, water oak and willow oak	N,NPK	Broadfoot & Ike 1968
Georgia	One-year-old yellow-poplar seedlings	N,NP	Broadfoot & Ike 1968
Georgia	One-year-old sycamore seedlings	N	Broadfoot & Ike 1968
Tennessee Valley	20-75-year-old mixed stands of yellow-poplar, red and white oaks, and hickories	N,NP	Farmer et al. 1970

alteration of soil pH. Changes in soil reaction following the introduction of fertilizers can be either temporary or permanent.

The saturated solutions that diffuse from dissolving fertilizer granules have pH's ranging from very acid to slightly alkaline. These saturated solutions will temporarily alter soil pH and affect soil chemical and physical properties. The composition and pH of saturated solutions of several important P carriers is shown in table 2.

During the hydrolysis of urea or urea-containing fertilizers, transitory alkaline solutions are formed which have both direct and indirect effects on the forest floor, as well as on mineral soil (*Beaton et al. 1969; Bengtson 1970*).

Most ammonium-containing or forming fertilizers will permanently lower the pH of agricultural soils. Development of acidity is the result of nitrification or oxidation of NH_4-N to NO_3-N as illustrated below (*Tisdale and Nelson 1966*):

$$2NH_4^+ + 3O_2 \longrightarrow 2NO_2^- + H_2O + 4H^+$$
$$2NO_2^- + O_2 \longrightarrow 2NO_3$$

Soil reaction has a pronounced effect on nitrification, the optimum pH being close to 8.5 (*Tisdale and Nelson 1966*). Nitrification can occur, however, over a range of reaction between pH 5.5 to about 10. It is known to take place in some agricultural soils at pH values as low as 4.5 and 3.8, but in forest soils nitrification may practically cease at pH's below 5.0. Nitrification is usually considered to be relatively minor in forest soils. Consequently, the acidifying effect of nitrification is probably not as complete in forest soil environments as it is in agricultural soils because the former are generally more acid to begin with.

Drastic reductions in soil pH are not usually desirable for several reasons. First, loss of nutrient cations by leaching is enhanced by acidic soil conditions. Second, when soil pH decreases below 5.5 there is a very great increase in concentration of Al in soil solution. Soluble Mn becomes high at pH's below 5. High levels of these two elements are toxic to plants. Third, available P in soil can be reduced markedly through the formation of insoluble iron and aluminum phosphates.

Preliminary investigations by Dr. S. P. Gessel, Dr. I. Morrison and Dr. T. N. Stoate at the University of Washington suggest that Mn toxicity may be the factor limiting growth of Douglas-fir in one area of northwestern Washington (*Anonymous 1971*). Apparently the presence of exessive amounts of Mn has induced an Fe deficiency. In trials established by these investigators, Douglas-fir has shown a better response to Fe plus N than to N alone.

Phosphorus fertilizers, with the exception of phosphoric acid and the ammonium phosphates, do not generally have any marked effect on soil pH. The common K carriers similarly do not alter soil reaction.

Table 2.—Composition of saturated solutions of phosphorus fertilizers

		Composition of saturated solution at 25°C		
Fertilizer	Symbol	pH	P	Cation
			Mole/liter	
$Ca(H_2PO_4)_2.H_2O$	MCP	1.48	3.98	1.44
$NH_4H_2PO_4$	MAP	3.47	2.87	2.87
KH_2PO_4	MKP	3.99	1.69	1.69
$(NH_4)_2HPO_4$	DAP	7.98	3.82	7.64
K_2HPO_4	DKP	10.1	6.10	12.2

Source: Lindsay, Frazier, & Stephenson 1962.

Table 3.—Equivalent acidity and basicity of common fertilizer materials

Fertilizer	Percent N	Equivalent acidity or basicity (B)— Per kg. of N	Per 100 kg. of material
		kg of pure lime	
Ammonium sulphate	21	5.35	110
Ammonium nitrate	33.5	1.80	62
Urea	45-46	1.80	84
Urea-ammonium nitrate solution	32	1.80	57
Calcium nitrate	15	1.35 (B)	20 (B)
Potassium nitrate	13	2.00 (B)	23 (B)
Monoammonium phosphate	11	5.30	58
Diammonium phosphate	18	5.30	96

Source: Tisdale & Nelson 1966.

Equivalent acidity or basicity of several of the most widely used fertilizer materials is shown in table 3. Ammonium sulphate will result in considerably more acidity than either ammonium nitrate or urea. Ammonium phosphate products also have considerable potential for acidifying soil.

Salt Index

All fertilizers increase the salt concentration of the soil solution. Salt index is a measure of this effect. It is defined as the percentage rise of the osmotic pressure brought about by a fertilizer in comparison with the effect of the same quantity in weight of sodium nitrate (*Baule and Fricker 1970; Tisdale and Nelson 1966*).

Some fertilizer salts, when present in low concentration, appear to cause injury to plants by interfering with metabolic processes, while others do not seem to be harmful until osmotic pressure of the soil solution is raised above that of cell sap. Table 4 shows that there is considerable difference in the salt index of the various products available for forest fertilization. Materials with the lowest index should be used in situations where salt injury is or could be a problem—forest nurseries, planting holes, etc.

Chloride

The Cl component of fertilizer materials may result in injury to conifer seedlings (*Baule and Fricker 1970*), espe-

Table 4.—Salt index of common fertilizer materials

Fertilizer	Percent N, P or K	Salt index per unit of plant nutrient
Ammonium sulphate	21	3.25
Ammonium nitrate	35	2.99
Urea	46	1.62
Ordinary superphosphate	8.7	.39
Concentrated superphosphate	20.9	.21
Monoammonium phosphate	22.2	.49
Diammonium phosphate	23.6	.64
Potassium chloride	50.0	1.94
Potassium nitrate	38.3	1.58
Potassium sulphate	45.0	.85
Potassium magnesium sulphate	18.3	1.97

Source: Tisdale & Nelson 1966.

cially to sensitive species such as Norway spruce. It is not clearly understood if the detrimental effect is due to higher osmotic pressures in the soil solution or toxicity of the ion itself. Chloride-containing materials can probably be used without reservation when applied at reasonable rates to older stands, particularly broad-leaved trees. Other factors that have a bearing on the suitability of products containing Cl are frequency, time, and rate of application; precipitation patterns; and ease with which the ion moves out of the root zone.

Free Ammonia

Several of the N and N-P fertilizers when applied to soil may form or release NH_3. Free ammonia is toxic and can move freely through cell walls, whereas NH_4+ cannot. Because of this factor the effectiveness of urea, diammonium phosphate, ammonium carbonate and ammonium hydroxide might be less under certain conditions than that of monoammonium phosphate, ammonium sulphate, and ammonium nitrate.

Selection of a Nitrogen Fertilizer

A variety of fertilizers provide NO_3-N, and many other materials supply or form NH_4-N in soil. Three of the many factors that may influence the choice of a N fertilizer are: preference, if any, of tree species for NH_4+ or NO_3-; potential for acidifying forest soil and increasing the rate of release of nutrient cations from the forest floor; and prospective leaching losses of NO_3-N.

Growth of mycorrhizae, which are often essential to tree growth, is suppressed more by NO_3- than NH_4+ (*Pritchett and Smith 1969*). Ammonium and urea compounds are generally the preferred N forms for forest species (*Pritchett and Smith 1969*). It is also suspected that NO_3-N and high levels of inorganic N may increase the susceptibility of forest species to certain plant pathogens.

Other important factors that will affect the selection of N sources are cost per unit of N; commercial availability of product; and costs associated with handling, storage, and application. The rather wide acceptance of urea for forest fertilization in North America, especially in operational-scale programs, is probably due mainly to the above reasons. The advantages in applying this most concentrated solid N source are obvious.

A number of investigators (*Bengtson 1970; Volk 1970;* and *Watkins et al. 1972*) have been concerned about gaseous losses of NH_3 during the hydrolysis of urea in forest floor environments. These losses, if significant, would tend to detract from urea's desirable characteristics and advantages. Substantial losses of NH_3 from urea were found in laboratory studies conducted by Watkins et al. (*1972*) in the Pacific Northwest. Variables such as air movement, temperature, and pH of mineral soils all had considerable influence upon the ammonia losses. Gaseous losses of NH_3 from prilled urea applied to several slash pine sites in Florida were less than 10 percent of the total N applied (*Volk 1970*).

There is no doubt that some volatilization of NH_3 takes place following the application of urea to forest soils but the losses are expected to be rather minor, especially if the fertilizer is applied during periods of mild temperatures plus significant precipitation.

Applications of urea have pronounced effects upon the forest floor. The alkaline solution that forms upon the hydrolysis of urea will solubilize large amounts of organic matter and plant nutrients such as P (*Beaton et al. 1969*). Cations such as K, Na, Ca, and Mg are displaced from forest humus by this solution; and Fe, Mn, Cu, and Zn are transported into the soil profile in association with the dispersed organic matter (*Cole and Gessel 1965*). Although these solutions persist for only rather short periods of time, they are apparently capable of breaking down otherwise resistant humus complexes. These solubilized organic complexes may also undergo further breakdown by soil microorganisms. Thus applications of urea will aid in the recycling of plant nutrients stored in forest humus.

There is a possibility that substantial quantities of urea are immobilized in forest humus (*Ogner 1972*). It is not known if this immobilization reduces the effectiveness of urea dressings. If the resulting humus complexes are reasonably reactive, they may act similarly to controlled-release N sources. On the other hand, stable complexes may release insufficient amounts of N.

Supplies of ammonium sulphate are very plentiful in North America, and this product may find greater use in forest fertilization, especially if the cost per unit of N is low enough to compensate for higher transportation and handling costs. In addition, the S component may have a favorable effect upon tree growth (*Beaton 1966; McGregor and Goebel 1968; Pritchett, personal communication 1972; Turner 1968; and Youngberg and Dyrness 1965*).

Before using large amounts of ammonium sulphate on forest soils, it is prudent to recall its high residual acidity in soil and the attendant leaching of nutrient cations (*Beaton et al. 1969; Cole and Gessel 1965*). However, when soil base status is adequate, greater release of cations and acidification should not be a serious problem. Greater movement of cations will probably not adversely affect soil fertility when tree-root systems are sufficiently well developed to intercept and absorb most, if not all, nutrients in solution.

Homogeneous combinations of urea-ammonium sulphate have considerable promise as N-S fertilizers because their physical properties are superior to those of urea alone (*Beaton and Fox 1971*). Furthermore, the possibility of sizable losses of NH_3 during hydrolysis of urea should be greatly lessened by the dilution effect of ammonium sulphate. The ratio of N to S in these products is more nearly in keeping with plant requirements than it is in ammonium sulphate. Soil acidity developed from urea-ammonium sulphate products should be less than with ammonium sulphate only.

Ammonium nitrate is a very popular source of N for agricultural crops, but it has not been generally accepted for forest fertilization. Presumably, factors such as the possible leaching of NO_3-N, somewhat higher costs for the N as well as for handling and application, and the potential of this material for lowering the ignition point of combustible materials have all contributed to a lack of interest in its use. It should be noted, however, that beginning in 1968 there was a marked shift in the source of N applied to Swedish forests (*Holmen 1969*). Urea was used almost exclusively in the years 1964-67 while in 1968 urea accounted for only 69 percent of the total N applied and ammonium nitrate represented the remaining 31 percent.

Pritchett and Smith (*1969*) indicated that controlled-release N materials such as urea-formaldehyde and sulphur- or paraffin-coated urea have promise in the fertilization of young slash pine plantations. Slow-release products probably have their greatest potential for treatment of young stands before crown closure and before root systems are adequately developed to intercept most of the dissolved plant nutrients.

An experimental product prepared by coating granular urea with a slurry composed of 72 percent elemental S, 18 percent bentonite, and 10 percent ammonium sulphate by weight appeared to offer advantages over ammonium nitrate and urea-only treatments in Douglas-fir trials on Vancouver Island, British Columbia (*unpublished data, 1970, Pacific Logging Company Limited and Cominco Ltd.*).

The final analysis of this material was 39 percent N and 11 percent S. Its greater effectiveness is believed to be due mainly to the coating that slightly delays and prolongs the dissolution of urea.

Selection of a Phosphorus Fertilizer

A number of P carriers are available for use in forestry. Ordinary and concentrated superphosphate are the most extensively used sources of P. Other promising water-soluble P fertilizers are mono- and diammonium phosphate and ammonium polyphosphate. The ammonium present in ortho- and polyphosphates will provide supplemental N and may also have the favorable effect of enhancing P absorption. Polyphosphate products offer some degree of chelation, which might be beneficial in situations of marginal micronutrient nutrition.

All of these water-soluble P sources will react with various soil constituents—including Fe, Mn, and Al—to form less soluble reaction products. Availability of P is decreased when this occurs, especially if the reaction products are coarsely crystalline. Additions of soluble sources will immobilize excess Al and Mn in some acid soils and reduce the mobility of these elements within plants. The concentrated P solution, which diffuses from dissolving granules of ammonium ortho- and polyphosphate, dissolves soil organic matter and releases plant nutrients (*Bengtson 1970*). Diammonium phosphate products are likely to have the most pronounced effect, due to the high pH of their saturated solution. Table 5 shows the composition of various saturated fertilizer solutions following their reactions in a podzol soil.

Water-soluble P carriers are likely to produce the greatest benefit when a prompt response is desired, as in forest nurseries, for plantings on severely P-deficient soils, and on older stands suffering from a shortage of this nutrient. Their effectiveness will probably be greatest on poorly drained organic or coarse-textured soils low in soluble Fe and Al and on near-neutral or alkaline soils.

Slowly available or sparingly soluble P sources—including colloidal phosphate, rock phosphate, and basic slag—have been used successfully in a number of forestry trials. These materials are inexpensive, but they have serious limitations of low analysis with attendant high transportation and handling costs and of difficulty in applying because of their finely divided state. Although granulation could eliminate difficulties in application, the products would become more expensive. Source of the phosphate rock is an important consideration because there are significant differences in response of trees to applications of rock phosphate obtained from different deposits (*Bengtson 1971*).

The most favorable opportunities for use of slowly available P carriers appears to be in areas close to phosphate mining operations such as in Florida and North Carolina. They are likely to have their greatest effectiveness on acid, sandy soils

Table 5.—Composition of saturated fertilizer solutions following reaction in podzol soil

Fertilizer	P source	Composition of saturated solutions following reaction with podzol soil				
		pH	Organic matter	K	Ca	Mg
			p.p.m.		*g./liter*	
11-55-0	MAP	4.2	3,070	413	600	138
18-46-0	DAP	7.2	5,730	580	70	13
23-23-0	MAP	4.1	1,760	975	825	175
27-14-0	MAP	3.9	1,280	925	115	160

Source: Unpublished data, Cominco Ltd., Trail, B. C.

with reasonable to good drainage. Under these conditions, particularly if the soils are also low in soluble Fe and Al, P supplied by water-soluble sources could be lost by leaching.

A fertilizer containing both readily available and water-insoluble P is currently being evaluated for forestry uses in the southeastern United States (*Bengtson 1971*). It is a granulated partially acidulated rock phosphate prepared at TVA. Rock phosphate-S materials are another interesting possibility because the H_2SO_4 produced by the oxidation of S will form water-soluble P (*Beaton and Fox 1971*). Unreacted phosphate rock would serve as a source of slowly available P. Mixtures of pulverized rock phosphate and 7 to 16 percent elemental S have been granulated with the aid of ball clay at TVA.

The form in which supplemental P is added to forest soils may be less critical than it is for agricultural crops. Even if water-soluble P reverts to less soluble forms, trees are probably able to utilize it through extraction by their mycorrhizal roots (*Pritchett and Smith 1969*).

Selection of a Potassium Fertilizer

The need for supplemental K can be met by several common fertilizers. These are KCl, K_2SO_4, KNO_3, and $K_2SO_4.2MgSO_4$. The first three materials have high K concentrations ranging between about 37 and 51 percent K (44 and 61 percent K_2O), while the latter product typically contains 18 percent K (22 percent K_2O). Because these forms of K are all water-soluble and the K will react with soil after application, any differences between sources is expected to be due to the accompanying anions.

Potassium chloride and K_2SO_4 are the two principal carriers used thus far for forest fertilization. If the price per unit of K in K_2SO_4 is reasonably competitive with that of KCl, use of the former should probably be encouraged for three or more reasons. As indicated earlier, K_2SO_4 has a lower salt index than KCl. In addition, the Cl component of KCl may be detrimental to certain sensitive coniferous species, especially in early stages of growth. Furthermore, K_2SO_4 provides plant nutrient S, which is expected to be needed more frequently and extensively in the future.

Fertilizer grade KNO_3 was manufactured in the United States up until this year. This material is now being imported from Israel, but it is not known if deliveries are dependable. The accompanying NO_3 is probably of value to most forest species, provided it is not leached out of the root zone.

Potassium magnesium sulphate is a good source of K, S, and Mg. Because sandy soils are often deficient or low in all three nutrients, $K_2SO_4.2MgSO_4$ is probably the best K source on such soils.

Sulphur-coated KCl may be a practical way of reducing consumption of K, minimizing leaching losses of K on sandy or highly weathered soils, and avoiding high concentrations of troublesome Cl. Relatively new materials such as potassium metaphosphate and some of the potassium polyphosphates may also be more effective under soil conditions where leaching losses of K are substantial.

Monopotassium phosphate and its ammoniated double salt, monopotassium phosphate-monoammonium phosphate, are potentially valuable fertilizers (*Beaton 1971*) and once they are commercially available they should find their way into forest fertilization. Plans for commercial production of potassium phosphates in the U.S. were announced recently. Initially, a 9-48-16 chloride-free fertilizer will be introduced, followed by materials analyzing 0-48-31 and 5-45-29. When manufacturing facilities are completed, the products will be a 0-50-40 granular solid fertilizer and a 0-25-20 solution.

Selection of Calcium, Magnesium, and Sulphur Fertilizers

Calcium is not usually applied to forest soils, especially because soil pH is raised by the addition of common sources such as calcite and dolomite. Forest species, especially conifers, are usually quite tolerant to low pH. The benefits from reducing soil acidity are probably confined mainly to enhanced humus decomposition.

Magnesium deficiencies can probably be best corrected by application of either magnesium sulphate or potassium magnesium sulphate. Magnesium oxide can also be used, particularly in situations where there is a possibility of substantial leaching losses of more soluble forms of Mg.

The fertilizer materials containing S that have the greatest promise for forest fertilization were discussed earlier in the sections concerning N and K.

Selection of Micronutrient Fertilizers

Although favorable effects of micronutrient additions to forest lands are less common than effects from the macronutrients N, P, K, Ca, Mg, and S, an increasing need for micronutrients is indicated. Brief descriptions of some of the important sources of these plant nutrients follow.

Water-soluble inorganic salts.—Borax, granular borate, boric acid, copper sulphate, ferrous sulphate, manganese sulphate, zinc sulphate, zinc nitrate, zinc chloride, and sodium molybdate are popular water-soluble sources of micronutrients. The sulphates are the most commonly used metallic salts. They are relatively inexpensive, and they are suitable for use with mixed fertilizers. Granular sulphate salts are prepared by extrusion, compaction, or granulation by several methods. Sparingly soluble zinc-manganese-ammonium sulphite is also marketed.

Water-insoluble inorganic salts.—Metal ammonium phosphates such as Fe, Zn, Mn, Cu, and Co having the general formula $MeNH_4PO_4.xH_2O$ have been prepared. Insoluble inorganic salts, including carbonates and oxides of Cu, Mn, and Zn, are also used.

Synthetic chelating agents.—Synthetic chelating agents form ring compounds in which a polyvalent metal ion is held between two or more atoms. Among the best-known chelating agents are ethylenedia minetetraacetic acid (EDTA), hydroxethylenediaminetriacetic acid (HEDTA), diethylenetriaminepentaacetic acid (DTPA), ethylenediaminedi (C-hydroxyphenylacetic) acid (EDDHA), and nitrilotriacetic acid (NTA). These materials are expensive and must be at least ten times as effective as the inorganic salts to compete with them on the basis of cost per pound of micronutrient. Chelates are very useful in the formulation of liquid mixtures because they will often remain in solution.

Silvichemical complexing agents.—Natural organic complexes such as ammonium lignin sulphonate plus wood sugars and polyflavonoid chemically extracted from western hemlock bark also have the ability to complex metallic micronutrient ions. These organic complexes are generally not as effective as chelates, but they are usually less expensive. Sometimes they are not compatible with mixed fertilizers.

Fritted glasses.—Fritted micronutrients are water-soluble micronutrients that have been fused into a silicate or glass matrix; the products are compacted and granulated before bagging and storage. Solubility of the metallic salts in the frits is controlled by particle size and changes in the composition of the matrix. More than one micronutrient may be included to provide custom mixes for various crops.

Most micronutrients are applied to the soil in mixed fertilizers rather than as individual sources (*Mortvedt and Cun-*

ningham 1971). Application of micronutrients alone has several disadvantages, among them are nonuniform distribution of the small amounts generally used, and increased spreading costs. Therefore, combining the micronutrient with solid and liquid fertilizers is usually the preferred practice.

PROPER RATES OF REQUIRED NUTRIENTS

Plant nutrient application rates are usually closely related to soil-stand conditions. Nitrogen rates of 112 kg./ha. or less are probably adequate for young stands before crown closure. The rates of N applied to older coniferous stands in Scandanavia and in the Pacific Northwest are customarily in the range of 168 to 336 kg./ha. of N. However, there is evidence that rates of 448 kg. of N/ha. or even higher are beneficial for the growth of Douglas-fir and western hemlock on Vancouver Island.

Nitrogen responses generally persist for 5 to 10 years. Thus applications of N at the rates referred to above would be made only every 5 years or so during the period when additional growth is desired or possible.

Soluble P fertilizers are usually applied at rates between 28 and 112 kg. of P/ha. to pine stands on the Atlantic Coastal Plain (*Bengtson 1971*), 45 to 56 kg. of P/ha. being the most common (*Bengtson 1971; Crutchfield 1969*). Less-soluble sources such as rock phosphate should be supplied at rates approximately three times that of soluble P carriers. Growth responses of southern pines to P fertilization last for at least 15 years, and as a result a single dressing may maintain satisfactory growth through a full 20- to 30-year rotation.

Supplements of 112 kg. of K per ha. were maximal for red pine in New York State (*Stone and Leaf 1967*). The beneficial effects of single applications of K have been found to be remarkably long-lived, lasting for up to 24 years on red pine in New York.

Rates of S fertilization should probably be about 28 to 56 kg. of S/ha. for sulphate sources and approximately twice as much should be applied when granular elemental S products are used. The need for S is closely associated with the amount of N applied, and in severely S-deficient agricultural areas 1 kg. of S/ha. is added for every 5 to 7 kg. of N/ha. used. Where additions of P and S are needed, a general guideline of 1 kg. of S for each 1.3 to 1.5 kg. of P can be used for estimating S needs.

Satisfactory growth responses of conifers occurred after treatment with 25 to 75 kg. of Mg/ha. as either $MgSO_4$ or MgO (*Pritchett and Smith 1969*).

Because the range between B deficiency and toxicity is rather narrow, it is essential that B sources be applied uniformly to soil. Additions of from 0.25 to 3 kg. of B/ha. are generally recommended for agricultural crops. Foliar or soil applications of 15 to 60 g. of B per tree are recommended for several fruit and nut crops. Sodium borate ($Na_2B_4O_7$) is the most common B fertilizer.

Copper sulphate ($CuSO_4$) is the usual Cu supplement for agricultural crops. However, CuO, mixtures of $CuSO_4$ and $Cu(OH)_2$ and Cu chelates are sometimes used. Applications of 7 to 14 kg. of $CuSO_4$/ha. are generally recommended for most crops, and they can be effective for several years on most soils.

Soil application of from about 5 to 40 kg./ha. of Mn as $MnSO_4$ is the most common method of correcting deficiencies of Mn. The higher rates are often required on organic soils.

Correction of Zn deficiency can be achieved by a variety of methods, including soil and foliar applications and tree injections. Foliar applications are quite effective and are used mainly for tree crops. Applications of 3 to 5 kg. of

Zn/ha. as $ZnSO_4$ or ZnO are usually effective for most field crops. Response of citrus to $ZnSO_4$ or ZnO applied at the rate of 0.5 to 1 kg. of Zn/tree will persist for up to 5 years after application.

Iron deficiency is often more difficult to control than deficiencies of the other micronutrients. Soil applications of inorganic Fe salts have generally proved ineffective. Repeated foliar application of solutions containing 5 percent $FeSO_4$ at rates equivalent to 245 liters/ha. have successfully eliminated Fe deficiency in grain sorghum. Synthetic chelates or natural organic complexes containing Fe have proved helpful under some conditions, but their high cost prohibits widespread use. The chelate FeEDTA is recommended for acid soils.

The small amounts of Mo required to overcome deficiencies of this nutrient are usually added with liming mixtures and fertilizers, or as a seed treatment. Safe limits for soil application are probably considerably less than 1 kg./ha. of Mo. Foliar applications of Na_2MoO_4 have been effective under some conditions. Single applications of Mo have been found to favorably influence crop growth for the next 5 to 6 years.

ENSURE PLANT NUTRIENT SUPPLY IS ADEQUATE WHEN NEEDS ARE GREATEST

Fertilizer treatments should be timed so that plant nutrient supply is adequate when tree needs are greatest. Those factors that have the greatest influence on the timing of plant nutrient supplementation are (1) soil-forest stand condition, (2) stage of growth and management objectives, (3) seasonal differences in effectiveness of fertilization, and (4) fertilizer properties.

When levels of one or more nutrients are inadequate for new forest stands, fertilization should of course be carried out shortly before or soon after seedling establishment. If nutrient limitations do not occur until some years after establishment, applications of the required nutrients can be postponed, but they should be made before tree vigor declines significantly. Because tree growth can be reduced by inadequate nutrition some years before distinctive deficiency symptoms appear, it is important to ensure that marginal nutrient levels are improved early rather than late in the rotation.

Stage of growth and management objectives are also important in deciding when fertilizers should be used. Beaton and MacRae (*1967*) proposed the following opportunities for sound use of fertilizers in the management of Douglas-fir forests on Vancouver Island:

- For tree improvement through stimulation of growth of plus trees used as sources of scions and fertilization of clone banks, seed orchards, and seed production areas.
- For maintenance of soil fertility in forest nurseries.
- For overcoming "planting check" after planting of nursery-grown seedlings, particularly on difficult sites.
- For increasing growth, after crown closure, of trees between 15 and 40 years of age.
- For increasing growth of trees within 10 to 15 years of rotation age.
- For encouraging establishment of dominance in juvenile overstocked stands when average d.b.h. exceeds 9 cm.
- For increasing the proportion and size of merchantable trees at the first commercial thinning.
- For special purposes: for example, more sapwood on pole-size trees to be used for pilings; color and vigor of Christmas trees, etc.

Some of these opportunities probably also apply to the forests of eastern North America. Fertilization is believed to have considerable potential in the Atlantic Provinces of Canada for increasing the growth rate of stands approaching maturity, for breaking stagnation in very dense pole-size stands, and in the afforestation of difficult sites.

The time of year when fertilization produces the greatest benefits should also be taken into account when planning fertilization of forests. On the basis of observations in the Pacific Northwest this writer recommends that most fertilizer materials be applied at least 3 weeks before the first flush of growth in the spring. Fertilizer dressings made during periods of dormancy are probably satisfactory just so long as the added nutrients are not leached from or immobilized in soil before the growing season begins. Most of the urea applications on forests in the Pacific Northwest are now made in the fall, starting about the second week of September.

Time of fertilizer application will also be conditioned by fertilizer properties. Sparingly soluble materials which are expected to give long-lasting responses can probably be applied at almost any time with but one qualification—that they be applied sufficiently far in advance when early season responses or responses during early stages of growth are desired. If soluble nutrients are likely to be leached from or immobilized in soil, the fertilizer materials should be applied 3 to 4 weeks before the expected initiation of spring growth.

PLACEMENT OF FERTILIZERS FOR MAXIMUM EFFECTIVENESS

Placement of fertilizers so that nutrients are positionally available may not be as important for trees, which are long-lived and have deeper root systems than most annual agricultural crops. Forest tree species also have the capacity to utilize sparingly soluble nutrient sources. Many of the feeder roots of trees are situated close to the soil surface in forest humus layers, where they can readily absorb both recycled plant nutrients and those supplied in commercial fertilizers.

Placement of fertilizers in forestry situations is usually done during the site-preparation process for new stands. Phosphate fertilizers are often mixed into soil of the planting beds to improve seedling survival and to encourage early root development and tree growth. On soils with low P-fixing capacity, and where leaching of soluble P is not a problem, placement of fertilizer P is not critical. Incorporation or placement of fertilizer P is recommended on soils subject to drought.

Preparation of sites being planted to loblolly pine in the Atlantic Coastal Plain commonly includes placement of P in the bed. For example, approximately 44.5 kg. of P/ha. as concentrated superphosphate is broadcast after an area has been cleared but before bedding (*Wiley et al. 1970*). Both a wheeled skidding tractor equipped with a hopper-spreader and a helicopter have been used to broadcast the P fertilizers. The former type of equipment is favored in some instances because of more uniform application.

Broadcast application of N or other nutrients to established stands is equivalent to topdressing of agronomic crops. Aerial applications are often the only practical method of topdressing extensive areas of established stands because it is virtually impossible to drive fertilizer application equipment through most forest stands. Ground application is feasible only for small areas or where thinning techniques such as corrider thinning permit some degree of access.

AERIAL FERTILIZATION

Fixed-wing airplanes and helicopters are the main types of aircraft used for spreading fertilizers on forests. At the outset, use of helicopters was discouraged because of high application costs. However, due to great increases in payload capacity and improvements in spreaders and in fertilizer-handling systems on the ground, helicopter spreading costs are now competitive with those of fixed-wing aircraft, about 2.2 to 2.8 cents per kg. of fertilizer.

With fixed-wing airplanes, the economics of application are best with short flying distances—approximately 4.8 km. from runway to point of application. In areas too distant from conventional landing strips, "Kiwi" inclined airstrips can be constructed. Crown (*1971*) described one such strip that was built during the winter of 1968 in the Robertson River Valley on Vancouver Island. The site selected was at 335 m. above sea level and 152 m. above the valley floor. The strip was 256 m. long, including a loading area at the top of the slope. The lower two thirds of the runway had an 8 to 10 percent slope, while the upper third averaged 12 percent. Construction costs of the six inclined airstrips built up to the middle of June 1971 in coastal regions of B. C. ranged from $160 to $1,700.

Helicopters offer one important advantage in that they can take off and load in small clearings or on logging roads. The most popular helicopter systems use a pod or conical tank carried under the helicopter on a sling (*Page and Gustafson 1969*). The pod has a mechanism to meter fertilizer to a spinner that broadcasts fertilizer as the helicopter moves over an area. Spreader equipment may be driven by electric or hydraulic motors powered from the helicopter or by a radio-controlled gasoline engine mounted on the side of the pod.

Because of the high operating costs of helicopters it is essential that turn-around time at the landing point be minimized. The most efficient systems for reloading helicopters make use of two pods. One pod is refilled while the helicopter is spreading the load from the other.

It is desirable to have an adequate supply of fertilizer materials on hand well in advance of the spreading operations. One of the most satisfactory methods is to stockpile the required amounts of bagged fertilizer at each loading site 2 to 3 months before application. After testing numerous containers and systems for handling urea in the Pacific Northwest, 90-kg. bags of 7- or 8-ml. polyethylene seem to be the most suitable.

Air turbulence may make it difficult to obtain uniform application of fertilizers from aircraft, especially from helicopters. A large (–4+6 mesh) granular urea product has been developed in the Pacific Northwest to overcome this spreading problem. Ammonium nitrate of very large particle size is produced and marketed for forest fertilization in Norway and Sweden.

REFERENCES

Anonymous.
1971. REGIONAL FOREST NUTRITION RESEARCH PROJECT. Coll. Forest Resources Univ. Wash. 1970-1971 Annu. Rep. Seattle. 23 p.

Baule, H., and C. Fricker.
1970. THE FERTILIZER TREATMENT OF FOREST TREES. BLV, Munich, Germany. 259 p.

Beaton, J. D.
1966. SULFUR REQUIREMENTS OF CEREALS, FRUIT TREES, VEGETABLES, AND OTHER CROPS. Soil Sci. 101: 267-282.

Beaton, J. D.
1971. FERTILIZERS AND THEIR USE IN THE DECADE AHEAD. Agr. Res. Inst. Annu. Meet. Proc. 20: 67-101.

Beaton, J. D., and R. L. Fox.
1971. PRODUCTION, MARKETING AND USE OF SULPHUR PRODUCTS. *In* FERTILIZER TECHNOLOGY AND USE: 2nd ed., 335-379. Soil Sci. Soc. Amer., Inc., Madison, Wis.

Beaton, J. D., J. T. Harapiak, R. C. Speer and R. T. Gardiner.
1969. RELEASE OF PLANT NUTRIENTS FROM FOREST SOIL HUMUS TREATED WITH NITROGEN AND SULFUR FERTILIZERS. Can. Soc. Soil Sci., Annu. Meet. 14, Saskatoon, Saskatchewan.

Beaton, J. D., and I. MacRae.
1967. SOME ASPECTS OF FOREST FERTILIZATION IN BRITISH COLUMBIA. Can. Soc. Soil Sci. Annu. Meet 12. Macdonald College, Quebec.

Beaton, J. D., and S. L. Tisdale.
1969. POTENTIAL PLANT NUTRIENT CONSUMPTION IN NORTH AMERICA. Sulphur Inst. Tech. Bull. 16. Washington, D. C., 64 p.

Bengtson, G. W.
1968. PROGRESS AND NEEDS IN FOREST FERTILIZATION RESEARCH IN THE SOUTH. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 234-241. TVA, Muscle Shoals, Ala.

Bengtson, G. W.
1970. FOREST SOIL IMPROVEMENT THROUGH CHEMICAL AMENDMENTS. J. Forest. 68: 343-347.

Bengtson, G. W.
1971. TRENDS IN FOREST FERTILIZATION. *In* SEARCHING THE SEVENTIES: 72-77. TVA Nat. Fert. Develop. Cent. Bull. Y-34. 116 p. Muscle Shoals, Ala.

Bengtson, G. W., R. H. Brendemuehl, W. L. Pritchett, and W. H. Smith, (Ed.).
1968. FOREST FERTILIZATION . . . THEORY AND PRACTICE. 306 p. TVA, Muscle Shoals, Ala.

Brendemuehl, R. H.
1968. RESEARCH PROGRESS IN THE USE OF FERTILIZERS TO INCREASE PINE GROWTH ON THE FLORIDA SANDHILLS. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 191-196. TVA, Muscle Shoals, Ala.

Broadfoot, W. M., and A. F. Ike.
1968. RESEARCH PROGRESS IN FERTILIZING SOUTHERN HARDWOODS. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 180-184. TVA, Muscle Shoals, Ala.

Cole, D. W., and S. P. Gessel.
1965. MOVEMENT OF ELEMENTS THROUGH A FOREST SOIL AS INFLUENCED BY TREE REMOVAL AND FERTILIZER ADDITIONS. *In* FOREST-SOIL RELATIONSHIPS IN NORTH AMERICA: 95-104 Oreg. State Univ. Press, Corvallis.

Crown, M.
1971. "KIWI" STRIPS MAKE FOR EFFICIENT FOREST FERTILIZATION. Forest. Chron. 47: 120.

Crutchfield, D. M.
1969. FOREST FERTILIZATION—FACT OR FICTION? S. Fert. Conf. October 1969, Miami, Fla.

Farmer, R. E., Jr., G. W. Bengtson, and J. W. Curlin.
1970. RESPONSE OF PINE AND MIXED HARDWOOD STANDS IN THE TENNESSEE VALLEY TO NITROGEN AND PHOSPHORUS FERTILIZATION. Forest Sci. 16: 130-136.

Gagnon, J. D.
1965. EFFECT OF MAGNESIUM AND POTASSIUM FERTILIZATION ON A 20-YEAR OLD RED PINE PLANTATION. Forest. Chron. 41: 290-294.

Gessel, S. P.
1968. PROGRESS AND NEEDS IN TREE NUTRITION RESEARCH IN THE NORTHWEST. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 216-225. TVA, Muscle Shoals, Ala.

Heiberg, S. O., and D. P. White.
1951. POTASSIUM DEFICIENCY OF REFORESTED PINE AND SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15: 369-376.

Holmen, Hilmar.
1969. FOREST FERTILIZATION IN SWEDEN. Kungl. Skogs-och Lantbruksakademiens arbetsgrupp för skoglig växtnäringsforskning Medd. 1. Stockholm, Sweden. 8 p.

Jones, H. C., III, and J. W. Curlin.
1968. THE ROLE OF FERTILIZERS IN IMPROVING THE HARDWOODS OF THE TENNESSEE VALLEY. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 185-190. TVA, Muscle Shoals, Ala.

Lafond, A.
1958. Les Déficiences En Potassium Et Magnésium De Quelques Plantations. Laval Univ. Forest. Res. Found. Bull. 1. Quebec

Leaf, A. L.
1968. POTASSIUM, MAGNESIUM, AND SULPHUR DEFICIENCES IN FOREST TREE NUTRITION. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 88-122. TVA, Muscle Shoals, Ala.

Leaf, A. L.
1972. PLANT ANALYSIS AS AN AID IN FERTILIZING FORESTS. *In* SOIL TESTING AND PLANT ANALYSIS. 2nd ed., in press. Soil Sci. Soc. Amer., Inc., Madison, Wis.

Lindsay, W. L., A. W. Frazier and H. F. Stephenson.
1962. IDENTIFICATION OF REACTION PRODUCTS FROM PHOSPHATE FERTILIZERS IN SOILS. Soil Sci. Soc. Amer. Proc. 26: 446-452.

MacRae, I., and J. D. Beaton.
1968. OPERATIONAL SCALE FOREST FERTILIZATION TRIALS ESTABLISHED IN 1963 ON VANCOUVER ISLAND, BRITISH COLUMBIA. Amer. Chem. Soc. Nat. Meet. 156. Atlantic City, N. J.

McFarlane, D. M., and H. H. Krause.
1972. SOIL FACTORS LIMITING BLACK SPRUCE GROWTH IN CENTRAL NEW BRUNSWICK. Can. Soc. Soil Sci. Annu. Meet. 17. Univ. Prince Edward Island, Charlottetown, P.E.I.

McGregor, Wm. H. D., and N. B. Goebel.
1968. EFFECTIVENESS OF NITROGEN FERTILIZERS AND MULCH FOR THE AMELIORATION OF SEVERE PLANTING SITES. *In* TREE GROWTH

AND FOREST SOILS: 65-72. Oreg. State Univ. Press, Corvallis.

Mader, D. L., B. W. Thompson, and J. P. Wells.
1969. INFLUENCE OF NITROGEN ON SUGAR MAPLE DECLINE. Mass. Agr. Exp. Sta. Bull. 582. 19 p.

Mortvedt, J. J., and H. G. Cunningham.
1971. PRODUCTION, MARKETING, AND USE OF OTHER SECONDARY AND MICRONUTRIENT FERTILIZERS. *In* FERTILIZER TECHNOLOGY AND USE, 2nd ed.: 413-454. Soil Sci. Soc. Amer., Inc., Madison, Wis.

Ogner, G.
1972. THE COMPOSITION OF A FOREST RAW HUMUS AFTER FERTILIZATION WITH UREA. Soil Sci. 113: 440-447.

Page, J. M., and M. L. Gustafson.
1969. EQUIPMENT FOR FOREST FERTILIZATION. Soc. Auto. Eng. Nat. W. Coast Meet. Pap. 690553. 10 p. Seattle.

Pritchett, W. L.
1968. PROGRESS IN THE DEVELOPMENT OF TECHNIQUES AND STANDARDS FOR SOIL AND FOLIAR DIAGNOSIS OF PHOSPHORUS DEFICIENCY IN SLASH PINE. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 81-87. TVA, Muscle Shoals, Ala.

Pritchett, W. L., and H. Hanna.
1969. FOREST FERTILIZATION: RESULTS TO DATE, POTENTIAL GAINS IN SOUTHEAST GENERATE CAUTIOUS OPTIMISM. Forest Ind. 96 (11): 26-28.

Pritchett, W. L., and W. H. Smith.
1968. FERTILIZING SLASH PINE ON SANDY SOILS OF THE LOWER COASTAL PLAIN. *In* TREE GROWTH AND FOREST SOILS: 19-41. Oreg. State Univ. Press, Corvallis.

Pritchett, W. L., and P. H. Smith.
1969. SOURCES OF NUTRIENTS AND THEIR REACTIONS IN FOREST SOILS. Soil and Crop Sci. Soc. Fla. Proc. 29: 149-158.

Stone, E. L., Jr.
1953. MAGNESIUM DEFICIENCY IN SOME NORTHEASTERN PINES. Soil Sci. Soc. Amer. Proc. 17: 297-300.

Stone, E. L., and A. L. Leaf.
1967. POTASSIUM DEFICIENCY AND RESPONSE IN YOUNG CONIFER FORESTS IN EASTERN NORTH AMERICA. Colloq. Int. Potash Inst. Forest Fert. Proc: Jyväskylä, Finland.

Stratton, K. G., L. O. Safford, and R. A. Struchtemeyer.
1968. TWO FERTILIZER STUDIES WITH WHITE PINE IN MAINE. Res. Life Sci. Summer 1968: 1-5.

Swan, H. S. D.
1969a. FERTILIZERS, THEIR ROLE IN REFORESTATION. Pulp and Pap. Res. Inst. Can. Woodlands Pap. 9. Pointe Claire, Quebec. 11 p.

Swan, H. S. D.
1969b. EASTERN CANADA PROBES LESS COSTLY WOOD-TREES ON GOOD SITES, NEAR MILLS, FERTILIZED. Forest Ind. 96 (12): 32-35.

Tisdale, S. L., and W. L. Nelson.
1966. SOIL FERTILITY AND FERTILIZERS. 2nd ed., 306 p. Macmillan Co., New York.

Turner, D. O.
1968. SULPHUR RESPONSE OF DOUGLAS-FIR CHRISTMAS TREES. Sulphur Inst. J. 4 (3): 11-12.

van Lear, D. H., and W. H. Smith.
1972. RELATIONSHIPS BETWEEN MACRO- AND MICRONUTRIENT NUTRITION OF SLASH PINE ON THREE COASTAL PLAIN SOILS. Plant and Soil 36: 331-347.

Vimmerstedt, J. P., and C. A. Osmond.
1968. RESPONSE OF YELLOW-POPLAR TO FERTILIZATION. *In* TREE GROWTH AND FOREST SOILS: 127-154. Oreg. State Univ. Press, Corvallis.

Volk, G. M.
1970. GASEOUS LOSS OF AMMONIA FROM PRILLED UREA APPLIED TO SLASH PINE. Soil Sci. Soc. Amer. Proc. 34: 513-516.

Ward. W. W., and T. W. Bowersox.
1970. UPLAND OAK RESPONSE TO FERTILIZATION WITH NITROGEN, PHOSPHORUS AND CALCIUM. Forest Sci. 16: 113-120.

Watkins, S. H., R. F. Strand, D. S. De Bell, and J. Esch, Jr.
1972. FACTORS INFLUENCING AMMONIA LOSSES FROM UREA APPLIED TO NORTHWESTERN FOREST SOILS. Soil Sci. Soc. Amer. Proc. 36: 354-357.

Wells, C. G.
1968. TECHNIQUES AND STANDARDS FOR FOLIAR DIAGNOSIS OF N DEFICIENCY IN LOBLOLLY PINE. *In* FOREST FERTILIZATION THEORY AND PRACTICE: 72-76. TVA, Muscle Shoals, Ala.

White, D. P.
1968. PROGRESS AND NEEDS IN TREE NUTRITION RESEARCH IN THE LAKE STATES AND NORTHEAST. In FOREST FERTILIZATION . . . THEORY AND PRACTICE: 226-233. TVA, Muscle Shoals, Ala.

White, D. P.
1969. RESEARCH AND DEVELOPMENT IN FOREST FERTILIZATION IN NORTHEAST AND MIDWEST. Forest Ind. 96 (10): 29-31.

Wiley, J. J., Jr., D. M. Crutchfield, J. Marton, and N. M. Berenyi.
1970. FOREST FERTILIZATION IN THE SOUTH CAROLINA COASTAL PLAIN. TAPPI 53 (11): 2136-2138.

Youngberg, C. T., and C. T. Dyrness.
1965. BIOLOGICAL ASSAY OF PUMICE SOIL FERTILITY. Soil Sci. Soc. Amer. Proc. 29: 182-187.

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WATER-QUALITY—LIMNOLOGICAL CONCERNS ABOUT FOREST FERTILIZATION

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ABSTRACT. From the viewpoint of a limnologist, the author discusses possible effects of forest fertilization on the aquatic ecosystems of streams and lakes and raises a number of questions for consideration. Since forest fertilization is still in its infancy, we should begin an intensive search for answers to these questions, hoping that the fears of limnologists may be unfounded.

WE ARE ALL aware of the serious threat posed by water pollution to our lakes and streams. Much of the supply of relatively clear uncontaminated water lies in forested areas. Consequently, limnologists look with some concern at the recent appearance of forest fertilization as a potential threat to the quality of these clear waters.

Since I am a limnologist and know little about soil chemistry, I will simply make what I presume are reasonable assumptions about what one could expect as inputs into the aquatic ecosystem as a result of forest fertilization. These are:

(1) Fertilization will result in an increase in the concentration of nutrients entering streams and lakes, both those nutrients that are applied and possibly others that may be released from the soil. The magnitude of the increase is undetermined and will vary with soil types, slope, amount of precipitation, vegetation, and a host of other variables.

(2) There will be an increase in the rate of productivity both in the target species and other plant components of the forest, which will result in an increase in the input of dissolved and particulate organic matter into the stream or lake.

Little is known about the impact of forest fertilization on lakes and streams. Recent work at Hubbard Brook (*Likens et al. 1970*) has shown that cutting over and chemically treating watersheds can have profound effects on water quality. It seems reasonable to expect that forest fertilization might also affect water quality. However, investigations of this nature are limited. One approach might be to draw analogies between agricultural fertilization and forest fertilization. The relationship between agricultural fertilization practices and water quality have been much more thoroughly investigated (*Sawyer 1947*). However, it could be misleading to try to draw parallels.

Farm crops are grown on bare soil unprotected from rain, whereas forest land is usually protected from erosion. Rarely if ever does the farm crop keep the stream in shade as the forest does. Frequently the forested land is in areas where the slope and soil are such that farming would be impossible. Consequently, drainage patterns would be quite different. Thus it seems that forest fertilization is unique enough to require a separate analysis.

Since relatively little work has been done on the effect of forest fertilization and water quality and no long-term work comparable to the time needed to prepare a forest crop for harvesting, I shall simply speculate on what possible consequences might occur and attempt to raise questions from a limnologist's point of view.

FOREST FERTILIZATION AND STREAMS

Streams are characterized by longitudinal gradients in terms of temperature and chemical constituents and exhibit very little vertical stratification. Upstream areas are generally cooler and contain lower concentrations of dissolved compounds than downstream reaches. However, due to the turbulent flow exhibited in streams, there is rather good mixing with reasonable uniformity from bank to bank and from surface to stream bottom (*Hynes 1970*).

Turbidity levels are frequently high in streams, particularly during high flows or in areas disturbed by man. In forested watersheds, turbidity levels are lower. High turbidity tends to reduce productivity by reducing the amount of light reaching the stream bottom. However, in those areas where the forest canopy completely encloses a small stream, light reaching the stream is already greatly reduced. In coniferous forests this condition would persist year round. In deciduous forests increased light would be expected in the spring before the leaves appear and in the fall after leaf fall. Summer would be the period of minimal light for stream plants (*Minckley 1963*).

Water entering a stream is derived from either surface sources or through underground flow. During periods of heavy rain or snowmelt, surface runoff adds considerably to the volume of water in the stream. However, during most of the year, water that has percolated through the soil is the primary source. This explains why the concentration of dissolved solids is highest in low-flow periods and lowest during spate conditions. Conversely, the total quantity of material removed from the watershed is often highest during periods of heavy rain or snowmelt and lowest in the dry part of the year.

Terrestrial vegetation plays a role also, in that it slows down the movement of water into the stream, thus reducing the load of particulate matter and increasing the proportion of dissolved matter. This results from the reduction in water velocity due to the intercepting effect of the vegetation. In forested areas very little surface flow would be expected.

Plant nutrients enter a stream directly through material dissolved in rainwater, by leaching from the soil and bedrock, and through decomposition of organic matter, such as leaves, carried in from the watershed. The input resulting from rainwater is not small (table 1), particularly when compared to minimum values of some Wisconsin lakes. It is clear that a basin filled with rainwater would make a reasonable approximation to some existing soft-water lakes (*Hutchinson 1957*).

The contribution made by allochthonous organic matter, although frequently overlooked, can also be considerable. Chandler (*1941 and 1943*) estimated the N return to the soil from leaves at 23.6

Table 1.—Chemical composition of rainwater and water in dilute Wisconsin lakes (from Hutchinson 1957)

Compound	Rainwater	Minimum concentration, Wisconsin lakes
	Mg./l.	*Mg./l.*
Cl	0.5	0.1
Br	.03	—
I	.001	—
SO_4	2.0	.75
B	.01	—
Na	.4 +	.13
K	.03 +	.25
Mg	.1 +	< .5
Ca	.1-10	.13
N NH_3	.5	< .01
N NO_3	.2	< .004

pounds per acre for conifers and 16.6 pounds per acre for hardwood forests. The values for phosphorus were 1.8 and 3.3 pounds per acre for conifer and hardwood forests respectively. Of course, much of this is recycled within the forest ecosystem, but a significant portion also enters the aquatic ecosystem (*Teal 1957*). Probably the major pathway for nutrient uptake by the stream, however, is through leaching of the soil and bedrock.

Plants in streams require approximately the same array of nutrient salts as their terrestrial counterparts: K, N, and P, along with a large number of minor elements such as Fe, S, Si, etc. Neither K nor any of the minor elements has been shown to be a factor limiting plant growth in streams (*Hynes 1970*). As a result, N and P are the elements of particular concern to limnologists.

P is tightly held by the soil, and relatively little leaching occurs (*Donahue 1965*). Many investigators feel that the major port of entry is via soil particles themselves. Owens and Johnson (*1966*) have suggested streambank erosion as a major source; others feel that silt transported in during high-flow periods may bring in P. In undisturbed forested areas where little erosion occurs, the addition of P in this manner would probably be slight.

N is more readily leached from the soil and, in addition, some forms of algae (*Nostoc* and *Rivularia*) have the capability of fixing atmospheric N.

Potentially, at least, the stream could draw its nutrients from the entire upstream drainage basin. The area drained by a given section of stream has been estimated, and on the average 1.0 square km. of drainage area supports 1.4 km. of stream (*Leopold et al. 1964*). Since streams are relatively narrow and have considerably smaller surface areas than the basins they drain, they may receive rather large inputs from small amounts of leaching per unit area of drainage basin.

For example, suppose a headwater stream 2 m. wide and 1.4 km. long drained an area of 1 km^2. It would be draining an area of 1,000,000 m.^{2}, whereas its area would be 2,800 m.^{2}—a ratio of 357:1. If this drainage basin were fertilized at a rate of 100 kg./ha., less than 0.3 kg./ha. would have to be lost to the stream to have the same impact as direct fertilization on the stream surface at a rate of 100 kg./ha. This value would vary, of course, with streams of different widths. Consequently, the potential of accumulating small quantities of nutrients from a large drainage area into a small stream must be borne in mind when interpreting leaching results.

Efforts have been made to estimate the productivity of the plant community in unpolluted streams. In most cases the conclusion was reached that the plants in the stream were producing just enough energy for their own needs and that very little if any excess was being produced (*Nelson and Scott 1962; Hoskin 1959*). Heterotrophy, then, is dependent, to a large degree, on allochthonous imports of organic matter. Such things as leaf litter, particulate and dissolved organic matter from the soil, and terrestrial animals are major sources of energy for the stream heterotrophs.

With this as a background, we can begin to examine some of the limnological consequences of forest fertilization.

To begin with, a relatively small (< 1 percent) removal of fertilizer through leaching and subsurface flow could lead to substantial quantities being transported to the stream. Cole and Gessel (*1965*) estimated nutrient loss to the 3-foot level in porous soils on the West Coast, using tension lysimeters after fertilization with ammonium sulfate and urea. Their results indicated a slight increase in N levels at the 3-foot level over controls. The increase was about 0.07 to 0.23 percent of the N applied as fertilizer.

If one could assume that all the N that reaches the 3-foot level could move with the ground or subsurface water to the stream unhindered and use the stream area/drainage area relationship previously discussed, this then would be equivalent to fertilizing directly on the stream surface at a rate of 164 pounds per acre of ammonium sulfate or 50 pounds per acre of urea. This probably doesn't happen, but it is clear that we need more information about the fate of nutrients after they pass through the rooting zone and enter the subsurface or ground water.

But assume the worst, and imagine that large quantities of nutrients do reach the stream from fertilization: What would be their impact? One of the few direct attempts to study this was an effort by Huntsman (*1948*). He placed bags of fertilizer in streams and sprinkled large amounts on the stream bank and then measured the effect on the stream biota. His conclusion was that fertilization increased population levels of algae, which led to a subsequent increase in bottom invertebrates and fish populations. However, the surprising result was that the impact of this extended for just a short distance downstream. The maximum distance that any observable effect was noted was 150 yards from the point of fertilization.

Other workers (*Neel 1951; Minckley 1963*) have noted rapid uptake of plant nutrients in the stream, attributable to plant activity. Such a phenomenon, if borne out by more careful study, would lead to the conclusion that high concentrations of nutrients might develop in very restricted areas, characterized by high algal populations and high productivity. So, not only is it important to know the distance travelled by nutrients underground, but how extensively and—more importantly—how rapid are their movements in the open stream channel? It is clear that ultimately they must move downstream. Very few mechanisms exist for transporting nutrients upstream save migrations of biological material such as fish or mayflies. Consequently, the rate of downstream movement over the long term would be of paritcular interest.

What role does light play in all this? Phinney and McIntyre (*1965*), working with stream algae in artificial channels, have shown that productivity (measured as net oxygen production) was highest at 11,400 lux at 18°C. Below this, productivity dropped until at 620 lux more oxygen was being respired than produced. Since nutrient demand would be related to photosynthetic rate, the uptake of nutrients by stream plants in a shaded forest stream might be inhibited at low light intensities. This could have important implications for downstream movement of nutrients and possibly lake eutrophication. Unfortunately, we know very little about this aspect of stream limnology.

Another facet that should be investigated is the relationship between increased terrestrial plant growth and the input of allochthonous organic matter to the stream. If fertilization results in increased terrestrial productivity, will this lead to increases in the quantity of dissolved and particulate organic matter entering the stream? Organic matter from leaf fall would raise the BOD (Biochemical Oxygen Demand) and might be expected to reduce oxygen concentrations in still pools. On the positive side, trout feed heavily on terrestrial insects washed into the stream (*Reed and Bear 1966*). If fertilization increases terrestrial insect production, it may also improve trout production.

FOREST FERTILIZATION AND LAKES

Lakes, in contrast to streams, act as catchment basins, accumulating materials in the sediments, which can sometimes be recycled. Recycling is hampered by several things, but most important is the fact that lakes are vertically stratified during the warm growing season. In the summer a warm well-mixed layer, usually high in oxygen and low in nutrients and carbon dioxide, rests above a cold dark layer, sometimes low in oxygen and usually high in nutrients and carbon dioxide.

The upper layer (epilimnion) is the zone of high photosynthesis, which normally fixes more energy than can be consumed by the heterotrophic components of the ecosystem. The lower layer (hypolimnion) is usually dark and thus fixes little energy, but does consume the production of the epilimnion, releasing nutrients in the process. The two layers are separated by a transition zone called the metalimnion, which inhibits mixing until fall turnover.

The summer stratification period in the Northeast may last from April through October, depending on the latitude, morphometry of the lake basin, and weather. This, of course, is the period of greatest biological activity and the period during which many forest-management practices, such as fertilization, are likely to occur.

The epilimnion is the only layer that has contact with the atmosphere throughout the period of stratification. It is usually well mixed and consequently well oxygenated. In this zone most of the photosynthetic activity takes place, also contributing oxygen to the water and frequently depleting carbon dioxide. Nutrients utilized by the algae are to a certain extent recycled within the epilimnion, but a substantial fraction is removed from the epilimnion in the form of the dead bodies of organisms, which settle into the deeper portion of the lake.

Here decomposition processes release the nutrients, using oxygen in the process. The hypolimnion then becomes enriched with nutrients, which are not available to the plants in the lighted epilimnion. It also may become anoxic as a result of the respiratory demands of the heterotrophs and the fact that it has no source of resupply, either from contact with the atmosphere or from photosynthesis.

In a sense the lake may have a kind of limit on its productivity during the stratification period. Since nutrients are lost to the hypolimnion as a result of production, late in the stratification period the lack of certain key elements may act to inhibit productivity. Inputs of nutrients from the drainage basin either via stream flow or underground flow may, of course, supplement some of these losses. On occasion, certain vital nutrients such as P can be trapped in the hypolimnion when Fe is present.

What impact would forest fertilization have on standing bodies of water? To begin with, we would expect an increase in nutrients entering either via underground seepage similar to streams or through streamflow. An increase in nutrients would speed up the rate of eutrophication.

The eutrophication process is well know (*Hasler 1947; Sawyer 1966*). It begins with an increase in plant density, which leads to increased production of all trophic levels. The quantity of organic matter settling into the hypolimnion increases, leading to higher BOD's. Eventually, a time is reached when respiratory demands exceed the hypolimnetic oxygen supply, and the hypolimnion becomes anoxic. In severe cases, particularly in the winter, when the lake has a thick blanket of snow, the entire lake can become anoxic.

For example, Ball (*1950*) added inorganic fertilizer to two lakes in Michigan at a rate of 100 pounds per acre, four or five times during two consecutive growing seasons. Two neighboring lakes were retained as controls. The fertilizer was 10-6-4, high in N and P. Fertilization increased algal biomass in both lakes for two years subsequent to the introduction of the fertilizer. In addition, during the second winter, both lakes suffered a winterkill; oxygen became sufficiently depleted in the lake under the ice that large numbers of fish died as a result. Winterkill was not experienced in the control lakes.

Thus it is clear that in small lakes at least the addition of fertilizer in concentrations similar to what one would put on the land could have drastic effects, particularly in the Northeast, where winters are long and are characterized by heavy snowfall.

Even if winterkill is avoided, other unpleasant effects might be expected. Such things as a reduction in water clarity, occurrence of algal blooms, and low oxygen in the hypolimnion, leading to a loss of cold water fishes such as trout, are all possible consequences of the eutrophication process.

DISCUSSION

A completely efficient forest-fertilization program would convey all nutrients added to the soil into harvestable tree tissue. If this happy circumstance occurred, the water-quality problem would disappear. Unfortunately, this is unlikely to be the case. Therefore there is an urgent need to answer several vital questions.

(1) How far are nutrients transported in the subsurface water and ground water? (2) What is the effect of soil type and slope on the loss of nutrients? (3) What types of management practices might reduce the loss of nutrients to the stream?

Aquatic ecologists are faced with several questions also. (1) What happens to fertilizers that enter the stream, particularly N and P? What forms do they take? Where can they be found? Are they available to plants? (2) How far and how rapidly downstream are nutrients transported? (3) What is the impact of shading on the downstream movement of nutrients? (4) What role does an increase in allochthonous organic matter have on the stream ecosystem? (5) In lakes, what will be the impact of forest fertilization on the natural eutrophication process? Would winterkill result? (6) Are there positive benefits to be derived such as increasing fish production?

It seems to me, since forest fertilization is still in its infancy, but showing signs of robust growth, that we should begin an intensive search for answers to these questions. I hope we shall discover that the fears of the limnologists are unfounded.

REFERENCES

Ball, R. C.
1950. FERTILIZATION OF NATURAL LAKES IN MICHIGAN. Trans. Amer. Fish. Soc. 78: 145-155.

Chandler, R. F., Jr.
1941. THE AMOUNT AND NUTRIENT CONTENT OF FRESHLY FALLEN LEAF LITTER IN THE HARDWOOD FORESTS OF CENTRAL NEW YORK. J. Amer. Soc. Agron. 33: 859-871.

Chandler, R. F., Jr.
1943. AMOUNT AND MINERAL NUTRIENT CONTENT OF FRESHLY FALLEN NEEDLE LITTER OF SOME NORTHEASTERN CONIFERS. Soil Sci. Soc. Amer. Proc. 8: 409-411.

Cole, O. W., and S. P. Gessel.
1965. MOVEMENT OF ELEMENTS THROUGH A FOREST SOIL AS INFLUNCED BY TREE REMOVAL AND FERTILIZER ADDITIONS. *In* FOREST-SOIL RELATIONSHIPS IN NORTH AMERICA: 95-104. Oreg. State Univ. Press, Corvallis.

Donahue, R. L.
1965. SOILS. AN INTRODUCTION TO SOILS AND PLANT GROWTH. Prentice-Hall, Englewood Cliffs, N. J. 2nd ed. 363 p.

Hasler, A. D.
1947. EUTROPHICATION OF LAKES BY DOMESTIC SEWAGE. Ecology. 28: 383-395.

Hoskin, C. M.
1959. STUDIES OF OXYGEN METABOLISM OF STREAMS OF NORTH CAROLINA. Univ. Tex. Inst. Mar. Sci. Publ. 6: 186-192.

Huntsman, A. G.
1948. FERTILITY AND FERTILIZATION OF STREAMS. J. Fish. Res. Board Can. 7(5): 248-253.

Hutchinson, G. E.
1957. A TREATISE ON LIMNOLOGY. Vol. 1. GEOGRAPHY, PHYSICS, AND CHEMISTRY. John Wiley & Sons, New York. 1015 p.

Hynes, H. B. N.
1970. THE ECOLOGY OF RUNNING WATERS. Univ. Toronto Press. 555 p.

Leopold, L. B., M. G. Wolman, and J. P. Miller.
1964. FLUVIAL PROCESSES IN GEOMORPHOLOGY. W. H. Freeman & Co., San Francisco. 522 p.

Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher, and R. S. Pierce.
1970. EFFECTS OF FOREST CUTTING AND HERBICIDE TREATMENT ON NUTRIENT BUDGETS IN THE HUBBARD BROOK WATERSHED-ECOSYSTEM. Ecol. Monogr. 40(1): 23-47.

Minckley, W. L.
1963. THE ECOLOGY OF A SPRING STREAM DOE RUN, MEADE COUNTRY, KENTUCKY. Wildlife. Monogr. Chestertown 124 p.

Neel, J. K.
1951. INTERRELATIONS OF CERTAIN PHYSICAL AND CHEMICAL FEATURES IN A HEADWATER LIMESTONE STREAM. Ecology. 32: 368-391.

Nelson, D. J., and D. C. Scott.
1962. ROLE OF DETRITUS IN THE PRODUCTIVITY OF A ROCK-OUTCROP COMMUNITY. Limnol. Oceanogr. 7: 396-413.

Owens, G. E., and M. G. Johnson.
1966. SIGNIFICANCE OF SOME FACTORS AFFECTING YIELDS OF PHOSPHORUS FROM SEVERAL LAKE ONTARIO WATERSHEDS. Gt. Lakes Res. Inst. Publ. 15: 400-410.

Phinney, H. K., and C. D. McIntyre.
1965. EFFECT OF TEMPERATURE ON METABOLISM OF PERIPHYTON COMMUNITIES DEVELOPED IN LABORATORY STREAMS. Limnol. Oceanogr. 10: 341-344.

Reed, E. B., and G. Bear.
1966. BENTHIC ANIMALS AND FOOD EATEN BY BROOK TROUT IN ARCHULETA CREEK, COLORADO. Hydrobiologia 27: 227-237.

Sawyer, C. N.
1947. FERTILIZATION OF LAKES BY AGRICULTURAL AND URBAN DRAINAGE. J. New England Water Works Assoc. 61: 109-127.

Sawyer, C. N.
1966. BASIC CONCEPTS OF EUTROPHICATION. J. Water Pollut. Contr. Fed. 38: 737-744.

Teal, J. M.
1957. COMMUNITY METABOLISM IN A TEMPERATE COLD SPRING. Ecol. Monogr. 27 (3): 283-302.

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POTENTIAL IMPACT OF FOREST FERTILIZATION ON STREAMFLOW

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ABSTRACT. Forest fertilization may cause a decline in quantity of streamflow by stimulating additional leaf surface area and root occupancy, thus increasing water losses to transpiration and interception. Water quality may be affected by application of fertilizers directly into stream channels and by an increase in the amount of nutrients transported to the stream by subsurface flow. The magnitude of increases in nutrients in subsurface flow will depend on such factors as type and form of fertilizer nutrients applied, efficiency of root uptake, and water regime and cation exchange capacity of the site. The use of gaged watersheds appears to be the best method for quantifying the potential impact of forest fertilization on streamflow.

THE CONTINUING CONCERN over environmental quality suggests to us that forest fertilization must not be attempted on any large scale without first considering the potential impact on quantity and quality of streamflow.

We have virtually no documented evidence about how forest fertilization might affect streamflow in eastern North America. However, a background of forest hydrology and soils information and past experiences in agriculture are available to draw upon for at least an initial discussion of the potential impact of fertilization. We have chosen information from these sources to point out some considerations that must be made about fertilization and streamflow.

QUANTITY OF STREAMFLOW

Studies of forest hydrology have some implication about forest fertilization and quantity of streamflow. Gaged-watershed studies have demonstrated that reduction of forest cover results in proportional increases in quantity of streamflow (*Hibbert 1967*). These studies show that increases in streamflow decline as the forest regrows and that the rate of decline varies, depending on how rapidly revegetation occurs.

The decline in streamflow during the regrowth cycle is due to accumulation of biomass in the new forest, particularly as foliage and roots, thus increasing water losses to transpiration and interception (less than 1 percent of the water uptake by trees is stored in biomass). As the stand regrows, actual evapotranspiration approaches the potential or maximum possible evapotranspiration for the site, the result being less water available for streamflow. The corollary for forest fertilization is that increases in biomass due to fertilization may possibly be accompanied by increased evapotranspiration and a decline in streamflow.

A study at the Coweeta Hydrologic Laboratory in North Carolina showed that quantity of streamflow will respond to fertilization (*Hibbert 1969*). A mountainous 9-hectare watershed was converted from hardwood forest cover to grass and heavily fertilized. During the first year under grass, water use was essentially the same as that by the original forest. In succeeding years, however, the productivity of the grass declined as fertilizer reserves were exhausted. By the fifth year after conversion to grass, the watershed was yielding 150 mm. per year more water than would have occurred from the original forest.

At this point in the experiment the grass cover was again fertilized and restored to original productivity. Annual water use immediately returned to about the same level as used by the original forest. Thus by withholding or applying fertilizer, annual streamflow was varied over a 150-mm. range.

The significance of this experiment lies in the strong relationships between streamflow and biomass production as stimulated by fertilization. The results have only indirect application for forests that vary greatly from grasses in transpiring surface, physiological response, and root occupancy. Information is limited as to how forest fertilization will affect the biomass components of hydrologic interest such as leaf surface area and rooting.

In perhaps the most appropriate study available, Heilmann and Gessel (*1963*) found that N fertilization applied to relatively poor soils caused foliar material in Douglas-fir stands to increase 20 to 53 percent. Safford (*1972*) noted that the fine root biomass doubled under a 90-year-old beech-birch-maple forest in New Hampshire after heavy application of lime (1,120 kg./ha.) and 15-10-10 N-P-K fertilizer (6,720 kg./ha.).

We can also infer from studies of site productivity that site improvement by fertilization will increase the amount of leaf surface area. Leaf and Leonard (*1969*) reported growth characteristics of 30-year-old red pine on a medium productive site versus a site with severe K deficiency. The medium productive site had a needle mass weighing over 11,000 kg./ha. and a needle surface area of 12 hectares per hectare. Needles on the K-deficient site weighed only 5,500 kg./ha. and had a surface area of about 7 hectares per hectare. The medium productive site was estimated to intercept 10 percent more precipitation than the K-deficient site.

Ovington (*1965*) found that a greater weight of leaves tends to be present in forests on better soils. Whittaker's (*1966*) detailed ecological studies in the Great Smoky Mountains indicated that leaf surface area for both hardwood and conifer species will increase as growing-site conditions improve.

From studies such as these it does not appear unrealistic to anticipate that improvements in site conditions through forest fertilization will increase both leaf surface area and root occupancy and in turn bring about an increase in water use.

Many factors will affect the magnitude of changes in water use that might result from fertilization. One of the most important will be the age of the stand at fertilization. Consider three periods when fertilizer application is likely: (1) near harvest, (2) before crown closure, and (3) after crown closure. Near harvest, the actual evapotranspiration for the stand is usually closest to potential, and the possibility for significant increases in water use will be at a minimum. Also, biomass increases resulting from fertilization of older stands will be more in the form of woody material than foliage (*Kawana 1966*).

Fertilization before crown closure increases leaf area and hastens crown closure. And since evapotranspiration at earlier ages will normally be furthest below potential, chances for increasing water use will be at a maximum. Effects of fertilization at some point after crown closure can be expected to be intermediate to the above two conditions, depending on the length of time since closure.

If forest fertilization increases water uses, what will be the impact on the fertilized area and areas downstream? First, there will be less water to move laterally through the soil to the stream, and thus leaching losses may be reduced. For example, a reduction of 1 cm./year of streamflow that would have transported 10 to 20 mg./liter of dissolved solids would result in several kg./ha. of nutrients remaining on site. Another advantageous impact may be greater availability for moisture storage, thus creating potential for reducing stormflow volume. A detrimental impact would be a lesser volume of water being available for downstream use.

Determining changes in quantity of streamflow due to fertilization may prove both expensive and difficult, particularly since the magnitude of the changes will probably be small. The two most feasible methods appear to be to monitor soil-moisture data (*Cope and Trickett 1965*) and to use paired gaged watersheds (*Wilm 1944*). Soil-moisture data may be useful in detecting increased water use due to fertilization, but they cannot give a direct measure of streamflow as compared to gaged-watershed data.

The neutron scattering technique is presently the favored way of monitoring soil-moisture data. However, the standard error is of the magnitude of daily evapotranspiration (*Federer 1970*), and this method could be used only for studying changes in water use that accrue over long intervals of time.

Because of the lag in moisture movement through the soil to the stream, the gaged-watershed technique is good only for determining streamflow changes over a month or more. However, when careful control is maintained, this method can detect changes of a centimeter of streamflow per month. An added advantage is that this method allows simultaneous determination of effects of forest fertilization on water quality. Both methods will present special problems in the event that the stand in question is in a period of rapid regrowth. The proportion of the increase in water use due to natural regrowth and that due to added growth from fertilization will be difficult to separate.

We must put the potential changes in quantity of streamflow in perspective. On a regional basis, it is doubtful that any changes in stream quantity would be noticeable unless extremely large proportions of the area were fertilized. On a local basis, such as where smaller forested watersheds feed a lake or a municipal water supply, a decline in streamflow due to fertilization might be of some consequence, especially during the late growing-season months when streamflow is usually at a minimum.

QUALITY OF STREAMFLOW

Over the past few years a lively controversy has developed over whether or not agricultural fertilizers impair water quality. Ecologists have expressed concern that a sizable proportion of nutrients applied as fertilizers are being leached or eroded into surface and groundwater systems, causing eutrophication and toxicity problems (*Kohl et al. 1971; anonymous 1969*).

On the other hand, Viets (*1971*) reasoned that fertilizers reduce sedimentation and area in cropland, so he began his paper with the statement: "Commercial fertilizers improve water quality."

Like it or not, forest fertilization is being caught in this same controversy. But unlike agriculture, forest fertilization is still basically in its infancy. At least in the Northeast, forest fertilization has not progressed much beyond a few field trials. So we still have the opportunity to research and evaluate the impact of forest fertilization on water quality before large-scale applications are made.

There are three major means by which nutrients applied as fertilizers can reach the stream channel: (1) application directly into the stream, (2) incorporated with organic and inorganic materials eroded or blown into the stream, and (3) solutes or sediment in water moving as either overland or subsurface flow.

Fertilizers that fall directly into the stream channel during application will produce an immediate and measureable response. However, with a degree of care in application, the amounts involved should not be of concern, and any effects should be short-lived.

The importance of nutrients incorporated with eroded and wind-blown material is unknown. Erosion usually is a negligible factor from forests, particularly if the stand is established. A problem may arise if fertilizer is applied at the start of a new rotation, when chances for erosion are maximum because of more moist soils and greater areas of exposed mineral soils from logging. If we follow Viets' (*1971*) reasoning, fertilizers may actually reduce erosion losses by generating additional biomass and thus added soil protection.

Overland flow is rare in forests and ordinarily will not be an important source of transport for fertilizer nutrients. Subsurface flow, on the other hand, is the pathway for the major volume of water reaching the stream channel. As a result, transport of nutrients by subsurface flow, usually termed leaching, will normally be the means by which the greatest proportion of fertilizer nutrients reach the stream.

Established or undisturbed forests are usually efficient at preventing leaching of nutrients (*Cooper 1969*). This is true even though forests commonly occupy sites conducive to leaching. Studies of nutrient cycling in hardwood forests of central New Hampshire provide an illustration. The study area is located on steep slopes with thin sandy-loam podzol soils and receives abundant precipitation, but the streams draining undisturbed forest seldom have total ionic concentrations exceeding 20 mg./liter. However, removal of the forest cover quickly increased nutrient leaching and raised annual stream ion concentration to nearly 80 mg./liter (*Likens et al. 1970*).

In addition to having low leaching losses, forest ecosystems also seem to have the capacity for accumulating and retaining added nutrient ions. The best example is an experiment at Pennsylvania State University, in which forests have been used to renovate treated sewage. Effluent containing an average 12 mg./liter of organic and nitrate N and 8.5 mg./liter of P was applied in frequent 2.5- and 5-cm. irrigations to a natural hardwood stand and a red pine plantation located on deep sandy-loam soils. Soil percolate measurements indicate that 62 to 85 percent of the N and virtually all the P were retained in the surface 30 cm. of soil (*Pennypacker et al. 1967*).

Further illustrations have been provided by various forest-fertilization studies. In a study using tension lysimeters, Cole and Gessel (*1965*) found that during the first 10 months after fertilization of a Douglas-fir plantation on coarse-textured soils in Washington, nutrient losses by leaching were small, although the levels of N, P, K and Ca in the leachate were 1.3 to 4 times greater than the low initial levels.

Moore *(1970)* reported that fertilization of Douglas-fir in southwest Oregon with urea at 224 kg. N/ha. caused streamwater concentrations of urea, ammonia- and nitrate-N to increase only slightly above background values. By the fourth week after application, all forms of N in the stream had returned to pretreatment levels.

Nearly identical results were found after urea applications to forests on both clay-loam and sandy outwash soils of the Capitol Forest near Olympia, Washington (*McCall 1970*), and to a 35-year-old Douglas-fir tract in the Cascade Mountains of Oregon (*Malueg et al. 1972*).

A study using tension lysimeters in northern Quebec indicated leaching losses of less than 1 kg./ha. during the growing season after urea fertilization at 444 kg.N/ha. in a dense black spruce stand growing on a podzolic soil with a thick raw humus layer (*Roberge et al. 1971*).

These studies provide an indication that established forests will be able to receive added nutrients in the form of fertilizers without greatly increasing leaching to streams. To avoid abusing this capability, consideration must be given to a number of important variables that affect nutrient leaching. These variables, which serve to influence the path nutrients follow in the soil environment (fig. 1), include type and form of the fertilizer nutrient, efficiency of root action, water regime of the site, and cation exchange capacity.

Type and form of nutrients.—Although a variety of nutrient deficiencies may occur in forests (*Leaf 1968; Stone 1968*), the majority of fertilizer applications have been limited to the three major elements: N, P, and K. Of these three, additions of P will be of least concern in regard to water quality. Practically all P applied as fertilizer is converted to water-insoluble forms within a few hours (*Taylor 1967*). This immobilization is due to the strong adsorption of P by finely divided soil mineral particles (fig. 1). The P-fixing power of forest soils in the Northeast is usually so enormous that the main concern is not with leaching losses but with freeing P for plant use.

K exhibits a strong tendency to be reincorporated into solid weathering products, especially certain clay minerals.

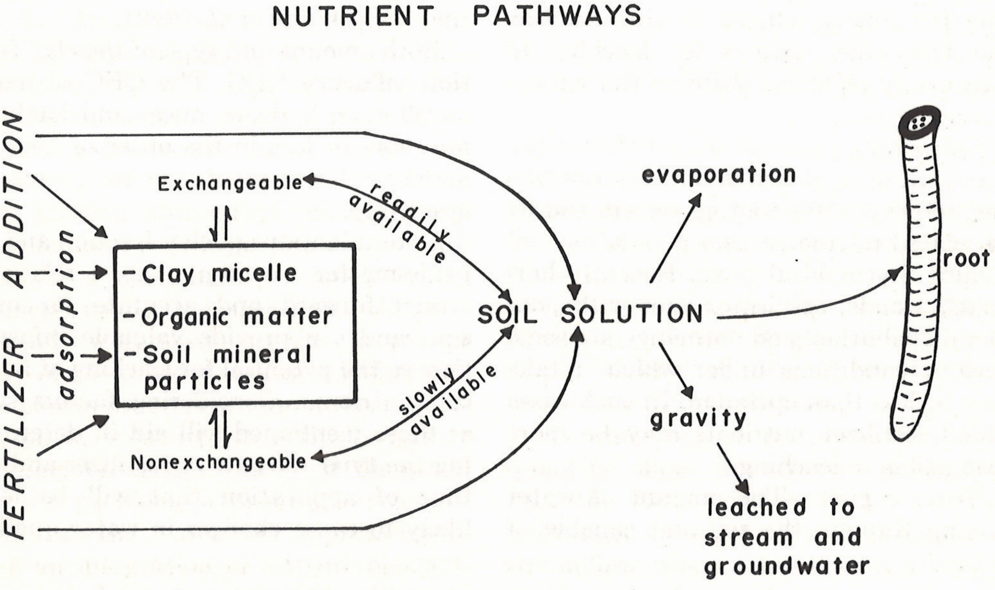


Figure 1.—Some of the forces acting on fertilizer nutrients.

Thus K is relatively immobile in most soils but sometimes may be leached from acid sandy soils (*Allen 1968*). A review of K movement in soils by Munson and Nelson (*1963*) indicated that fertilizer formulated as potassium calcium pyrophosphate (K_2 Ca P_2 O_7) will minimize K leaching from acid sands. The commonly used potassium chloride (KCl) appears to be the formulation most susceptible to leaching losses.

N fertilizers, because of the large volume applied and ease of solubility, represent the greatest hazard to water quality. Depending on formulation, N fertilizers have potential for increasing stream concentrations of urea, ammonium- and nitrate-N, and total organic N. Leaching of nitrate, which as an anion is not tightly held by the soil exchange complex, constitutes one of the main pathways for loss of N from soils (*Allison 1965*). Ammonium-N, which is a cation, presents less of a leaching problem.

Certain N formulations may create secondary leaching problems by increasing soil acidity. For example, compounds supplying the ammonium form of N may undergo the following reaction:

$$2NH_4^+ + 3\ 0_2 \longrightarrow \quad 2\ NO_2^- + 4H^+ + 2\ HOH$$

The H^+ ions produced in this reaction can free other cations for leaching to streams by replacing them on the soil exchange sites.

Efficiency of root action.—Efficient nutrient uptake depends on distribution and activity of the rooting system and its associated microorganism population, including mycorrhizal fungi. Recently harvested stands, species or sites with poor root distribution, and dormancy are some obvious conditions under which uptake may be less than optimum. In such cases added fertilizer nutrients may be more susceptible to leaching.

Water regime.—The amount of water moving through the soil and capable of transporting nutrients will depend in part upon rainfall intensity, duration, and frequency. The possibilities for leaching losses will generally increase as the excess of precipitation over evapotranspiration becomes greater.

Soil textural class and structure, position on slope, and vegetative cover as they affect infiltration and percolation, will also have major influences on nutrient leaching. If these characteristics combine to prolong residence time of soil water, there is greater opportunity for nutrients to solubilize and be transported to streams.

Cation exchange capacity (CEC).—The ability of a soil to retain applied nutrients will depend to a large degree on its CEC. Organic matter and the clay fraction are primarily responsible for CEC and act to retard nutrient movement and leaching (fig. 1). The organic-matter content of mineral soils may range from 0.1 to 5 percent or more and can account for 30 to 60 percent of the exchange capacity (*Jones 1947*). Organic materials composing the forest floor also provide some exchange capacity. In northern hardwood stands and in strongly podzolized soils, the forest floor may constitute the major proportion of the CEC (*Wilde et al. 1949*).

Both amount and type of the clay fraction influence CEC. The CEC of montmorillonite, hydrous mica, and kaolinite are more or less in the order of 100, 35, and 10 millequivalents per 100 grams, respectively.

Determinations of clay fraction and organic-matter content are relatively straightforward and accurate for most soils and can provide valuable information on the potential for leaching of fertilizer nutrients. Considering factors such as those mentioned will aid in determining the type and rate of fertilizer and the time of application that will be least likely to cause changes in water quality.

EVALUATING THE IMPACT ON WATER QUALITY

Either small watersheds (*Bormann and Likens 1967*) or lysimeters are the best for evaluating potential changes in water quality resulting from forest fertilization. Comparing the two approaches, the advantages of lysimeter studies include somewhat less expense, quicker results, and a better opportunity to replicate experiments in terms of location and types and amounts of fertilizers applied. But lysimeters also have serious drawbacks. They can be used to evaluate changes in soil leachate, but these results then have to be extrapolated in terms of how surface streams will be affected.

Also, a major criticism is that lysimeters of all types (both filled-in and monolith types) containing undisturbed soil are to varying degrees artificial systems (*Allison 1965*). They have abnormal and limited water movement in comparison to actual soil profiles. Tension-plate lysimeters were designed to overcome this problem (*Cole 1958*), but they have also led to difficulty in accurately quantifying nutrients leached within the soil profile (*Cochran et al. 1970*).

Nutter and Ike (*1970*) have pointed out that lysimeters can only sample discrete sections of the hydrologic continuum from stream to ridgetop. Streamflow and the nutrients it transports are generated from this continuum in a non-linear composite fashion, depending on distance from stream, antecedent moisture, and other factors; so it is particularly difficult to make a meaningful extrapolation of lysimeter results to larger areas.

Small watershed studies overcome many of the disadvantages of lysimeters. The effects of fertilization on water quality can be measured directly by stream sampling (*Nelson 1970*). And there will be fewer problems with interpretation of results as the watershed approach provides an integration of all variables acting to influence nutrient leaching to streams. If the watershed is gaged, then streamflow measurements can be used with chemical-concentration measurements to determine nutrient losses from the basin in terms of mass per unit area or time.

The main disadvantages to using gaged watersheds are the expense in both time and money and the fact that replication of an experiment can seldom be afforded. For these reasons, careful planning and implementation are essential when using gaged watersheds to study effects of any kind of forest treatment on streamflow.

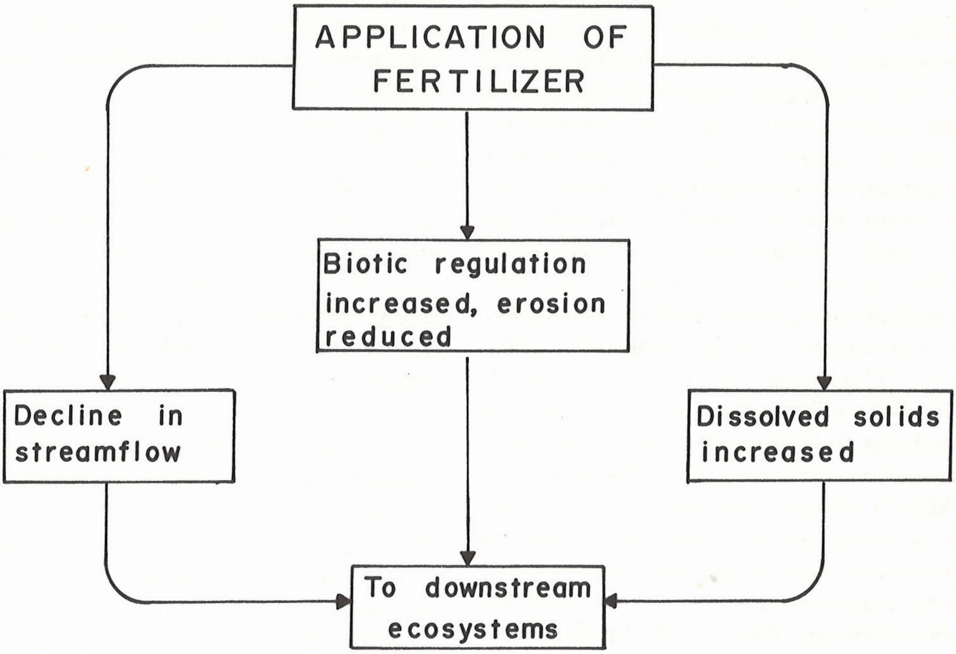
At the Hubbard Brook Experimental Forest we have a hardwood forested watershed that has been carefully calibrated for both water quantity and quality, and it will soon receive a fertilizer application. Since we do not have extra watersheds for any additional fertilizer experiments, we are finding that seemingly simple decisions such as form and rate of fertilizer to apply are really agonizing. It now appears that we will want to supplement our gaged-watershed study by testing additional forms and rates of fertilizers either on ungaged watersheds or with lysimeters.

CONCLUSION

By drawing inferences from various sources we can speculate about the potential impact of fertilization on streamflow. Three major areas of concern include hydrologic and chemical aspects and erosion (fig. 2). The overall impact might be a decline in streamflow, an increase in dissolved solids in stream water, and a reduction in erosion.

We can suggest ways to study and quantify these impacts on streamflow. But the fact remains that our basic knowledge of what actually happens to streamflow when a forest is fertilized is pretty meager.

Figure 2.—Potential impact of forest fertilization on streamflow. Little quantitative information is available for the various changes listed within the blocks.



LITERATURE CITED

Allen, S. E.
1968. Characteristics and comparative performance of some conventional and special purpose fertilizer sources of K, Mg, and S. *In* Forest fertilization . . . theory and practice: 123-131. TVA, Muscle Shoals, Ala.

Allison, Franklin E.
1965. Evaluation of incoming and outgoing processes that affect soil nitrogen. *In* Soil nitrogen. Amer. Soc. Agron. Monogr. 10: 578-606. Madison, Wis.

Bormann, F. H., and G. E. Likens.
1967. Nutrient cycling. Science 155: 424-429.

Anonymous.
1969. Nitrates: boom and bane? Chem. Eng. 76(8): 52-54.

Cochran, P. H., Giles M. Marion, and Albert L. Leaf.
1970. Variations in tension lysimeter leachate volumes. Soil Sci. Soc. Amer. Proc. 34: 309-311.

Cole, D. W.
1958. Alundum tension lysimeter. Soil Sci. 85: 293-296.

Cole, D. W., and S. P. Gessel.
1965. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. Forest-Soil Relationships in North America: 95-104. Oreg. State Univ. Press, Corvallis.

Cooper, Charles F.
1969. Nutrient output from managed forests. *In* Eutrophication: causes, consequences and correctives: 446-463. Nat. Acad. Sci., Washington, D.C.

Cope, F., and E. S. Trichett.
1965. Measuring soil moisture. Soils and Fertilizers 28: 201-208.

Federer, C. Anthony.
1970. Measuring forest evapotranspiration—theory and problems. USDA Forest Serv. Res. Pap. NE-165. 25 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Hibbert, A. R.
1967. Forest treatment effects on water yield. Int. Symp. Forest Hydrol: 527-543. Pergamon Press, New York.

Hibbert, A. R.
1969. Water yield changes after converting a forested catchment to .grass. Water Resources Res. 5: 634-640.

Heilman, P. E., and S. P. Gessel.
1963. Nitrogen requirements and the biological cycling of nitrogen in Douglas-fir stands in relationship to the effects of nitrogen fertilization. Plant and Soil 18: 386-402.

Jones, U. S.
1947. Availability of humate potassium. Soil Sci. Soc. Amer. Proc. 12: 373-378.

Kawana, A.
1966. Method of forest fertilization. Potassium Rev. 22: Parts 1 and 2.

Kohl, Daniel H., Georgia B. Shearer, and Barry Commoner.
1971. FERTILIZER NITROGEN: CONTRIBUTION TO NITRATE IN SURFACE WATER IN A CORN BELT WATERSHED. Science 174: 1331-1334.

Leaf, Albert L.
1968. K, Mg AND S DEFICIENCIES IN FOREST TREES. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 88-131. TVA, Muscle Shoals, Ala.

Leaf, Albert L., and Raymond E. Leonard.
1969. FOREST FERTILIZATION, THE ENVIRONMENT, AND TOTAL DRY-MATTER PRODUCTION. S. Lumberman 219 (2720): 24-26.

Likens, Gene E., F. Herbert Bormann, Noye M. Johnson, D. W. Fisher, and Robert S. Pierce.
1970. EFFECTS OF FOREST CUTTING AND HERBICIDE TREATMENT ON NUTRIENT BUDGETS IN THE HUBBARD BROOK WATERSHED ECOSYSTEM. Ecol. Monogr. 40: 23-47.

Malueg, K. W., C. F. Powers, and D. F. Krawczyk.
1972. EFFECTS OF AERIAL FOREST FERTILIZATION WITH UREA PELLETS ON NITROGEN LEVELS IN A MOUNTAIN STREAM. NW. Sci. 46:52-58.

McCall, Merley.
1970. THE EFFECTS OF AERIAL FOREST FERTILIZATION ON WATER QUALITY FOR TWO STREAMS IN THE CAPITOL FOREST. 20 p. Wash. State Dep. Ecol. Olympia.

Moore, D. G.
1970. FOREST FERTILIZATION AND WATER QUALITY IN THE PACIFIC NORTHWEST. Agron. Abstr. 1970: 161.

Munson, Robert D., and Werner L. Nelson.
1963. MOVEMENT OF APPLIED POTASSIUM IN SOILS. J. Agr. Food Chem. 11: 193-201.

Nelson, Daniel J.
1970. MEASUREMENT AND SAMPLING OF OUTPUTS FROM WATERSHEDS. *In* ANALYSES OF TEMPERATE FOREST ECOSYSTEMS: 257-267. Springer Verlag, New York.

Nutter, Wade L., and Albert F. Ike.
1970. EVALUATING EFFECTS OF FOREST FERTILIZATION ON WATER QUALITY. Agron. Abstr. 1970: 160.

Ovington, J. D.
1965. ORGANIC PRODUCTION, TURNOVER AND MINERAL CYCLING IN WOODLANDS. Biol. Rev. 40: 295-336.

Pennypacker, S. P., W. E. Sopper, and L. T., Kardos.
1967. RENOVATION OF WASTEWATER EFFLUENT BY IRRIGATION OF FOREST LAND. J. Water Pollut. Contr. Fed. 39: 285-296.

Roberge, M. R., G. F. Weetman, and R. Knowles.
1970. AN ECOLOGICAL AND MICROBIOLOGICAL STUDY OF UREA FERTILIZATION AND THINNING IN A BLACK SPRUCE STAND. *In* TREE GROWTH AND FOREST SOILS: 73-96. Oreg. State Univ. Press., Corvallis.

Safford, L. O.
1972. EFFECT OF FERTILIZATION ON THE BIOMASS OF FINE ROOTS IN A BEECH-BIRCH-MAPLE STAND. (Abstr.): N. Amer. Forest Biol. Workshop 2. Corvallis, Ore.

Stone, Earl L.
1968. MICROELEMENT NUTRITION OF FOREST TREES: A REVIEW. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 132-175. TVA, Muscle Shoals, Ala.

Taylor, Alan W.
1967. PHOSPHOROUS AND WATER POLLUTION. J. Soil and Water Conserv. 22: 228-231.

Viets, Frank G., Jr.
1971. FERTILIZERS. J. Soil and Water Conserv. 26: 51-53.

Whittaker, R. H.
1966. FOREST DIMENSIONS AND PRODUCTION IN THE GREAT SMOKEY MOUNTAINS. Ecology 47: 103-121.

Wilde, S. A., F. G. Wilson, and D. P. White.
1949. SOILS OF WISCONSIN IN RELATION TO SILVICULTURE. Wis. Conserv. Dep. Pub. 525-49. 171 p.

Wilm, H. G.
1944. STATISTICAL CONTROL OF HYDROLOGIC DATA FROM EXPERIMENTAL WATERSHEDS. Amer. Geophys. Union Trans. Part II: 618-622.

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QUANTITY AND QUALITY OF STREAMFLOW AFTER UREA FETILIZATION ON A FORESTED WATERSHED: FIRST-YEAR RESULTS

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ABSTRACT. Streamflow was analyzed to determine the effects on the quantity and quality of water flowing from a 74-acre calibrated watershed that had been fertilized with 500 pounds of urea per acre. During the first year after fertilization, no change was detected in the quantity of streamflow. Water quality, as determined from analysis of 829 samples, remained high. Comparison of nitrogen discharge data for the year before and after fertilization revealed approximately 18 percent greater nitrogen discharge after fertilization. Loss of nitrogen was accompanied by increased loss of certain metallic cations.

WE ARE FACED with a dilemma. A substantial amount of our productive forest land is lost annually to highways, airports, impoundments, recreational areas, wilderness reserves, shopping centers, home sites, and agriculture; yet our increasing population demands more wood. Correcting one or more of the conditions that limit tree growth may help resolve our dilemma.

It is known from agronomic research that insufficient soil N will limit plant growth. Therefore it has been proposed that forest fertilization, with N, will increase tree growth. Though the application of N fertilizer may increase growth, its widespread use cannot be recommended until its effects on the environment have been determined.

A pilot study was designed and is being conducted on the Fernow Experimental Forest near Parsons, West Virginia, to evaluate effects of fertilizing a forested watershed with urea. The specific objective of this pilot study is to determine how applications of a relatively large amount of soluble N (230 pounds per acre) as urea to a young hardwood stand would affect the quantity and quality of streamflow from the watershed. This paper presents the first-year results of this study.

EXPERIMENTAL AREAS AND PROCEDURES

The study area is a 74-acre east-facing watershed from which all marketable trees were cut in 1957-58. The average slope is 40 percent, with a range of 14 to 65 percent. The watershed now supports a dense stand of vigorously growing sprouts and seedlings as well as some advance growth and cull residuals from the clearcutting. Dominant species are oaks (*Quercus* spp.), yellow-poplar (*Liriodendron tulipifera* L.), basswood (*Tilia americana* L.), maples (*Acer* spp.), American beech (*Fagus grandifolia* Ehrh.), and black cherry (*Prunus serotina* Ehrh.). The stand averages about 30 feet in height and has a basal area of 43 square feet per acre (in trees greater than 5 inches d.b.h.). Understory vegetation is typical of Appalachian hardwood forests.

The soil, mapped as Calvin channery silt loam, is derived from sandstone and acid red shale of the Hampshire (formerly Catskill) geologic formation. It is a member of the loamy-skeletal mixed mesic family of Typic Dystrocrepts. Soil depth ranges from 2 to 5 feet, with an average depth of 32 inches.

The nearby control watershed has remained undisturbed since a clearcutting about 1905-10. It has and will continue to be closely monitored for quantity and quality of streamflow. Soil type and stream discharge (as percentage of precipitation) are practically the same as on the experimental watershed.

Fertilization was begun at 4:30 p.m. 14 May 1971 and ended about noon the following day. Five hundred pounds per acre of urea (230 pounds of N per acre) were applied by helicopter. (Urea was provided by the Agrico Chemical Company of Memphis, Tennessee.) The helicopter flew about 100 feet above the tree tops and distributed prilled urea in swaths about 50 to 60 feet wide. No attempt was made to avoid the stream channel, because the perennial channel area was small (estimated to occupy only 0.03 percent of the watershed) and the intermittent portions of the channel were not flowing at the time of application. Uniformity of distribution was checked with 312 open containers distributed over 52 randomly located sampling plots.

A 4-acre area, located near the watershed's western ridge, was left unfertilized to provide within-watershed comparison plots.

Soil and bud samples were obtained from fertilized and unfertilized plots before fertilization and 1 year later in an attempt to provide supplemental information about the effect of urea fertilization on the environment.

Water-yield data and some water-quality data (specific conductance, total alkalinity, pH, and turbidity) extend back to 1951. Concentrations of Ca, Mg, Na, K, Zn, Cu, Mn, Fe, sulfate, total phosphate, ammonium-N, and nitrate-N in the stream have been recorded since July 1969.

Specific conductance, pH, and turbidity were determined with a specific conductance Solu bridge, a Hellige comparator, and a Hach model 1860 laboratory turbidimeter, respectively. Alkalinity was determined by the methyl orange titration method. Ca, Mg, Na, and K determinations were made on 20-ml. samples containing 2 ml. of 1-percent Lanthanum in 5-percent HCl solution, using a Perkin-Elmer model 290B atomic absorption spectrophotometer connected to a Texas recorder. Zn, Cu, and Mn determinations were made on concentrated samples (concentrated by boiling down to one-tenth original volume), using the same instruments and procedures as above. Sulfates, Fe, total phosphate, ammonium-N, and nitrate-N determinations were made according to Hach's: SulfaVer III, FerroVer, PhosVer III, Nesslers, and NitraVer IV methods respectively.

(The use of trade, firm, or corporation names is for information only and should not be considered an endorsement by the Forest Service or the U.S. Department of Agriculture.)

During application and for 66 hours thereafter, 300-ml. water samples were obtained from the fertilized watershed at 15-minute intervals. However, when the helicopter spread urea directly over the lower portion of the stream channel, and during stream rise after spring showers, samples were taken every 2 minutes. In addition, every 6 hours throughout this period, quart-size water samples were obtained from both the fertilized and control watersheds. The 300-ml. samples were collected in glass bottles having pressure-type stoppers. Once filled and sealed, these bottles contained no air bubbles. The quart-size samples were collected in polypropylene bottles.

Samples were taken to the laboratory as soon as possible and placed in a refrigerator maintained at 34°F. Most ammonium-N and nitrate-N analyses were completed within 24 hours after collection. All analyses were completed within 7 days of sampling. In general, only ammonium-N and nitrate-N determinations were made on the 300-ml. samples, and all 16 analyses were made on the larger samples.

During the 30 days after urea application, 463 water samples were collected and analyzed from the fertilized watershed. A total of 643 samples were analyzed during the 1971 growing season and 186 samples during the dormant season. Sampling frequency of at least one per day, and as frequently as one every minute during rapid stream rise, lasted through the end of June. From June through mid-September streamflow was frequently too low for sampling.

RESULTS

Actual rate of urea distribution varied between 400 and 600 pounds per acre, with no evidence of "skips" (all open containers received some urea). Highest rates of application occurred on the upper slopes; application in the channel vicinity tended to be near or below the planned rate of 500 pounds per acre.

Flow-prediction analyses of stream discharge revealed no detectable change in water yield during the first year after urea fertilization.

Rainfall during April and June 1971 was substantially below normal (table 1). During the first 165 days after fertilization, what rain did fall generally fell as light showers, and on only 23 days did rainfall exceed ¼ inch. As a result, mean daily stream discharge from the fertilized watershed was very low during June, July, August, and early September (fig. 1). Mean daily stream discharge from the control watershed was similar.

The soil and bud analysis (tables 2 and 3) provided cursory information relating to the initial effect of urea fertilization on the nutrient balance of soil and plants. Additional data will be collected before an interpretation of the data is attempted.

Ammonium-N and nitrate-N concentrations in the stream, for the 72 hour period commencing with the start of urea application, are shown in figure 2. The increases in ammonium-N concentration coincident with application can be seen. Within the first 24 hours, the ammonium-N concentration in the stream increased from a prefertilization level of about 0.15 p.p.m. up to about 0.8 p.p.m. This level was maintained for the next 19 hours, followed by a gradual decline to near prefertilization level by the end of the first week. Except for storm influences (to be discussed later) the ammonium-N concentration has since remained rather consistent at or below 0.2 p.p.m.

Nitrate-N increased gradually from a

Table 1.—Precipitation and stream discharge for the fertilized watershed

	Prefertilization (1970-71)			Postfertilization (1971-72)			20-year average (1952-71)		
Month	Ppt.	Stream discharge		Ppt.	Stream discharge		Ppt.	Stream discharge	
	Inches	*Inches*	*% of ppt*	*Inches*	*Inches*	*% of ppt*	*Inches*	*Inches*	*% of ppt*
May	2.31	0.41	17.7	5.51	2.62	47.5	4.88	2.21	45.3
June	4.71	.18	3.8	2.85	.19	6.7	5.30	.96	18.1
July	7.37	.50	6.8	4.27	.05	1.2	5.44	.77	14.2
August	4.66	.20	4.3	5.35	.19	3.6	4.99	.89	17.8
September	4.63	.26	5.6	7.42	1.54	20.8	3.63	.82	22.6
October	2.44	.09	3.7	2.55	.30	11.8	3.50	.62	17.7
Growing-season total	26.12	1.65	6.3	27.95	4.88	17.5	27.77	6.28	22.6
November	3.58	1.13	31.6	4.84	1.56	32.2	3.72	0.96	25.8
December	8.33	4.50	54.0	2.75	2.48	90.2	5.11	2.45	47.9
January	5.90	4.33	73.4	6.85	4.30	62.8	5.01	3.07	61.3
February	4.48	4.10	91.5	7.92	4.91	62.0	4.54	2.89	63.7
March	4.76	3.05	64.1	4.58	4.06	88.6	5.85	3.97	67.9
April	1.78	.91	51.1	6.89	4.67	67.8	5.19	2.95	56.8
Dormant-season total	28.83	18.01	62.5	33.83	21.98	65.0	29.44	16.28	55.3
Water-year total	54.95	19.66	35.8	61.78	26.86	43.5	57.21	22.56	39.4

Figure 1.—Mean daily stream discharge (cubic feet per second per square mile) from the fertilized watershed for the 1971 growing season and 1971-72 dormant season. Arrow indicates application of urea fertilizer.

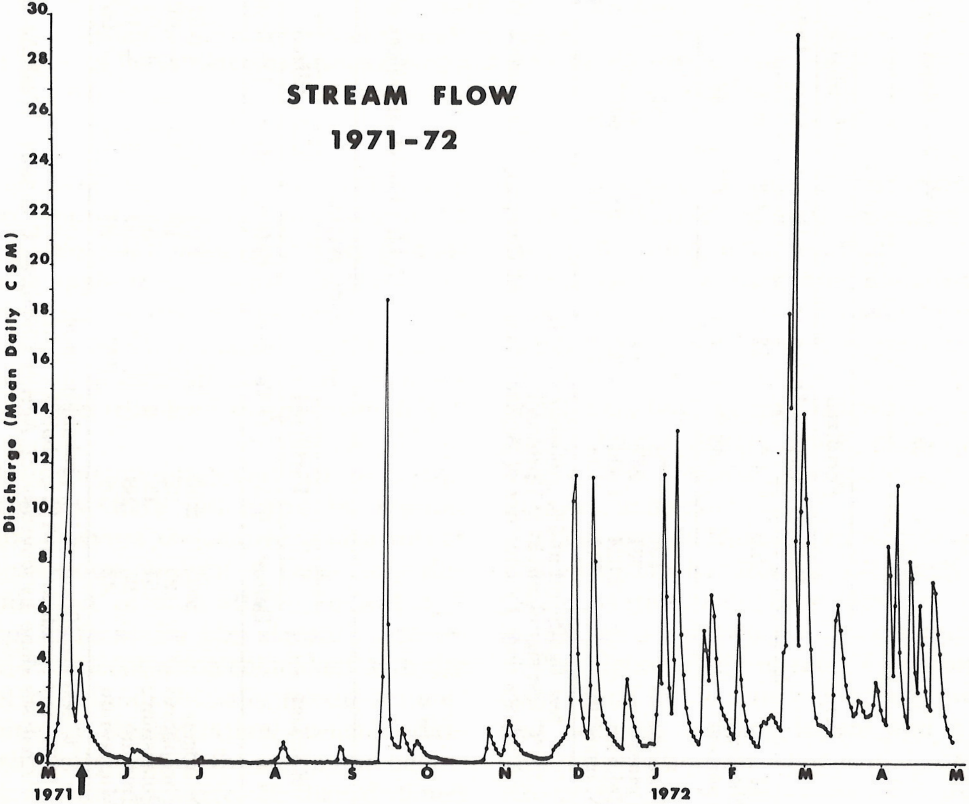


Table 2.—Mean values of soil analyses[1]

Item	0 - 2-inch depth						2 - 10-inch depth					
	Fertilized			Unfertilized			Fertilized			Unfertilized		
	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
pH	5.0	4.8	−0.2**	4.5	4.8	+0.3**	4.7	4.7	0	4.7	4.6	−0.1
Nitrogen (percent)	.61	.48	− .13**	.57	.44	− .13	.22	.18	− .04**	.25	.15	− .10*
						Pounds per acre						
Phosphorus	101	70	−31**	99	51	−48*	37	22	−15**	24	15	−9*
Potassium	331	247	−84**	200	218	+18*	151	158	+7	118	150	+32*
Calcium	2,324	1,500	−824**	883	608	−275*	837	665	−172**	333	300	−33
Magnesium	311	195	−116**	212	153	−59	101	84	−17**	63	42	−21

* "t" test significant at 5% probability level.

** "t" test significant at 1% probability level.

[1] Analyses done by courtesy of Agrico Chemical Company, Agronomic Service Laboratory, Washington Courthouse, Ohio.

Table 3.—Mean values of bud nutrient analyses[1]

Element	Yellow-poplar						Sugar maple			American beech		
	Fertilized			Unfertilized			Fertilized			Fertilized		
	Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
						Percent						
Nitrogen	2.33	2.55	+0.22**	2.20	2.27	+0.07	1.80	2.03	+0.23**	1.68	1.82	+0.14*
Phosphorus	.20	.22	+ .02**	.19	.18	− .01	.18	.16	− .02**	.19	.17	− .02*
Potassium	.51	.66	+ .15	.51	.57	+ .06**	.32	.45	+ .13**	.24	.32	+ .08*
Calcium	.95	.88	− .07**	1.00	.88	− .12	2.45	1.92	− .53**	1.01	.86	− .15
Magnesium	.43	.38	− .05**	.40	.35	− .05*	.27	.25	− .02**	.27	.23	− .04*

*"t" test significant at 5% probability level.

**"t" test significant at 1% probability level.

[1] Analyses done by courtesy of Agrico Chemical Company, Washington Courthouse, Ohio.

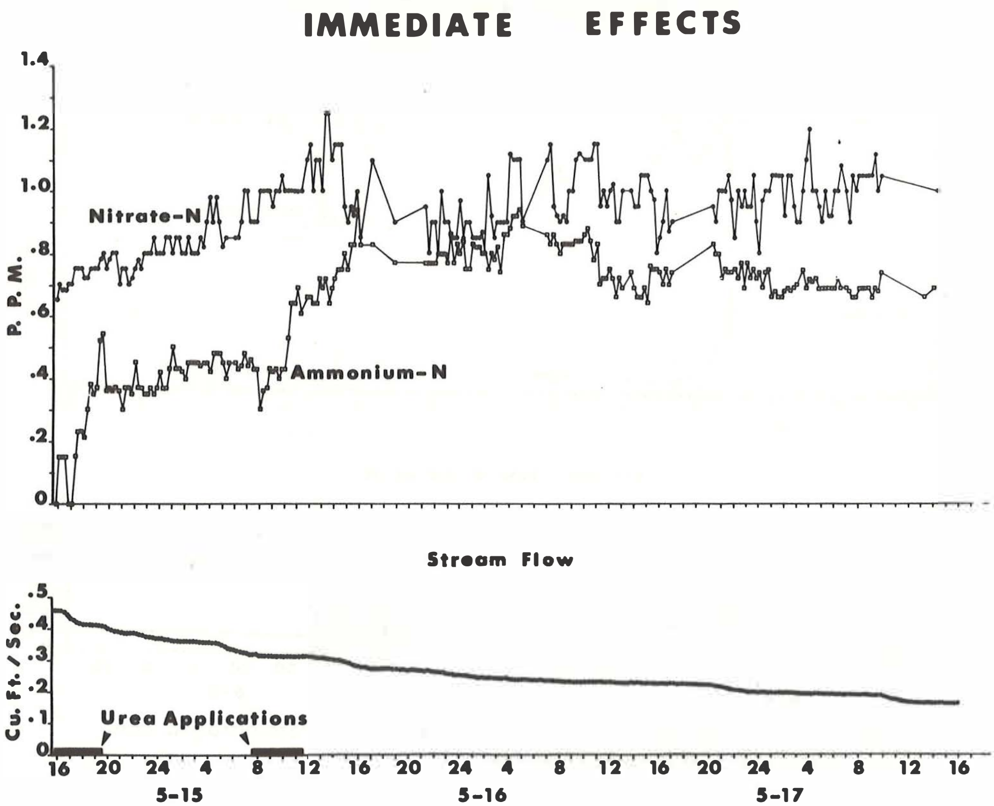


Figure 2.—Ammonium- and nitrate-nitrogen concentrations in the stream of the fertilized watershed during and immediately after urea application.

prefertilization level of about 0.7 p.p.m. up to approximately 1 p.p.m. within 24 hours. No relationship between periods of urea application and nitrate-N concentrations in the stream was observed. The nitrate-N level remained at approximately 1 p.p.m. for an additional 48 hours, then increased to approximately 2 p.p.m.

Both ammonium-N and nitrate-N concentrations were influenced by storms. Figure 3 shows the influence of a rather intense storm on June 4. Data from this storm, and several others, indicated a sharp increase in the stream's ammonium-N concentration coincident with the onset of rainfall. Usually maximum ammonium-N concentration occurred during the early part of the storm and before peak stream discharge. It then declined to near and sometimes below prestorm level, even though rainfall continued and stream discharge remained high.

Nitrate-N concentrations likewise showed a sharp increase associated with rainfall. However, maximum nitrate-N concentrations usually occurred later, proportionately greater increases took place, higher levels were maintained longer, and decline was more gradual than for ammonium-N.

These same conditions appear to have existed before fertilization, although our prefertilization sampling intensity was insufficient for drawing a firm conclusion.

The highest daily nitrate-N concentrations found in the stream for the growing and dormant seasons before and after urea fertilization are shown in figure 4. Except for storm influences on 4 June,

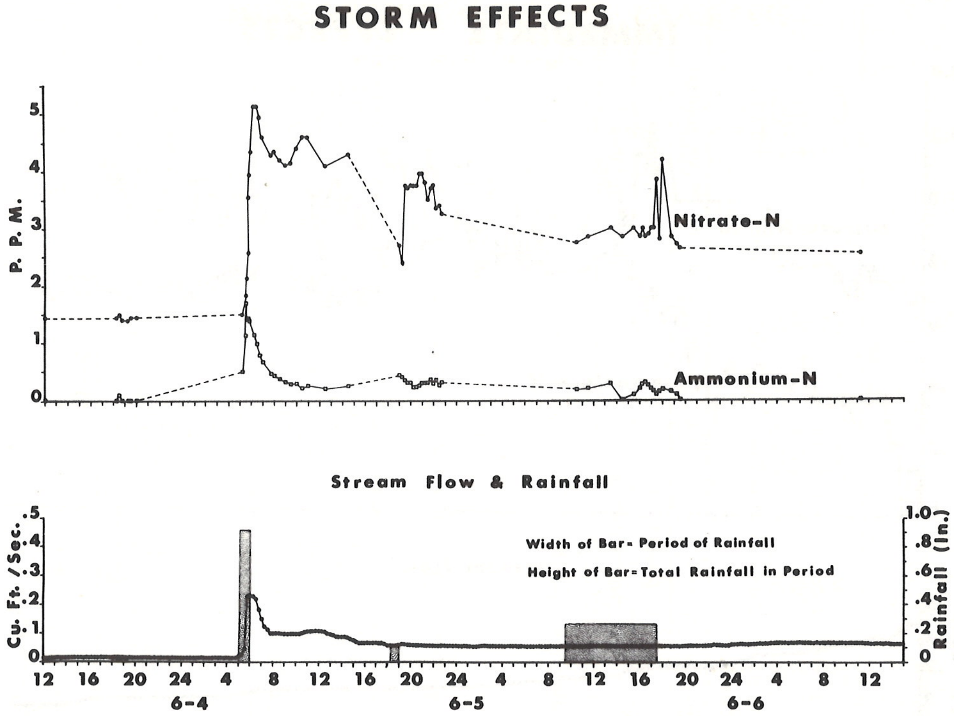


Figure 3.—Relationship between ammonium- and nitrate-nitrogen concentrations and rainfall and streamflow.

the nitrate-N level gradually decreased throughout June to approximately 1 p.p.m. or almost to the prefertilization level. At this point, dry weather and summer storms influenced the conditions. Rainfall for June through early September was below normal, and although some flow continued in the gravel of the stream channel, it was frequently too low for sample collection. As a result, there are gaps in our data during an important part of the growing season, and interpretation of the data after flow-producing storms is complicated.

The relationship between nitrate-N concentration and stream discharge is apparent when one compares figures 1 and 4. Between May 1971 and March 1972, high storm-produced stream discharges were accompanied by above-average nitrate-N concentrations. Average post-fertilization nitrate-N concentrations appear to be about 5.0 to 5.5 p.p.m. (about 7 times prefertilization levels). High nitrate-N concentrations were not associated with high storm-produced stream discharge during March and April 1972. The data suggest that nitrate-N outflow has been declining since the first of March despite substantial stream discharge.

The highest nitrate-N concentrations were generated during June through mid-September (fig. 4) by flow-producing storms that followed dry periods in which little or no stream discharge occurred. Maximum nitrate-N concentration and discharge occurred in mid-September. A prolonged dry period occurred before 12 September; surface streamflow was nonexistent—then came 4.6 inches of rain within 48 hours. The concentrated soil solution, high in nitrate, was flushed from the soil; and nitrate-N concentration for this storm was 14.1 p.p.m.

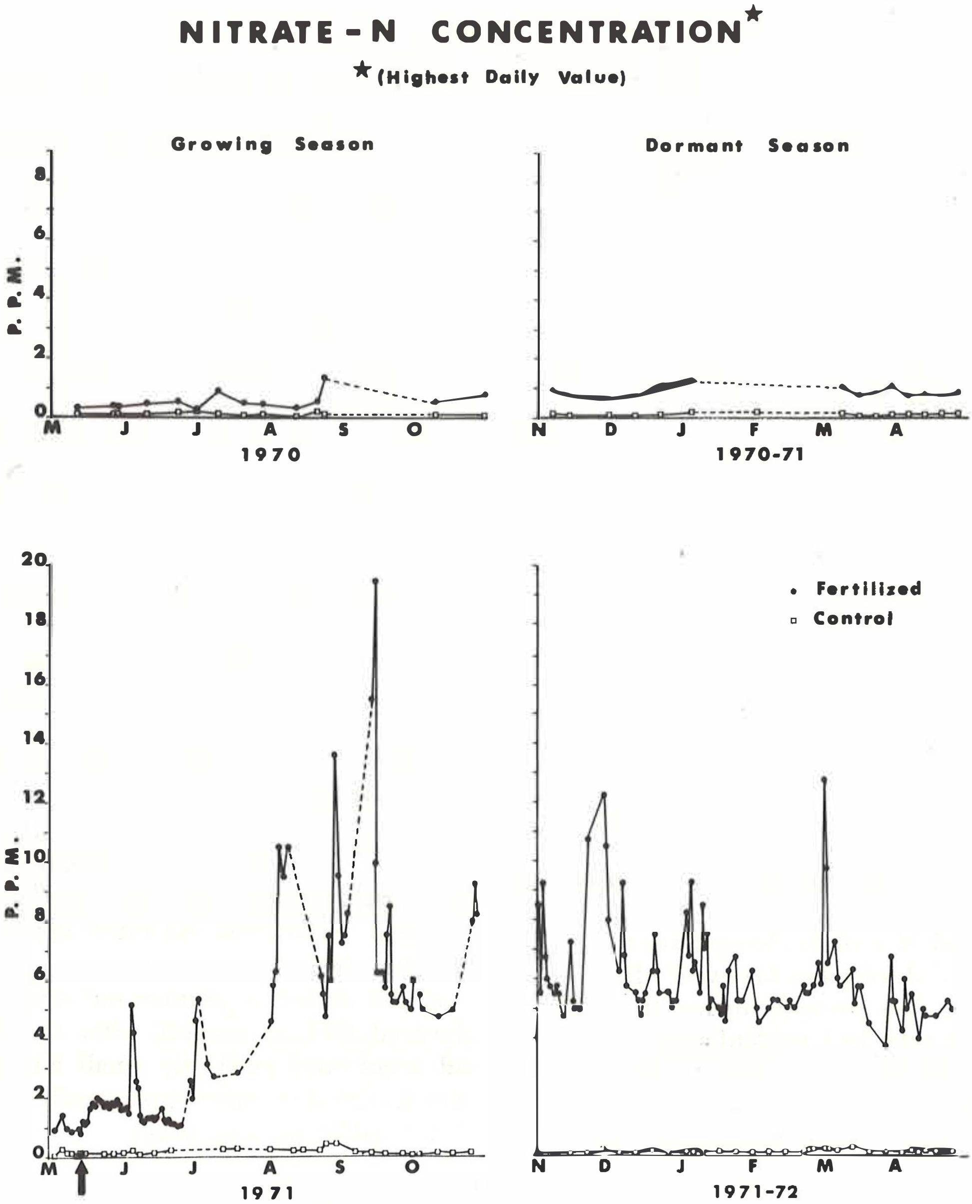


Figure 4.—Highest daily nitrate-nitrogen concentrations in the stream from the fertilized and control watersheds before and after fertilization. Arrow indicates time of application of urea fertilizer.

The first part of the storm occurred between 6:00 p.m. 12 September and 6:00 a.m. 13 September, and 2.3 inches of rain fell. Peak stream discharge of 0.73 cubic feet per second and maximum nitrate-N concentration of 17.1 p.p.m. occurred about midnight 12 September. The nitrate-N concentration dropped to 12.2 p.p.m. by noon 13 September. Throughout the day, sporadic light showers maintained stream discharge, while the nitrate-N concentration averaged about 13 p.p.m. The second part of the storm occurred between midnight 13

September and 4:00 p.m. 14 September, with 2.1 inches of rainfall. Nitrate-N concentration increased gradually to 14.5 p.p.m. at 6:30 a.m., then jumped to 19.8 p.p.m. at 6:35 a.m.; decrease was rapid, and by the end of the storm the concentration had returned to 13.0 p.p.m. Peak stream discharge of 5.11 cubic feet per second also occurred at 6:35 a.m.

This combination of high nitrate-N concentration and high stream discharge accounted for 73 percent of the nitrate-N discharged from the watershed during the 1971 growing season (4.8 pounds per acre of nitrate-N were discharged during the week of 12-19 September 1971). After this flushing, the nitrate-N concentration dropped to about 5.5 p.p.m.—signaling the beginning of a definite trend where the nitrate-N concentrations stabilized around 5.5 p.p.m. while stream discharge increased.

A tenfold increase in nitrate-N discharge occurred during the first growing and dormant season after fertilization (table 4). If one considers the increased loss of N as coming entirely from the urea fertilizer, then 17.8 percent of the applied N was discharged from the watershed during the first year after fertilization (2.4 percent during the growing season and 15.4 percent during the dormant season). This does not include possible losses as urea, through volatilization, or in various organic forms.

The dissolved substances in the streams from the fertilized and control watersheds are quantified in table 5. Averages presented are simple averages (concentrations divided by the number of samples). The average concentration of dissolved solids in the fertilized watershed's stream increased 110 percent during the year after fertilization. The increase in the concentration of dissolved solids was accompanied by increases in the concentrations of nitrate-N, Ca, Mg, Na, K, Cu, and Zn; it was also accompanied by decreases in the concentrations of total phosphate, Fe, sulfate, Mn, and ammonium-N.

It should be pointed out and emphasized that the changes in composition noted in the stream from the fertilized watershed are not all due to the urea application. Increases in concentrations of Ca, Mg, K, Cu, Zn, and nitrate-N, and decreases in Fe, total phosphate, and Mn concentrations were also noted in the stream from the control watershed. Concentrations of ammonium-N, sulfate, and Na in the streams from the control and fertilized watersheds exhibited opposite changes (table 5).

It also should be pointed out and emphasized that, in general, what changes did occur were relatively small and inconsequential in terms of permissible levels for public drinking water.

Table 4.—Pounds per acre of ammonium- and nitrate-nitrogen discharged from the experimental watershed before and after urea fertilization

Year	Ammonium-N	Nitrate-N
1970 growing season	0.6	0.8
1970-71 dormant season	.7	3.9
Total, year before fertilization	1.3	4.7
1971 growing season	0.2	6.6
1971-72 dormant season	.5	38.4
Total, year after fertilization	0.7	45.0

Table 5.—Average concentrations of dissolved substances in streams before and after urea fertilization
[In p.p.m.]

Dissolved substance	Growing season				Dormant season				Full year[2]			
	1970		1971		1970-71		1971-72		1970-71		1971-72	
	Fertilized	Control	Fertilized	Control	Fertilized	Control	Fertilized	Control	Fertilized	Control	Fertilized	Control
Dissolved[1] solids	31	13	60	13	27	12	60	12	29	12	60	12
Nitrate-N	0.55	0.11	3.91	0.26	0.95	0.10	5.79	0.13	0.76	0.10	4.86	0.21
Ammonium-N	.45	.36	.16	.23	.15	.13	.10	.14	.23	.19	.13	.20
Phosphate (total)	.044	.038	.019	.008	.029	.020	.008	.006	.036	.029	.014	.007
Potassium	1.00	.73	1.42	.63	.74	.52	1.33	.63	.86	.62	1.39	.63
Calcium	3.24	1.07	4.94	1.22	2.00	.71	8.12	1.17	2.58	.88	6.36	1.20
Magnesium	1.32	.52	1.46	.46	.88	.35	2.10	.41	1.09	.43	1.69	.44
Sodium	.97	.66	1.17	.46	.86	.48	1.18	.43	.91	.56	1.17	.45
Sulfate	6.8	3.4	5.3	3.3	5.8	3.0	4.4	3.4	6.4	3.2	4.8	3.4
Iron	.14	.16	.07	.06	.23	.07	.08	.08	.18	.11	.07	.07
Copper	.015	.012	.030	.026	.016	.012	.029	.024	.015	.012	.029	.025
Manganese	.015	.015	.009	.009	.017	.014	.003	.003	.016	.014	.006	.006
Zinc	.029	.025	.069	.091	.030	.035	.052	.091	.029	.029	.060	.091

[1] Estimated from specific-conductance measurements (dissolved solids = 0.70 X specific conductance).

[2] Average of all values obtained between 1 May 1971 and 30 April 1972.

DISCUSSION

Urea application was completed within 20 hours with relatively uniform distribution over the watershed. Since no attempt was made to avoid the small perennial stream, some urea fell directly into the stream. Estimates, based on the area of the stream and average application rate, indicate that 11 pounds of urea (equal to 5 pounds of nitrogen) probably fell into the stream and presumably left the watershed as dissolved urea, ammonia, or nitrate.

The amount of N lost through ammonia volatilization is open to question. A light intermittent rain began within 10 hours after application. This rain (only 0.30 inch in 24 hours) dissolved the urea on the foliage and litter; but due to the duration of the rain and its low intensity, it is doubtful if much of the dissolved urea moved into the mineral soil. Little, if any, was flushed into the stream, because stream discharge continued to decline throughout the period. Most of the dissolved urea probably was absorbed in the microbiologically active organic layers.

No rain fell for the next 12 days and, as the litter layer dried and ammonification took place, some N was lost from the watershed through volatilization; an ammonia odor could be detected in the atmosphere within 60 hours of application. This odor was noticeable for about 1 week. Additional N probably was lost to the atmosphere through the decomposition of understory vegetation killed by localized excess urea. This decomposing organic material also provided a source of mineralizable N.

The question of how much of the applied N left the watershed in the organic form cannot be answered. However, with low stream discharge and the fact that a limited number of determinations made before application showed almost no organic N in the stream, we feel that little of the applied N was discharged from the watershed in organic form.

The definite increase in ammonium-N content coincident with periods of urea application (fig. 2) raises several questions, because it is an established principle of soil science that ammonia is held rather tightly by the exchange complex. The fact that a definite increase occurred cannot be questioned because more than 200 samples were collected and analyzed during the period and a plot of values shows a definite and well-defined increase associated with periods of urea application (fig. 2).

It is proposed that the increased ammonium-N, which occurred during urea application, resulted from urease conversion of the urea that fell into the stream. Stream pH was 6.2 throughout the period. Although our method for determining ammonium-N does not measure urea dissolved in distilled water, an equal amount of urea added to a stream-water sample will, within a short period of time, produce a marked increase in the ammonium-N concentration.

The reason why it required about 1 week for the ammonium-N concentration to return to prefertilization level is not clear. It is doubtful that any urea that fell into the water could persist for a week. Therefore, it is proposed that some of the urea that fell on the moist stream-side soil moved through the acid soil (pH 4.7 to 5.0) and into the stream as dissolved urea. Once in the stream it was converted into ammonium.

Actually, the immediate effects of urea fertilization on water quality were small and short-lived (fig. 2 and 4). Except for storm influences, ammonium-N and nitrate-N concentrations had returned to prefertilization levels by 1 June and 1 July, respectively.

During this time, streamflow decreased to a trickle, a condition maintained to mid-September. As a result, the only samples that could be obtained were associated with flow-producing storms. This biased our data to the higher-than-normal ammonium-N and nitrate-N concentrations found to be associated with storms. Although this accentuated the ammonium-N and nitrate-N concentrations generally, the small volume of discharge precluded large amounts of N being discharged from the watershed.

The data indicate that during the first growing season after urea fertilization, the amount of N discharged from the watershed was small (table 4) and almost entirely storm-related. We hypothesize that the storm-related increase in ammonium-N came with the rain or was washed from streamside vegetation, while the increased nitrate-N came from the solution flushed out by the rain. Probably the increased nitrate-N in the soil solution did not come entirely from the fertilizer, because urea is known to stimulate dissolution of humus fractions and mineralization of organic N.

The onset of fall rains, accompanied by decreased transpiration and nutrient uptake associated with leaf fall and plant dormancy, brought increased streamflow. Ammonium-N concentration stabilized at slightly less than 0.2 p.p.m. while nitrate-N concentration averaged about 5.5 p.p.m. The combination of relatively high streamflow and relatively high nitrate concentration resulted in a substantial amount of N being discharged from the watershed during the fall and winter months.

The relatively high nitrate-N concentration during the fall and early winter months may have been due, in part, to release of N taken up by the vegetation during the growing season. Leaf-fall was early, and the temperature was generally mild through the first of the year.

These data suggest the possibility of an interaction between urea fertilization and the discharge of metallic cations. The specific conductance, which is a measure of the ionic activity in the stream, about doubled during the first growing season after urea fertilization and was almost 2¼ times greater during the dormant season (table 5). This reflected the greater concentration of certain metallic cations that accompanied the expected increase in nitrate-N outflow. Although the reason for the increase in cation concentration is not fully understood, it is reasonable to expect increased cation discharge to accompany increased nitrate discharge, since soil bases are known to move as nitrates in noncalcareous soils. Also, the added N probably increased the microbial activity and decomposition of the organic substrate, resulting in greater nutrient release and discharge.

The inconclusive results from our soil analyses point out the fact that the application of 500 pounds of urea per acre of forested watershed did not produce any major change that could be interpreted as being detrimental to the environment. It is probable that weather conditions affected the nutrient status of the soil more than the urea application did.

Pre- and postfertilizaiton soil samples were taken during April 1971 and 1972 respectively. Rainfall for February through April of the prefertilization year was 29 percent less than the 20-year average. For the same 3 months of the postfertilization year, rainfall was 24 percent greater than the 20-year average. The difference in rainfall amounted to 8.37 inches. It is proposed that this marked difference in precipitation had a strong influence on the biologic and chemical transformation of N and other nutrients in the soil.

It is likely that, had we analyzed the organic layers, we could have accounted for a much larger portion of the applied N. We know that the light rain immediately after application dissolved the urea on the foliage and litter and probably only moved it into the biologically active organic layers. There the applied N presumably became microbiologically tied up in the soils' organic substrate. If, as postulated, a substantial portion of the applied N has become tied up in the organic substrate, it will be released in time.

It is also reasonable to assume that a portion of the applied N has been leached through the soil profile to below sampling depth. Most of this N will eventually be accounted for, either as N taken up by the plants or as nitrate-N flushed into the streams by soil water displacement.

The increased N content of the buds formed after fertilization was expected, and it supports our hypothesis that a substantial portion of the applied N would enter the ecosystem and be recycled. How this higher N content will influence the physiological activity of the trees during the second and subsequent growing seasons remains to be seen.

Basic to any water-quality study is the relationship between substances in the water and standards indicating the suitability of water for specific uses. The U.S. Public Health Service Drinking Water Standards are usually considered the standards of acceptance:

	Mg./L.
Copper	1.0
Iron	.3
Manganese	.05
Nitrate-N	10.0
Sulfate	250.0
Total dissolved solids	500.0
Zinc	5.0

Our average concentrations of dissolved substances (table 5) are all well below the Public Health limit. Concentrations of nitrate-N, the substance of major concern, were below Public Health limits 811 times out of the 829 samples analyzed. Of the 18 samples that exceeded the limit, 8 came from the storm of 12 September. All the high nitrate samples were associated with a flushing out of the soil solution.

Although the nitrate-N discharge from the fertilized watershed increased, as expected, during the first year after fertilization, this increase should not cause alarm. It should be obvious that only an infinitesimal part of the drainage basin's discharge came from the 74-acre fertilized watershed, and the slight increase of nitrate-N concentrations in the fertilized watershed's stream was diluted to obliteration as soon as this feeder stream flowed into the main channel.

The results of this study should, however, alert forest managers to the potential for water-quality impairment whenever large amounts of fertilizer are applied to large portions of a drainage basin.

The substantial amount of nutrients discharged during the first year after urea fertilization raises several major questions. Where did all the nutrients come from? Did all parts of the watershed lose nutrients equally, or did one area of the watershed contribute more than other areas? What would have been the results had an unfertilized buffer strip, say 1 chain wide, been left along each side of the channel? Would lower application rate substantially reduce the nutrient loss? And what about the form in which N was applied? Would a less soluble or a slow-release form have significantly reduced our first-year loss?

The answers to these questions cannot be found in this study. The main objective of this pilot study was to determine how the application of a relatively large amount of a readily available N fertilizer to a young hardwood stand would affect the quantity and quality of streamflow from the watershed. First-year results show that quantity of streamflow was unaffected, but a substantial amount of nitrogen was lost from the watershed. This loss of N was accompanied by increased loss of certain metallic cations. We can only speculate as to the mechanisms that caused these responses and as to what the results would be under different experimental conditions. Answers to the questions raised must await further research.

ENVIRONMENTAL ASPECTS OF SEWAGE-DERIVED FERTILIZERS

by J. D. GAGNON, *Canadian Forestry Service, Environment Canada, PO. Box 3800, Ste. Foy, Quebec 10, Quebec.*

ABSTRACT. A 10-year-old white spruce (*Picea glauca* (Moench) Voss) plantation established on sandy soil gave a 30-percent height-growth response over control trees 4 years after application of 500 pounds per acre of sewage sludge. This result is a challenge to foresters to turn what has always been a liability into a commercial asset without contributing to water pollution.

AS THE HUMAN population increases, so does the problem of disposing of sewage sludge, produced at approximately 50 pounds of dried matter yearly per person. In Canada, excluding Quebec province, 80 percent of the sewage sludge is discharged into lakes or rivers; the remainder is either incinerated or trucked to land-fill areas, or is lagooned. In Quebec, sewage sludge disposal has not changed since early colonization. Most of the 150,000 tons of sewage sludge produced annually is discharged into watercourses that flow into the St. Lawrence River, transforming the river into a huge sewer. Only a nominal portion of the sludge (less than 1 percent) is treated and given to farmers.

The water-pollution situation in Quebec is alarming, to such a degree that from Montreal to Quebec City pollution of the St. Lawrence River is a recognized fact. And from Quebec City toward the Gulf of St. Lawrence the ecological equilibrium of the river is seriously jeopardized. It is this kind of water that has to be pumped through purification installations and transformed into potable supplies for human and other uses. The consumer has no choice but to drink water that tastes of chlorine, sulphureous gas, or other prophylatic additions.

Although it is true that rivers can assimilate great quantities of sewage sludge, it should not be forgotten that there are limits to self-purification and biodegradation. Moreover, these limits are often markedly lowered by the continuous addition of industrial waste, so that the margin of safety becomes dangerously narrow. In a society constantly calling for economic controls, we foolishly contaminate a vital commodity and wonder why millions of dollars are required to purify it. The answer is obvious: stop dumping sewage sludge into waters and find a substitute for its disposal. For ecologists, the best means is to submit sewage sludge to secondary treatment and to urge that research be directed toward the more widespread utilization of treated sludge.

It was with this purpose in mind that it was decided to test the use of sludge in forestry. A study was undertaken at Grand'Mère plantations, using white spruce as the test tree. Results obtained after 4 years are sufficiently conclusive for the writer to believe that treated sewage sludge is a promising fertilizer for tree growth, especially for white spruce planted on sandy soils.

For greater appreciation of the value of sewage sludge as a growth stimulator, its physico-chemical properties have been compared (table 1) with forest humus layer (H layer) of medium quality and with farmyard manure. Used in another part of the study area in 1920, manure has already shown (*Gagnon and Boudoux 1968*) that it is well able to enhance the growth of white spruce.

Table 1.—Lower and upper limits of sewage-sludge physico-chemical properties compared with forest humus and farmyard manure

Item	pH	Water retention (%)	Organic matter (%)	$\frac{C}{N}$	N (%)	Ca	Mg	K	P
						(parts per million)			
Sewage sludge	5.2-5.9	150-200	30-56	15-16	1.1-1.9	4,800-22,000	840-2,000	920- 2,200	1,200-1,960
Forest humus	4.3-4.7	300-500	85-95	31-39	1.1-1.5	1,600- 3,800	4,800-6,000	1,000- 1,800	950-1,400
Farmyard manure	7.6-8.8	75-95	85-97	30-43	1.2-1.6	1,200-37,000	800-2,800	10,000-15,000	2,900-3,700

Note: These data are from 10 to 15 samples.

MATERIALS AND METHOD

The sewage sludge used in this study was obtained from the waterpurification installation at Valcartier military camp, some 15 miles northwest of Quebec City. Sludge, at this plant, is submitted to a primary treatment, which consists of a mechanical process grinding solids such as sticks and rags. After grinding, the material is sent to three grit chambers where smaller solids, such as soil particles, sand, and stones settle at the bottom of the chamber.

The sludge is then directed into two 50,000-gallon tanks through which water slowly passes, allowing suspended particles to sink to the bottom. After being chlorinated to kill harmful bacteria, the water is discharged into the Jacques Cartier river by pipe, and the solids are pumped into digestion tanks, heated to 90°F. to destroy pathogenic bacteria, and submitted to anaerobic decomposition for 3 months. During this last process, lime is added to the sludge to facilitate filtration and to raise its pH. The treated sludge is then pumped to sanddrying beds.

This material, called digested sewage sludge, was used for the experiment reported in this study. As it was only partially dried on filter beds, it was hauled to open fields and air-dried in piles for several days; occasionally it was turned over to permit aeration and avoid overheating. After being air-dried, the sludge was passed through a ¼-inch sieve and bagged. Samples of the bagged material were collected and prepared for laboratory work. Physico-chemical properties were determined, using conventional analytical methods. These properties were compared with forest humus (H layer) and farmyard manure (table 1).

Sample trees were selected from a slow-growing white spruce plantation, planted in 1958 on a terrace along the St. Maurice River near Grand'Mère, Quebec. The soil, composed of old marine sand deposits lacking organic matter, was excessively drained and covered with a carpet of *Polytrichum commune* (Hedw.). The mineral nutrient content of the first 8 inches (20 cm.) of surface soil was very low. June, July, and August rainfall recorded during 11 years (1961–71) varied from 6 to 14 inches (15 to 35 cm.). For the same period the monthly mean minimum temperature varied from 50° to 60° F. and the mean maximum from 70° to 80°F.

One acre of the planted area was divided into 25 blocks, 25 trees in each. Five blocks were selected at random, and the heights of 5 trees within each block, also selected at random, were measured with a graduated pole; the 25 trees were kept as control trees. Among the 20 remaining blocks, another 5 blocks, each containing 5 trees with a height to the nearest 1/10 foot (3 cm.) corresponding to the 25 control trees, were retained for fertilization. Thus 25 control trees were paired with 25 trees to be fertilized. The purpose of pairing trees was to remove a source of variation and increase precision. Sewage sludge was applied to the soil at 500 pounds per acre (560 kg./ha.).

In 1965 and 1966 autumn height measurements, made at internodes, were subjected to a two-tailed "t" test. After the addition of sludge, a one-tailed "t" test was used to determine if difference between control and treatment was significant.

RESULTS AND DISCUSSION

The addition of lime after primary sedimentation at the sewage-treatment plant contributed to raise the pH from about 3.5 to about 5.5. The low C/N ratio of sludge indicates that the organic matter contained in such material is already in a more advanced state of decomposition than that of the forest humus or farmyard manure. Its N, therefore, is more readily available to the plant. The physical properties of forest humus (water retention and percentage of organic matter) far exceed those of sewage sludge. But, while the mineral content in P and K is almost equal in sludge and humus, Ca is much greater in sludge, but Mg content is less. The mean K and P content of farmyard manure is higher than in sludge or forest humus (table 1).

Physico-Chemical Properties

Because the sludge samples were collected during different seasons, the variation in mineral nutrient content was noticeable. In Quebec, Ca is the major variable; this is explainable. During winter, calcium chloride is applied to streets at the rate of 1 ton per mile, and at much higher rates at stoplights, intersections, and hills, varying with the hill slope. Thus, sludge samples collected in winter or spring after snowmelt contain much more Ca than when collected during summer. Also, according to Lunt (*1959*), Garner (*1966*), Scott (*1969*), and Sopper (*1970*), the chemical properties of sludge are influenced by industrial and other wastes flowing into main sewers. Hence the material is variable in its chemical content. Similarly, the mineral content of farmyard manure is not constant, varying with the livestock and kind of fodder and bedding.

According to Anderson (*1956*), the mean composition of digested sewage sludge tends to correspond to the fertilizer grade 2.4-2.3-0.3 (N-P-K). The sludge used in my study correspond to about 2.0-1.1-0.4, and the farmyard manure used earlier at Grand'Mère to 1.4-1.7-2.5. The effectiveness of NPK values for sludge and farmyard manure for tree growth cannot be compared with identical values found in commercial inorganic fertilizers. Sludge and farmyard manure possess the most important growth factor, the capacity to retain water; commercial fertilizer does not possess this.

An interesting difference in P content is shown between sludge from Ohio and from Quebec. Ohio sludge contains from 3,000 to 14,000 p.p.m. of P, and Quebec 1,000 to 2,000 p.p.m. The Ohio material is richer, but more variable. Scott (*1969*) commented that the use of detergents and kitchen-sink macerators has considerably increased the quantity of P in sewage sludge.

In some ways the value of sludge as a forest fertilizer does not compare with forest humus. By its greater bulk and incorporation with mineral particles, humus imparts more desirable physical properties. In contrast, the effect of sewage sludge on physical soil properties is bound to be better than that of inorganic fertilizer, the effects of which in physical terms are practically nil. Moreover, sludge is also a soil amendment, and, from examination of tables presented by Lunt (*1959*) and Berrow and Webber (*1972*), sludge contains important quantities of trace elements necessary for nutrition to a greater extent than most commercial inorganic fertilizers.

Perhaps the most important asset of sewage sludge over inorganic fertilizers is its ability to retain water and to release nutrient elements slowly and longer. Commercial fertilizers have a quicker effect on tree growth, but this effect can be expected not to last as long as the more slowly decomposing sludge.

My experiment has not as yet, gone far enough to allow the value of digested sludge on tree growth to be compared with farm manure. But according to Lunt (*1959*), digested sludge compares favorably with farm manure used in agriculture, and its effect lasts longer. Today, as the supply of farm manure is becoming more and more limited, sludge could be a good substitute not only for agriculture but also for forestry.

For agriculture purposes, Le Riche (*1968*) has indicated that

> *heavy metals from industrial effluents can accumulate in sewage sludge and constitute a hazard if taken up by crops growing on sludge-treated soil.*

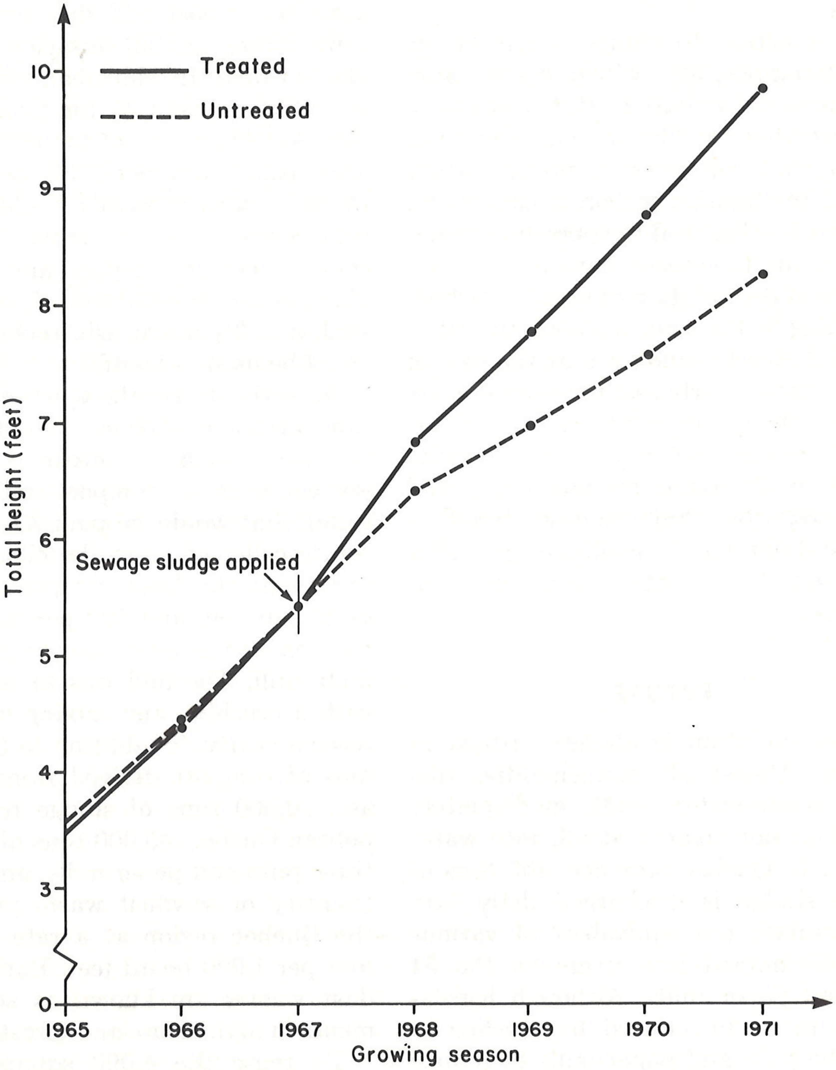
However, Le Riche's experimental evidence failed to fully support this contention, as the plants he studied did not take up abnormally large quantities of heavy metals. Le Riche's opinion is nevertheless shared by Berrow and Webber (*1972*), who wrote that heavy rates of sludge application over a number of years can constitute a hazard. It must be pointed out that the studies carried out by Berrow and Webber (*1972*) were made on a site on which 10 tons of dry sludge per acre was applied during 7 years.

In forestry there is no apparent problem, and the greatest use for sludge will be on trees growing on sandy sites that are always low in water-holding capacity; on plantations established on abandoned farmlands deficient in organic matter; and in nurseries where microbiological activity is reduced by weed-killer. Sludge is also acceptable for growing Christmas trees and preparing seed orchards.

Height Growth

Before sludge was applied, the total height of the trees to be treated in 1965, 1966, and 1967 was similar to that of control trees. In fact, the height-growth curve in 1965 and 1966 followed a similar pattern for both sets of trees, giving in 1967 an insignificant "t" value of 1.65 and a mean height difference of .03 foot (9 cm.). The "t" value of 1.65 for such a small height difference indicates that tree pairing was precise. During the first year after sludge application, the height of the treated trees exceeded that of the control trees by 7 percent, with a "t" value of 4.29, representing a difference in height significant at the P=0.001 level. In subsequent years this difference became

Figure 1.—Average total height of white spruce on treated and untreated sites.



even greater, reaching 30 percent after 4 years. Indeed, from the end of the 1967 growing season to the end of the 1971 growing season, the height of the control trees increased by 49 percent, and the treated trees by 79 percent.

This marked and speedy height-growth response to sludge indicates its value as a growth stimulator. Furthermore, as the mineral nutrient content of sludge is released slowly, due to its organic nature, nutrients are more steadily absorbed by tree roots. Consequently, the beneficial effect of sludge on tree growth can be expected to continue longer than that from solely mineral fertilizers.

An objection to sludge might be its slow decomposition, which could cause environmental pollution. But it has been demonstrated by Thomas and Bendixen (*1969*) that soil microorganisms utilize most of the organic carbon of sludge and that even wide soil-temperature variations during the season have no effect on the rate of degradation of organic carbon. According to the same authors, the addition of sludge to sandy soil at the rate of 6.8 tons/acre yearly and for several years has not shown an accumulation of organic residue. Hinesly and Sosewitz (*1969*), in discussing the use of digested sludge, reported that when scattered on soil it did not encourage flies or give off a disagreeable odor. My experiment confirms this.

FUTURE

Water pollution is already critical in Canada. Almost all municipalities discharge waste-water solids, inadequately treated or not treated at all, into water courses. In Quebec province, 400 tons of sewage sludge is discharged daily into watercourses; the equivalent of various solids discharged into rivers by the 54 pulp and paper mills. Although legislation is to be introduced by Quebec to force the pulp and paper mills to reduce this amount in 1974 to 240 tons a day (1 percent per ton of production), nothing has been done to control the vast quantities of sewage sludge, except extravagant wishes (*pieux voeux*) that cause conflict between government, industries, and municipalities. It is my opinion that the public will keep this conflict alive by demanding action. The time has arrived, therefore, for researchers to listen to and take action on opinion expressed by the public.

I maintain that the most rational solution to water pollution is to return waste to the land, where it belongs. A global solution would be to install in large urban areas a compost mill that would receive town refuse, and all sewage sludge, bark, and sawdust. In Montreal, town refuse is collected at about ½ ton yearly per person, and 85 percent of the refuse (50 percent paper products, 32 percent food waste, 3 percent wood) could be turned into compost. Of the remaining 15 percent, 7 percent metals and 5 percent glass, could be separated at the mill and sold, and 3 percent ash, rocks, dirt, etc., could be used as landfill.

An estimate for the Quebec metropolitan area—population 400,000—showed that an economical return could be expected from a compost mill (DANO type) that would be paid $5 per ton for refuse collected from the city; and after treatment the loose compost would sell at $5 per ton, and $20 per ton for compost packed in 50–pound bags, all prices f.o.b. mill. The mill was to be equipped with a crushing and mixing machine, to receive yearly, in addition to the 160,000 tons of compost derived from town refuse, 10,000 tons of sludge from metropolitan Quebec, 45,000 tons of bark from three pulp and paper mills, and a certain quantity of sawdust waste produced in the Quebec region at a rate of 1 cubic foot per 1,000 board feet. Bark and sawdust wastes are known as soil amendments in agriculture and forestry.

To reuse the 4,000 square miles of

abandoned land in Quebec province, reforestation is necessary. Located between Quebec city and Montreal, 600,000 acres of this land are sandy soil, deficient in nutrients, and similar to the soil of the Grand'Mère experimental area. Elsewhere in the province, 7 million acres are still under cultivation and need yearly soil amendment. There is an obvious market for organic soil amendments in forestry and agriculture, but before the benefit of compost application can be known, the selling price must attract customers.

Putting sewage sludge and urban and industrial waste back on the land where it belongs will occur sooner than we think, because it is the most acceptable and economical method of combating pollution created by other means of waste disposal. But researchers should continue to determine the optimum amount of waste disposal for maximum growth.

CONCLUSION

From this study on the effect of digested sludge on the height growth of a 10-year-old white spruce plantation established on sandy soil, it can be concluded that sewage sludge is a potential forest fertilizer of great value, and its use could turn an environmental pollutant into a financial asset.

LITERATURE CITED

Anderson, M. S.
1956. SEWAGE SLUDGES ARE VALUABLE FERTILIZERS. Crops and Soils. 8(4): 16-17.

Berrow, L. M., and J. Webber.
1972. TRACE ELEMENTS IN SEWAGE SLUDGES. J. Sci. Fed. Agr. 23(1): 93-100.

Gagnon, J. D., and M. Boudoux.
1968. DONNÉES NOUVELLES SUR LA FERTILISATION DES PLANTATIONS D'ÉPINETTE BLANCHE À GRAND'MÈRE, QUÉBEC. Can. Min. Pêches & Forêts. Rap. Inf. Q-X-5. 24 p.

Garner, H. V.
1966. COMPARISONS OF FARMYARD MANURE, SEWAGE SLUDGE, AND OTHER ORGANIC MANURES TESTED ON POTATOES AND A SUCCEEDING CEREAL CROP AT ROTHAMSTED. J. Agr. Sci. 67: 267-280.

Lunt, Herbert A.
1959. DIGESTED SEWAGE SLUDGE FOR SOIL IMPROVEMENT. Conn. Agr. Exp. Sta. Bull. 622. 30 p.

Hinesly, T. D., and B. Sosewitz.
1969. DIGESTED SLUDGE DISPOSAL ON CROP LAND. J. Water Pollut. Contr. Fed. 41 (5, pt. 1): 822-830.

Le Riche, H. H.
1968. MINERAL CONTAMINATION OF SOIL IN THE WOBURN MARKET-GARDEN EXPERIMENT RESULTING FROM THE APPLICATION OF SEWAGE SLUDGE. J. Agr. Sci. 71: 205-207.

Scott, A.
1969. LES BOUES D'ÉGOUTS. Agriculture 26: 28-34.

Sopper, William E.
1970. REVEGETATION OF STRIP MINE SPOIL BANKS THROUGH IRRIGATION WITH MUNICIPAL SEWAGE EFFLUENT AND SLUDGE. Compost Sci. 11(6): 6-11.

Thomas, R.E., and T.W. Bendixen.
1969. DEGRADATION OF WASTEWATER ORGANICS IN SOIL. J. Water Pollut. Contr. Fed. 41 (5, pt. 1): 808-813.

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WILDLIFE MANAGEMENT-FOREST FERTILIZATION RELATIONS

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ABSTRACT. There is a dearth of information about comprehensive management systems, and little more than crude speculation about forest fertilization-wildlife management relationships. To elucidate these relationships, studies of fertilization—including various combinations of goals and techniques—should be conducted. This research should include studies with timber production as the primary objective, with wildlife primary, and with neither favored.

THERE IS an abundance of information about the effects of fertilization on forest plants, and there is some information about the effects of fertilization on the nutritional quality of wildlife food. Some information is also available about the relative attractiveness of fertilized and unfertilized plants to herbivores. Thus it might be concluded that management systems utilizing this information are currently employed in forest-resource management. However this is not true: little more than crude speculation has actually been accomplished about the relationship of forest fertilization to wildlife management.

This paucity of information about fertilization—wildlife management relationships is not the result of a lack of interest or recognition of the potential importance of the problem. Hilmon and Douglas (*1967*) recognized the potential importance of forest fertilization to wildlife, stating that fertilization could affect the yield and nutrient content of food plants, their composition in the forest, and the rate of succession. They added that the potential for unfavorable response—damage of fertilized vegetation by wildlife—must also be recognized. This distinction, a favorable or unfavorable response depending on primary management objectives, permeates the bulk of the literature; and, in my opinion, this is responsible for the dearth of information about a comprehensive approach to forest management, including fertilization.

FERTILIZATION AND WILDLIFE FOODS

Williams (*1969*) has provided a partial review of the literature about the effects of fertilization on the nutritional quality of wildlife foods. Several investigations (*Wood and Lindzey 1967; Bailey 1968; Oh et al. 1970;* and *Ward and Bowersox 1970*) have found that N fertilization resulted in increases in crude protein in deer (*Odocoileus* spp.) browse. Bailey also found that mixed fertilizer, containing N, P, K, Mg, and S affected protein levels in the same manner as N fertilizer alone. However, the mixed fertilizer stimulated growth, thereby producing more browse, probably by lessening the P deficiency in the soil (*Bailey 1967*).

Wood and Lindzey, Ward and Bowersox and Oh et al. all found that deer preferred fertilized browse over unfertilized browse; and Oh et al. also found that N fertilization increased the fermentability, hence digestability, of Douglas-fir (*Pseudotsuga menziesii*) seedlings.

The results of Wood and Lindzey and Ward and Bowersox led them to state that the carrying capacity of forested areas for deer could be increased through fertilization. Wood and Lindzey went farther, stating that fertilization opens up the possibility of shifting herds locally from one parcel to another. Bailey cited the 13-percent increase in protein he observed as indicating great potential for managing browse quality. But he added that it is not known what this would mean to overwinter survival, reproductive success, or herd productivity.

Other references to fertilization and forest wildlife are concerned mainly with food patches rather than existing vegetation (*Mayer-Krapoll, 1956; Webb and Patric 1961; Yoakum and Dasmann 1969*). Still other reports are concerned mainly with the negative aspects of wildlife relative to forest fertilization. Thus Hilmon and Douglass cited problems with snowshoe hares (*Lepus americanus*) browsing fertilized conifers (*Heiberg and White 1951*) and squirrels preferring cones from fertilized slash pine (*Pinus elliottii*) (*Ahser 1963*). Mustonoja and Leaf (*1965*) cited several reports about the serious silvicultural problem due to the attractiveness of fertilized plants to animals.

I believe that the major biological relationships of forest fertilization relative to wildlife are reasonably clear. First, the nutritional quality of plants as food for wildlife can be increased. Second, the quantity of food may be increased. Third, herbivores will eat fertilized plants in preference to unfertilized plants. All this may result in increased survival and reproduction and improvement in the condition of individual animals.

The management implications of this are far less clear, and considerable work will be required to elucidate them. To that end the following approach is outlined.

FERTILIZATION AND MANAGEMENT

Wildlife may or may not be considered a high-priority management objective on a given forest area; but as many species eat plants, it must nonetheless be considered. I believe it is thus essential to initiate studies of forest fertilization where various combinations of management goals and techniques are employed. Studies of wood and wildlife production should be conducted on areas where wood is the primary objective, where wildlife has priority, and where neither is favored.

Further, the spatial and temporal relationships between fertilization of forest stands and of wildlife food patches must be ascertained. This could be approached by intensive plant and animal studies on areas involving no fertilization, fertilization of food patches only, fertilization of forest stands only, and fertilization of both.

Such studies would permit sound inference on the real, as well as potential, value of fertilization in increasing carrying capacity, and even in increasing populations. The proposed research would also be valuable in determining the real value of fertilization in controlling distribution of herbivores in time and space. The potential for thus concentrating animals in northeastern forests is illustrated by concentrations of large numbers of white-tailed deer (*O. virginianus*) feeding on aquatic vegetation (*Behrend 1966*) that has a relatively high ration of Na to K (*unpublished report by Behrend, Tierson, Leaf, and Halinar*).

Before such studies can be realistically conceived, planned, and executed, it is imperative that foresters and wildlife managers join hands as forest-resource managers. Until then, we are unlikely to know much more than we do today; that is, that forest fertilization has great potential for wildlife, and that wildlife is a great potential problem in forest fertilization.

LITERATURE CITED

Asher, W. C.
1963. SQUIRRELS PREFER CONES FROM FERTILIZED TREES. USDA Forest Serv. SE. Forest Exp. Sta. Res. Note SE-3. 1 p.

Bailey, J. A.
1967. MINERAL CONTENT OF DEER BROWSE ON THE HUNTINGTON WILDLIFE FOREST. N. Y. Fish and Game J. 14:76-78.

Bailey, J. A.
1968. EFFECTS OF SOIL FERTILIZATION ON THE CONCENTRATION OF CRUDE PROTEIN IN WITCHHOBBLE BROWSE. N. Y. Fish and Game J. 15:155-164.

Behrend, D. F.
1966. BEHAVIOR OF WHITE-TAILED DEER IN AN ADIRONDACK FOREST. Ph.D. thesis. State Univ. N. Y. Coll. Forest. at Syracuse Univ. 206 p.

Heiberg, S. O., and D. P. White.
1951. POTASSIUM DEFICIENCY OF REFORESTED PINE AND SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15:309-376.

Hilmon, J. B., and J. E. Douglass.
1967. POTENTIAL IMPACT OF FOREST FERTILIZATION ON RANGE, WILDLIFE, AND WATERSHED MANAGEMENT. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 197-202. TVA, Muscle Shoals, Ala.

Mayer-Krapoll, H.
1956. THE USE OF COMMERCIAL FERTILIZERS —PARTICULARLY NITROGEN—IN FORESTRY. Ruhn-Stickoff AG, Bochum, Germany. (Translated and published in U.S. by Nitrogen Div., Allied Chemical and Dye Corp., New York, 111 p.)

Mustonoja, K. J., and A. L. Leaf.
1965. FOREST FERTILIZATION RESEARCH, 1957-1964. Bot. Rev. 31:151-246.

Oh, J. H., M. B. Jones, W. M. Langhurst, and G. E. Connally.
1970. DEER BROWSING AND RUMEN MICROBIAL FERMENTATION OF DOUGLAS-FIR AS AFFECTED BY FERTILIZATION AND GROWTH STAGE. Forest. Sci. 16:21-27.

Ward, W. W., and T. W. Bowersox.
1970. UPLAND OAK RESPONSE TO FERTILIZATION WITH NITROGEN, PHOSPHORUS AND CALCIUM. Forest. Sci. 16:113-120.

Webb, W. L., and E. F. Patric.
1961. SEEDING HERBACEOUS PERENNIALS IN FOREST AREAS FOR GAME FOOD AND EROSION CONTROL. N. Y. Fish and Game J. 8:19-30.

Williams, G. L.
1969. EFFECTS OF FERTILIZERS ON THE NUTRITIONAL QUALITY OF WILDLIFE FOODS—A LITERATURE REVIEW. *In* RECENT ADVANCES IN WILDLIFE NUTRITION: 14-17. Colo. State Univ., Fort Collins.

Wood, G. W., and J. S. Lindzey.
1967. THE EFFECTS OF FOREST FERTILIZATION ON THE CRUDE PROTEIN, CALCIUM, AND PHOSPHORUS CONTENT OF DEER BROWSE IN A MIXED OAK FOREST. Natur. Can. 94:335-346.

Yoakum, J., and W. P. Dasmann.
1969. HABITAT MANIPULATION PRACTICES. *In* WILDLIFE MANAGEMENT TECHNIQUES: 173-231, 3rd ed., rev. Wildlife Soc., Washington, D.C. 623 p.

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URBAN FORESTRY AND RECREATION DEVELOPMENTS IN RELATION TO FERTILIZATION

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ABSTRACT. Urban and recreational forest areas present complex problems because of heavy use pressures, but their higher values increase feasibility for intensive management inputs such as fertilization wherever benefits can be shown. Situations in which fertilization is potentially useful are explored, including sites recently developed on stripped soils or poor quality made land, rehabilitation of sites deteriorated by overuse, treatment of vegetation damaged by direct or indirect people pressure, and treatments to counteract eutrophication effects on heavy use sites. Potential adverse effects of mass fertilization in urban and recreational forests are cautioned against. Fertilization needs to be developed as a more sophisticated tool to aid establishment, rehabilitation, and management of desired vegetation.

LAND MANAGERS in the Northeast are becoming increasingly involved with the management of vegetation under heavy urban and recreation pressures. The forestry profession has much background expertise that can be used in managing people-stressed vegetation. But compared to traditional forest management, this concern with heavy people pressures does present some new dimensions in focus, problems, and their potential solutions.

FEATURES OF URBAN AND RECREATIONAL FORESTS

We define urban and recreational forest as any area on which trees or understory vegetation are maintained primarily for their direct influences on people. These are areas subjected to heavy human pressure. Many of them are profoundly disturbed, both in developing the values sought and in the continuing process of their use. On ever more acres of northeastern woodland, human hooves are replacing cows' hooves as a significant force degrading soils and vegetation. Added to this are related effects of heavy use—construction, drainage changes, chemical additions, etc.; so many complex problems can be expected.

On the other hand, relatively high values are at stake in these vegetated areas. If a treatment such as fertilization is biologically effective, it is very likely to be economically feasible. We believe this opens up a much broader range of management potential than has generally existed for more traditional forest management in the Northeast.

Another feature of these areas is that we are generally concerned with a broad range of vegetative types and conditions. Though trees commonly provide the dominant vegetative structure, many of these areas are not fully forested landscapes. Other vegetation may be important: grass, especially in high impact areas; forbs and other ground-cover plants on less trampled areas; and shrubs located to serve as barriers, for wildlife food and cover, or for aesthetic effects.

In some special cases, protection of a unique biotic community is of prime concern. But more commonly, our concern is for a general vegetation effect to be maintained as long as possible with minimum inputs. Much substitution among species is possible. For example, pitch pine may serve as well as or better than white pine, beech as well as sugar maple. Criteria for suitability are often more flexible than for timber: the vegetation must only survive, grow, and produce the general effects desired.

SITUATIONS IN WHICH FERTILIZATION IS POTENTIALLY USEFUL

1. *Sites recently developed on areas stripped of surface soil, or on man-made land covered with poor soil material.*

Here the need is to accelerate development of soil productive enough to support satisfactory plant growth. Assuming that physical conditions, drainage, etc. are satisfactory (though frequently they are not), then low organic matter levels are a common problem. Direct additions of organic matter are generally feasible only for very intensive development, or where large quantities of organic waste are readily available, can be economically spread, and have no objectionable effects. For many relatively extensive forest recreation sites, it may be more practical to take the much slower tack of growing the organic matter in place, stimulated by inorganic fertilization.

Good examples of this are mountain ski slopes where the A and even B horizons have been scraped away during slope construction. At Whiteface Ski Center in the Adirondacks, fertilization and liming of such sparsely vegetated upper slopes increased grass and forb dry matter above-ground from 270 g./m.^{2} on control plots to 500 g./m.^{2} on the treated plots only 3 months after treatment. There were probably similar increases below ground. Though it would take several years to build up soil organic matter in this manner, the immediate benefits of improved soil cover for reduced erosion and better snow base were accomplished.

A more extreme example is an industrial waste area near Syracuse, N. Y., which is now public land and a potential future park site. Here the fine lime waste material is very unstable and unsuitable even to walk on in its sparsely vegetated condition. But addition of P and N, the known deficient elements in this case, increases above-ground dry weight of grass and forbs four- to six-fold, greatly reduces erosion, and provides enough cover to support light pedestrian traffic.

In both examples, the fertilizer costs are very modest for the effects obtained. The big problem is in getting management to recognize the results as desirable enough to take action. On the ski slope, fertilizer is most needed on the upper slopes that are hardest to fertilize, so most present fertilization is on the lower slopes which already are heavily vegetated. On the industrial waste site, no agency is yet taking responsibility for site improvement. Without changes in management approaches, such research results remain academic.

2. *Rehabilitation of sites deteriorated by overuse.*

Implicit in the terms *rehabilitation*, *deterioration*, and *overuse* are a complex of value judgments involving some concept of site carrying capacity for people. Carrying capacity involves the resolution of two sets of variables: the physical-/biological situation and the cultural demands. Considering a model of carrying capacity as a function of management inputs, we can imagine several possible forms of response curves. For example:

- A modest input to overcome a critically limiting factor may result in a substantial gain in carrying capacity, but increasing the same kind of inputs may have little additional benefit. Single site-rehabilitation techniques, or fertilizing with a critically limiting nutrient, would be examples of this.
- Or we may produce a stepwise pattern of increases by inputs to correct each limitation as it becomes obvious.
- Or an integration of management inputs—controlling structures with fertilization, special plantings, etc.—may produce fairly steady increases in carrying capacity with increasing management intensity.

Thus, for management inputs such as fertilization, we need to know not only what treatments do how much for site rehabilitation under what conditions, but more specifically, we need to know the nature of the response curves. It is actually more complex than this because the cultural element of carrying capacity itself involves a balance between two sets of variables: the number and kinds of people to be served, and the qualitative values these people expect of the landscape. So the result is a three-dimensional response surface upon which management decisions must be made.

We are very short of good information for doing this. But one attempt at such information is in progress in the White Mountains of New Hampshire in a cooperative effort by the Forest Service, the Appalachian Mountain Club, and the College of Forestry at Syracuse. Initial efforts are currently in a graduate-student project primarily to sort out the role of direct vegetation management, including fertilization, versus people control in Tuckerman's Ravine. We hope to expand this in the next few years to other sites and management variables.

A question one often encounters in site rehabilitation is engineering versus biotic approaches. Though biological solutions are generally preferred where feasible, it is often necessary to stabilize a site *for* vegetation rather than *with* vegetation, especially where very active erosion is in progress. Biotic approaches most commonly involve grasses and other effective groundcovers, either existent or planted; and intensive fertilization is a usual and often essential treatment for their establishment and maintenance.

A good example is work by a Syracuse College of Forestry-Forest Service Team —Ketchledge, Leonard, and others—to stabilize erosion and preserve fragile native vegetation on heavily trampled alpine areas on Adirondack high peaks (*Ketchledge and Leonard 1970*). The native dwarf shrubs, sedges, and clumpgrasses are poorly adapted to resist trampling. However, the stoloniferous grasses, red fescue (*Festuca rubra* L.) and Kentucky bluegrass (*Poa pratensis* L.), native in the region on better soils, are highly resistant to trampling. But they can be established on the acid, organic alpine areas only with intensive fertilization (N,P,K,Ca, and Mg).

On eroded areas where fine soil material remains, grass establishment is excellent even on heavily trampled trails. Where the fines have washed and blown out, leaving only a coarse peat mat, grass establishment is very poor; and engineering structures such as log barriers, stone riprap, etc. become very useful for holding fine soil in place. The grass areas should protect the remaining native vegetation community from further destruction by erosion, and we are hoping, with some promise to date, that native plants may reinvade areas stabilized by grass. However, some control of use will probably be needed to permit substantial recovery here, as has also been the experience in some U.S. National Parks (*Lindsay 1971*). We feel that urban and recreation forest managers must become more involved in all the variables of carrying capacity.

3. *Treatment of vegetation damaged by direct and indirect people pressure.*

Much cost and pain of site rehabilitation can be avoided if we can treat vegetation in its early stages of damage from people pressure. It is widely accepted that maintenance of high fertility may serve to compensate for a number of ills befalling vegetation under heavy use pressure. A vigorous plant community, with heavier foliage and thicker stems and bark, may be more *resistant* to damage—provided that it is genuinely healthy growth and not just highly succulent growth such as may result from heavy N fertilization. Vigorous plants are also more *resilient*; they recover more rapidly from damage. That an ounce of prevention suggests bushels of cures is evidenced by the frequency with which amateurs and professionals use fertilizer as a shotgun treatment for ailing plants, occasionally with some success. Perhaps a broader approach is in order.

To stop site degradation before it becomes serious, it is useful to view site degradation as the net result of *degrading* and *rehabilitating* processes. For example, damaged or removed plant parts are regenerated, lost litter and soil organic matter are replenished, compacted soil is loosened by frost action and biotic activity. The critical point occurs when the recovery processes begin falling substantially behind the degrading processes. There are no doubt many situations in which fertilization is helpful in holding this balance, but it is probably naive to count on it universally.

A sounder approach is to reduce the cause of damage as much as possible. One important factor is the seasonality of use pressures and their effects. Heavy use concentrated in a few summer months leaves several open months for recovery, whereas heavy spring-to-fall use does not. We are beginning to suspect that light use in spring, in the month after snow melt when soil is saturated and vegetative cover is at its annual minimum, may be far more detrimental than heavier use in mid-summer to early fall when soils are drier and vegetation is at its maximum. It is possible that careful seasonal timing of fertilizers to favor early spring growth of grass species might partially counteract these effects on some sites.

Site damage is of course lightest under good snow cover, and vigorous low vegetation is effective in maintaining snow. We do know that snow compaction may have adverse effects on plant microclimate and aeration, but to our knowledge plant vigor/snow compaction damage relationships have not been explored much on recreational lands. Perhaps the turfgrass specialists can give us some clues on this.

Pollution damage to plants is an increasingly important indirect effect of heavy people pressure. One might expect vigorous well-fertilized vegetation to either resist better or recover from periodic high air-pollution levels, and this is documented in at least one case: apparent ozone damage to Kentucky bluegrass in Maryland was greater on plots with moderate than with heavy N fertilization (146 vs. 293 Kg. N/ha.) (*Wilton et al. 1972*). Though differences in apparent pollution damage to trees among sites and individuals have been observed (*Wood 1968*), we are not aware of any studies of the role of fertilizer in reducing pollution damage to trees.

4. *Treatments to counteract effects of land eutrophication on heavy-use sites.*

Though we have often been aware of nutrient losses from intensively used sites due to erosion and plant or litter removal, the reverse process—land eutrophication—is more subtle. On urban and recreational forest sites where vegetative cover is maintained, erosion is reasonably controlled, and soil leaching is reduced by compaction, site eutrophication can be expected in time. A good example of this is Tuckerman's Ravine in the White Mountains, where many decades of nutrient concentration due to intensive camping activity has resulted locally in abnormally high fertility status for a mountain site.

To the extent that this builds up a balanced nutrient status, it may simply reduce needs for additional fertilizer inputs. However, unintentional mineral inputs may often lead to imbalances in certain nutrients or excesses of potentially toxic materials. This suggests that routine fertilization will need increasingly to be replaced by more specific formulations to correct imbalances. Calcium salts on roads (summer and winter), concrete, and wood ashes are a few of many sources of increased base status locally. While these may be beneficial in extremely acid soils, under more neutral conditions they may create nutritional problems for acid-soil plants—ericaceous plants, certain oaks, etc. Iron deficiency due to Fe immobilization is an increasingly observed problem for these plants in urban, recreational, and roadside areas, requiring repeated use of chelated iron fertilizer even where total native soil iron is high.

Damage to trees by road salting, especially where these salts accumulate in roadside drainage, has received much study in New England (*Holmes 1961; Rich 1968*). Treatment with gypsum ($CaSO_4.2H_2O$) has been recommended for these accumulation areas, but the long-term solutions lie in more careful and restricted road salting and better road-drainage design. For the sake of the total roadside community, we hope that changes to more salt-tolerant species will generally be considered only as a last resort. The obviously susceptible species are valuable phytometers here.

Accumulations of excess heavy metals are gaining more recognition as local problems. For example, wildlife specialists are increasingly concerned about lead accumulations along highways. Though liming has been shown to depress availability and uptake of heavy metals such as lead (*Cox and Rains 1972*) and suggests a stop-gap solution, we hope that the current campaigns to curtail heavy-metal inputs to our landscape will succeed in reducing this problem in the long run.

PUTTING FERTILIZATION IN BALANCE IN URBAN AND RECREATIONAL FORESTS

So far we have sought to show that fertilization is a potentially feasible treatment for many vegetation-soil problems in urban and recreational forestry, probably more so than in wildland forestry in the Northeast. Now we feel obliged to sound the cautions.

Because of the high use-values involved, the relative cheapness of fertilizer, and the widespread popular belief in its magical qualities, fertilization is rapidly increasing in the urbanizing Northeast and hardly needs more selling as a mass treatment. It is obvious that urban-suburban fertilization is rapidly surpassing agricultural fertilization in the Northeast as an important potential source of water pollution.

More subtle are the potential effects of indiscriminate fertilization on existent wild to semi-wild plant communities and their management. Many plant communities in our landscape depend on the relatively low fertility of their sites for protection from more aggressive invaders. This includes heaths, old-field poverty grass-mixed forb communities, fern glades, etc., which may often provide very satisfactory cover requiring little maintenance. Fertilization can destroy these communities, in some cases replacing them with more aggressive noxious weeds, and often increasing the need for mowing, brush cutting, and other control measures.

Thus there seems little justification for fertilization as a routine mass treatment in urban and recreational forests. Rather, it must be further developed as a highly sophisticated tool for aiding establishment, rehabilitation, and maintenance of desired plant communities.

LITERATURE CITED

Cox, W. J., and D. W. Rains.
1972. EFFECT OF LIME ON LEAD UPTAKE BY FIVE PLANT SPECIES. J. Environ. Quality 1: 167-179.

Holmes, F. W.
1961. SALT INJURY TO TREES. Phytopathology 51:712-718.

Ketchledge, E. H., and R. E. Leonard.
1970. IMPACT OF MAN ON THE ADIRONDACK HIGH COUNTRY. N. Y. Conservationist 25(2): 14-18.

Lindsay, D. J.
1971. PROTECTING AND MANAGING TREES AND WOODED AREAS SUBJECTED TO HEAVY RECREATIONAL USE. *In* TREES AND FORESTS IN AN URBANIZING ENVIRONMENT: 111-114. Univ. Mass. Coop. Ext. Serv.

Rich, A. E.
1968. EFFECT OF DE-ICING CHEMICALS ON WOODY PLANTS. Univ. Conn. Symp. Pollut. Roadside Environ. Proc. :46-47.

Wilton, A. C., J. J. Murray, H. E. Heggestad, and F. V. Juska.
1972. TOLERANCE AND SUSCEPTIBILITY OF KENTUCKY BLUEGRASS CULTIVARS TO AIR POLLUTION IN THE FIELD AND IN AN OZONE CHAMBER. J. Environ. Qual. 1:112-114.

Wood, F. A.
1968. AIR POLLUTION IN THE ROADSIDE ENVIRONMENT. Univ. Conn. Symp. Pollut. Roadside Environ. Proc. :57-63.

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INSECT AND DISEASE CONTROL: FOREST FERTILIZATION RELATIONS

by ALEX L. SHIGO, *Chief Plant Pathologist, USDA Forest Service, Northeastern Forest Experiment Station, Durham, N. H.*

ABSTRACT. Insect and disease control in the past emphasized reduction of damage to trees grown for wood products. Now control measures must include reduction of damage to trees in scenic areas, recreation sites, watersheds, and rural areas. Fertilizers are being considered for control, in combination with other materials. Some effects of fertilizers on insects and diseases are discussed.

INSECTS AND DISEASES cause considerable damage to trees not only because of their adverse effects on timber quality and quantity, but also because of their effects on trees in recreation areas, watersheds, scenic areas, backyards, and cities. All insect and disease problems must now be approached from this broad view, rather than strictly from the timber aspect. This means that we must change our views about what is and what is not a financially feasible control for a damaging insect or disease.

The use of fertilizers on trees has been aimed primarily at increasing growth, or to satisfy the timber requirement. In the last decade, many reports, mostly from Europe (*Foster 1967*), have pointed out that fertilizers also affect insects and diseases. The effects range from greatly increasing the injury caused by insects and diseases to greatly decreasing the injury. Reports in the literature conflict greatly.

Insects and fungi have received most attention from tree entomologists and pathologists. Although this trend will probably change little in the future, other destructive agents or stress factors have been receiving more attention in the last decade; and they will probably continue to receive more attention in the future—viruses, mycoplasmas, bacteria, nematodes, pollutants, environmental extremes, and man and his activities.

Insects and fungi often interact with these other stress factors. It could be that the results reported by some investigators conflicted because they focused on one destructive agent whereas actually interactions of several agents were involved.

The addition of fertilizers to the soil and tree triggers a multitude of events. It would be extremely unwise to treat lightly the subject of fertilizers as they affect insects and diseases. This is one area where tree entomologists and pathologists must interact. A fertilizer treatment may indeed increase growth and reduce the injury caused by a certain insect, but it may also increase the susceptibility of the tree to an aggressive pathogen.

The use of fertilizers on ornamental woody plants and annual crop plants has been practiced for many years. A vast amount is known about the effects of fertilizers on these plants. It would be profitable to learn as much as possible about the effects of fertilizers on ornamental and annual plants. Much of the basic information is applicable to trees.

Foster (*1967*), in a comprehensive review, discussed the effects of fertilizers on some of the economically important insect and disease problems. He gave information about insect and disease situations that are increased and decreased by fertilizers. I will not repeat this information, but will supplement it with some brief additional material to show the complexity of the subject; and I will mention some stress factors other than insects and fungi.

PHENOLS AND RESISTANCE

A great amount of information is known about healthy trees (*Kozlowski 1971*) and diseased trees (*Smith 1970*). Much of what is known about the biochemistry and physiology of diseased plants (*Goodman et al. 1967 and Tomiyama 1963*) is applicable to trees.

Phenol compounds play a major role in resistance of plants to disease. After wounding, oxidation of phenols occurs; and these oxidized products act as deterrents to infection. Nitrogen fertilizers often increase susceptibility of plants to infection by rust fungi while at the same time the amount of phenols is decreased. In trees, the same situation was found with the leaf-infecting fungus *Venturia inaequalis*. Kirkham (*1954*) showed that the ratio of soluble nitrogen to phenol compounds affected resistance of apple and pear leaves to *V. inaequalis*. Szweykowska (*1959*) gave a possible explanation for this by stating that aromatic biosynthesis and nitrogen metabolism may be regarded as competing pathways.

NUTRITIONAL PLANT CHANGES THAT AFFECT INSECTS

Rodriguez (*1960*) pointed out that fertilizers and other agricultural chemicals can change the composition of plants quantitatively, and consequently, their nutritive value for insects. An excellent discussion on the role of nutritional principals in biological control was given by House (*1966*). He stressed two important basic laws about food for insects: the food must possess characteristic properties that attract and induce an insect to feed; and the food must contain substances that fulfill the nutritional requirements of the insect. Anything, such as fertilizers, that alters these two basic characteristics of a foodstuff will alter the feeding pattern of insects. Further, an altered food base will also alter the feeding patterns of insects that feed on other insects, leading to an alteration of natural biological control patterns.

MYCORRHIZAE

The role of mycorrhizae in plant nutrition is well known. Marx (*1971*), working on a hypothesis of Zak's (*1964*), showed that ectomycorrhizae plays a protective role in reducing infection of feeder roots of pine by *Phytophthora cinnamomi*. Harley (*1963*) stated that the ectomycorrhizal habit is an adaption in some species to nutrient-deficient soil. Ectomycorrhizae are more prevalent in infertile soils (*Voigt 1971*). Recent results on the effects of fertilizers on mycorrhizae from Europe indicate that, depending on the fertilizer combination used, mycorrhizae usually increase (*Koberg 1966; Göbl and Platzer 1968*).

Many exceptions can be found. Richards and Wilson (*1963*) showed that by increasing soil N by adding NH_4NO_3 and lime, mycorrhizal development was reduced. If ectomycorrhizae are acting as protective barriers to other root-infecting fungi, then great care must be given to the amount and combination of fertilizer used, or the results could be more harmful than beneficial.

NEMATODES

Nematodes are common in forest soils *(Shigo and Yelenosky 1960)*. Many forms feed on tree roots and cause injury. Some nematodes are vectors for viruses (*Hewitt et al. 1958*) while others feed on mycorrhizal fungi (*Kuehle and Marx 1971)*. Dwinell *(1967)* showed that combinations of N, P, and K that altered susceptibility of *Acer saccharum* and *Ulmus americana* to *Verticillium dahliae* also altered the adequacy of the hosts to the plant parasitic nematode *Pratylenchus penetrans*.

VIRUSES

Different cultural practices affect plant susceptibility to viruses. The better plants are fed and grow, the more likely they are to become infected (*Broadbent 1964*). The principal vectors for viruses are sucking insects, and these are the insects that increase in numbers when fertilizers are used (*Rodriguez 1960; Watson 1964*). Many examples of increased susceptibility to viruses following increased nitrogen fertilization for crop plants are given by Broadbent. He stated that the increased amount of nitrogen affected susceptibility more than it affected the population of insect vectors.

INSECTS AND DROUGHT

Population density of many needle-eating insects of spruces and pines may vary greatly at the same time at different locations, or at the same location at different times (*Schwenke 1966*). Schwenke *(1966)* correlated these differences with differences in the moisture content of the soil. Further, he showed that, the lower the mortality rate of the larvae, the higher the weight of the pupae; and the shorter development time always corresponded to higher concentration values of the cell sap.

Results corresponding to this were obtained with fertilizers. Trees that had been treated with fertilizers, principally nitrogen, reacted to the harmful insects like trees on more humid soils; that is, through application of fertilizers, the propagation of the insects was checked. The sugar content of the needles was reduced on soils having a higher moisture content, during more humid weather, or on soils to which fertilizers had been applied. The nutritive value of the needles was decreased, and the propagation of the respective insect species was checked.

POLLUTANTS

The list of pollutants and combinations of pollutants that injure trees is increasing steadily. Cotrufo and Berry (*1970*) pointed out that fertilization with NPK improved the tolerance of white pine (*Pinus strobus*) to SO_2 injury.

UPTAKE OF ELEMENTS FROM SOIL TO WOOD IN LIVING TREES

Ellis (*1959*) showed that the quantity and quality of the minerals in the soils supporting grand fir *(Abies grandis)* was reflected in the wood. There were significant differences in mean values of most elements in buttwood ash of trees grown west and east of the Cascades. Wood decayed by the fungus *Echinodontium tinctorium* showed an increased ash content and an apparent accumulation of certain elements. Decay by *E. tinctorium* was found only on the east of the Cascades. Cowling (*1970*) pointed out that nitrogen is just as essential for the growth of wood-destroying microorganisms as it is for other organisms. Fertilizers may increase growth of the trees, but they may also increase growth of wood-destroying microorganisms.

CONCLUSIONS

The benefits of fertilization have been demonstrated overwhelmingly with food crops. Often to attain the desired benefits with food crops, resistant varieties are used in combination with intensive fertilizer and pesticide programs. But the problems are manyfold greater with trees. A greater quantity of food is the only goal with annual food crops. With trees, there are many goals, depending on where the tree is—forest, recreation area, watershed, city, or backyard.

We want and need trees for many reasons. We must assess the value of fertilizers in a new light. Fertilizers can do more than just increase growth. Used properly, fertilizers can increase the resistance of trees to certain insects and diseases. In many situations, healthy trees relatively free of insects and diseases may be the most desirable trees. And, as the values we put on trees change, controls that were considered not economically feasible in the past may be feasible in the future.

LITERATURE CITED

Broadbent, L.
1964. CONTROL OF PLANT VIRUS DISEASES. Plant Virol.: 330-364.

Cotrufo, C., and C. R. Berry.
1970. SOME EFFECTS OF A SOLUBLE NPK FERTILIZER ON SENSITIVITY OF EASTERN WHITE PINE TO INJURY FROM SO_2 AIR POLLUTION. Forest Sci. 16:72-73.

Cowling, E. B.
1970. NITROGEN IN FOREST TREES AND ITS ROLE IN WOOD DETERIORATION. (Abstr.) Univ. Uppsala. Diss. Sci. 19 p.

Dwinell, L. D.
1967. SELECTED INTERACTIONS OF *Verticillium dahliae, Pratylenchus penetrans,* AND MAJOR NUTRIENT ELEMENTS, *Acer saccharum* AND *Ulmus americana.* Forest. Abstr. 29:4120.

Ellis, E. L.
1959. THE EFFECTS OF ENVIRONMENT AND DECAY ON MINERAL COMPONENTS OF GRAND FIR WOOD. *In* MARINE BORING AND FOULING ORGANISMS. Friday Harbor Symp.: 477-513. Univ. Wash. Press, Seattle.

Foster, A. A.
1968. DAMAGE TO FORESTS BY FUNGI AND INSECTS AS AFFECTED BY FERTILIZERS. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 42-46. TVA, Muscle Shoals, Ala.

Göbl, F., and H. Platzer.
1969. [EFFECT OF FERTILIZING AND MYCORRHIZAL INOCULATION ON YOUNG SPRUCE PLANTS.] Forest. Abstr. 30:2191.

Goodman, R. N., Z. Király, and M. Zaitlin.
1967. THE BIOCHEMISTRY AND PHYSIOLOGY OF INFECTIOUS PLANT DISEASE. D. Van Nostrand Co., Inc. 354 p.

Harley, J. L.
1963. MYCORRHIZA. Vistas Bot. 3:79-103.

Hewitt, W. B., D. J. Raski, and A. C. Goheen.
1958. NEMATODE VECTOR OF SOIL-BORE FAN LEAF VIRUS OF GRAPEVINES. Phytopathology 48:586-595.

House, H. L.
1966. THE ROLE OF NUTRITIONAL PRINCIPLES IN BIOLOGICAL CONTROL. Can. Entomol. 98: 1121-1134.

Kirkham, D. S.
1954. SIGNIFICANCE OF THE RATIO BETWEEN THE WATER SOLUBLE AROMATIC AND NITROGEN CONSTITUENTS OF APPLE AND PEAR IN THE HOST-PARASITE RELATIONSHIPS OF *Venturia* SPECIES. Nature 173:690-691.

Koberg, H.
1967. [FERTILIZERS AND MYCORRHIZAE: POT EXPERIMENT WITH *Pinus sylvestris.*] Forest. Abstr. 28:3485.

Kozlowski, T. T.
1971. GROWTH AND DEVELOPMENT OF TREES. Academic Press, New York and London. Vol. I, 443 p., vol. II, 514 p.

Marx, D. H.
1971. ECTOMYCORRHIZAE AS BIOLOGICAL DETERRENTS TO PATHOGENIC ROOT INFECTIONS. *In* MYCORRHIZAE. N. Amer. Conf. Mycorrhizae Proc. 1; USDA Forest Serv. Misc. Publ. 1189:81-96.

Richards, B. N., and G. Wilson.
1963. NUTRIENT SUPPLY AND MYCORRHIZA DEVELOPMENT IN CARIBBEAN PINE. Forest Sci. 9:405-412.

Rodriguez, J. G.
1960. NUTRITION OF THE HOST AND REACTION TO PESTS. *In* BIOLOGICAL AND CHEMICAL CONTROL OF PLANT AND ANIMAL PESTS. Amer. Assoc. Adv. Sci. Publ. 61:149-167.

Ruehle, J. L., and D. H. Marx.
1970. PARASITISM OF ECTOMYCORRHIZAE OF PINE BY LANCE NEMATODE. Forest Sci. 17:31-34.

Schwenke, W.
1966. CLIMATIC AND EDAPHIC DEPENDENCE OF INSECT NUTRITION AND ITS IMPORTANCE FOR THE PROBLEM OF INSECT RESISTANCE IN FOREST TREES. *In* BREEDING PEST-RESISTANT TREES: 251-252. Pergamon Press, London.

Shigo, A. L., and G. Yelenosky.
1960. NEMATODES INHABIT SOILS OF FOREST AND CLEAR CUT AREAS. USDA Forest Serv. NE. Forest Exp. Sta. Res. Note 101. 4 p. Upper Darby, Pa.

Smith, W. H.
1970. TREE PATHOLOGY: A SHORT INTRODUCTION. Academic Press, New York and London. 309 p.

Szweykowska, A.
1959. THE EFFECT OF NITROGEN FEEDING ON ANTHOCYANIN SYNTHESIS IN ISOLATED RED CABBAGE EMBRYOS. Acta Soc. Bot. Polon. 28:539-549.

Tomiyama, K.
1963. PHYSIOLOGY AND BIOCHEMISTRY OF DISEASE RESISTANCE OF PLANTS. Annu. Rev. Phytopathol. 1:295-324.

Voigt, G. K.
1971. MYCORRHIZAE AND NUTRIENT MOBILIZATION. *In* MYCORRHIZAE. N. Amer. Conf. Mycorrhizae Proc. 1; USDA Forest Serv. Misc. Publ. 1189:122-131.

Watson, T. F.
1964. INFLUENCE OF HOST PLANT CONDITION ON POPULATION INCREASE OF *Tetranychus telarius*. Hilgardia 35:273-322.

Zak, B.
1964. ROLE OF MYCORRHIZAE IN ROOT DISEASE. Annu. Rev. Phytopathol. 2:377-392.

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SPECIAL FOREST CROPS AND FOREST FERTILIZATION

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ABSTRACT. The general objectives of fertilization for special forest crops such as maple syrup and Christmas trees are much the same as for other forest products—to increase production and improve quality. The problem of fertilization for increased syrup production is considered under the same nutrient and soil considerations necessary for increased production of other forest crops. Short rotation plus the high potential value of the crop make Christmas trees especially well suited to intensive cultural techniques such as fertilization. The greatest increase in returns to investment occurs when fertilization results in a shorter rotation and increased tree quality.

MAPLE SYRUP and Christmas trees are special crops, but the objectives of fertilization are the same as those for any other forest product—to increase production and quality. The types of responses that are sought are different. In sugarbushes, fertilizer treatments are intended to increase sap-flow volume and sap-sugar content. In Christmas tree plantations, the desired results are controlled growth rate and full crown development with good needle retention and color. Because these products are so different, each is dealt with separately.

SYRUP PRODUCTION

The production of maple syrup from sugar Maple (*Acer saccharum* Marsh.) is limited almost entirely to North America, principally in the northern tier of states from Maine to Minnesota and adjacent Canada. The processing of sap to make syrup is one of the oldest of our agricultural industries, which reached its peak in the United States around 1860 (*U.S. Tariff Commission 1930*) with the production of about 6.6 million gallons. Since then the industry had experienced a general decline, which has leveled off in recent years at an annual production of about 1.5 million gallons.

It has been estimated that less than 3 percent of the sugar maple trees over 10 inches d.b.h. are being tapped (*Willits 1965*). The potential for commercial maple sap production would seem to be extremely large. But, because of the high cost of labor along with other economic pressures, it is not likely that any large gains in production will be brought about by increasing the number of trees used (*Bell 1955; Foulds and Reed 1962; USDA 1962; Taylor et al. 1967*). Increases are being sought now in existing sugarbushes through improvements in sap-collection techniques and through advances in sugarbush management practices, including fertilization.

The processing of sugar maple sap to make syrup simply involves boiling until the sap has been evaporated to a sugar concentration of 65.5 percent. During the sugaring season, the average sugar content of sugar maple sap is about 2.5 percent (*Gabriel 1964*). According to Jones' (*1967*) "maple rule of 86", the number of gallons of sap required to produce 1 gallon of syrup is calculated as:

$$\text{Gals. sap} = \frac{86}{\%\ \text{sugar}}$$

Thus 34.4 gallons of 2.5-percent sap are required to make 1 gallon of syrup. As sugar content increases, less sap is required. Hence, 28.7 gallons of 3-percent sap, and 24.6 gallons of 3.5-percent sap will yield 1 gallon of syrup.

The economic implications of increasing sap-sugar content are obvious. More syrup could be produced for the same labor and equipment cost, and there would be considerable savings in fuel used for boiling.

Considerable variation in sap-sugar content exists between sugarbushes and between trees in the same sugarbush (*Taylor 1956*). Although sugar content varies from year to year and during the sap-flow season because of differences in weather conditions, sweeter sugarbushes tend to remain sweeter than neighboring bushes and individual trees are consistent in their performance relative to other surrounding trees (*Jones et al. 1903; McIntyre 1932; Morrow 1952; Taylor 1956*).

There is strong evidence that sweetness in individual trees is an inherited trait (*Kriebel and Gabriel 1969; Gabriel 1972*). Further evidence (*Marvin et al. 1957*) shows that sugar concentration is positively correlated with sap-volume yields. Thus, genetics must be considered as a significant factor contributing to the observed variation between trees, and perhaps to some extent between sugarbushes.

It must also be assumed that a certain amount of this variation, particularly between sugarbushes, is due to differences in environmental factors—specifically differences in site productivity. If this assumption is correct, improvements in site productivity brought about by fertilization would be expected to enhance sap-sugar production.

Increased syrup yields resulting from fertilization have been reported. Kriebel (*1961*) conducted an experiment in which 600 pounds per acre of N as ammonium nitrate was applied in 12-inch-deep holes at intervals of about 2-1/3 feet around the trees. A significant increase in sap-sugar concentration occurred the first year. This increase averaged about 0.25 percent and was maintained at about the same level over the 3-year period of measurement. Using 2.5 percent as the pretreatment average, the rise in sugar content represented a 10-percent increase. In practical terms, this increase in sugar content would yield 0.3 additional gallons of syrup for each 100 gallons of sap. In an adjacent test stand, no responses were obtained until the third year after treatment.

LaValley (*1969*) made five annual broadcast applications of N, P, and K amounting to about 18, 6, and 11 pounds per acre per year respectively. A response was noted the second year, when sugar concentration increased 18 percent over the control plot. During the fifth year, sap-sugar concentrations of the fertilized trees averaged 12.1 percent higher than the unfertilized trees. The fifth-year measurements also showed a 10-percent increase in sap volume. Interim data between the second and fifth years were not presented by the author.

Watterston *et al.* (*1963*) applied N, P, and K separately and in combination to sugar maple trees in central New York. The combined elements were broadcast at the rate of 300, 260, and 250 pounds of N, P, and K respectively—the equivalent of 6,000 pounds of 5-10-5 per acre. When applied separately, 200, 145, and 200 pounds of N, P, and K respectively were used per acre. The various treatments were found to affect total sugar yields either through sap volume or sap-sugar concentrations—and not always in a positive direction. The complete fertilizer application during the first sugaring season after treatment resulted in a significant increase in sap-sugar concentration. But it also resulted in a pronounced decrease in sap volume, with a net effect that total sugar yields were less than those of the controls. During the second season, both sugar concentration and sap volume were greater than those from the control trees, but this increase was not sufficient to compensate for the decrease the first season. The N and K fertilizers resulted in little change from the control trees, while the P fertilizer resulted in a significant decrease in sugar concentration.

In an experiment near Burlington, Vermont, Smith and Walters studied the effects of fertilization on sap production. N, P, and K, broadcast at rates of up to 160, 70, and 66 pounds per acre respectively, with and without 10 tons per acre of hydrated lime, failed to increase either sap-volume or sap-sugar during four consecutive seasons after fertilization. (Unpublished office report, Northeastern Forest Experiment Station, Burlington, Vt., 1972.)

The few studies reviewed here are all that could be uncovered by the authors that deal specifically with fertilization of sugar maple for sap-volume and sap-sugar production. Obviously much work needs to be done before the effects of fertilization can be evaluated realistically.

Many authors have reported that the ideal sugar tree is a vigorous, fast-growing, well-formed tree supporting a wide, deep crown. Sugar maples possessing these characteristics tend to produce sweeter and greater quantities of sap than slower growing smaller-crowned trees. The implication is that larger crowns have greater leaf surface area and therefore have a greater capacity for carrying on photosynthesis and accumulating reserve carbohydrate. However, Blum (*1971*) found no relationship between several tree characteristics and sap-sugar concentration.

If form and development are indeed precursors to higher sugar yields, the problem of fertilization for increased syrup production must be viewed in terms of the same nutrient and soil considerations necessary for increased production of other forest crops. It also follows that, for fertilization to be successful, a sugarbush—like any timber stand—must be given proper spacing and be young enough to show a growth response.

A major obstacle to resolving what kind, in what amounts, when, and where to apply fertilizers, is the extreme variation encountered in sap-sugar content and sap-volume flows. For example, Watterston et al. (*1963*) reported that the total sugar yields from their control trees varied by 137 percent from one year to the next. The within-season variation among the control trees was as high as

580 percent. They reported similar variation among the treated trees.

Data from our own sap-production studies in Vermont, have shown similar ranges in variation. This inter- and intra-seasonal variation is due mainly to climatic, genetic, stand, and soil-site factors. Yields can also be influenced significantly by other effects such as depth, location, and number of tapholes, microbial buildup within the taphole, and methods of sap extraction. The latter group are physical factors, and variation from these sources can be minimized in research studies by standardizing experimental technique.

The genetic and environmental factors are not necessarily insurmountable. Our data support the findings of other researchers that individual trees generally are consistent in their performance relative to other trees in the immediate area. One procedure that can be used to cope with the problem of variation is to calibrate individual trees or groups of trees for a certain period of years before treatment to establish a base for comparison. This should be an essential element in the design of fertilization studies as well as in other studies dealing with sugar yields from sugar maple.

CHRISTMAS TREES

The Christmas tree industry in the United States has developed rapidly into a multimillion dollar business, with a strong trend toward producing high-quality trees from intensively managed plantations. A nationwide survey in 1964 showed that 41 million trees with a retail value of $142 million were marketed (*Sowder 1965*). By 1975, due to our expanding population, it is expected to increase to an annual sale of 48 million trees with a value of $168 million. There is adequate economic justification for consideration of intensive Christmas tree culture.

The short-term rotation of Christmas trees presents an excellent opportunity for the profitable use of fertilizers. The time between the investment in treatment and the realization of returns is short. This holds interest charges to a minimum. In addition, the returns from a Christmas tree plantation are potentially high enough to justify intensive culture measures such as fertilization.

However, there are many unknowns in using fertilizers for Christmas tree culture. For instance, growers are unsure which species may need fertilizing, when and which fertilizer should be used, and what quantity of fertilizer is needed (*Richards and Leaf 1971*). Therefore the use of fertilizers in Christmas tree culture remains limited.

Three direct benefits can be derived from fertilizing Christmas trees: (1) reduce so-called "planting shock"; (2) maintain tree growth at optimum rate during the rotation (generally 12 inches per year); and (3) improve tree quality. The first two have the effect of shortening the rotation. Shortening the rotation by even 1 year is a real economic advantage to the Christmas tree grower. Reducing planting shock may increase seedling survival.

Growers are primarily concerned with the third benefit—improved quality. Most Christmas tree producers who use fertilizers said that darker foliage (improved color) was their main reason for fertilizing. Generally, fertilizer response can be seen in needle color, crown density, retention of second- and third-year needles, and increased growth. In addition, there are a number of other elusive characteristics that are directly related to a healthy, vigorous tree—such as reducing the incidence of insect and disease damage (*Larsen 1967*).

On the basis of information gathered from a survey of Christmas tree producers who use fertilizer, Larsen (*1967*) attempted to determine financial returns from fertilization of white spruce (*Picea glauca* (Moench) Voss), balsam fir

(*Abies balsamea* (L.) Mill.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and eastern white pine (*Pinus strobus* L.). He found that an increase in tree quality brought about by fertilization resulted in a price increase of 25 cents per tree, which increased returns to investment by 2 to 4 percent.

However, a greater impact occurred when fertilization resulted in a shortened rotation. Returns may be increased 10 percent or more if rotations are shortened one or more years. Ideally, a fertilization program would not only shorten the rotation, but would also increase tree quality. Larsen found that when fertilization of white pine resulted in increased tree quality and shorter rotations, the return to investment could be increased by as much as 24 percent.

Maki (*1958*) warned that an intensive fertilization program is not a magic cure-all, but rather another tool available to help in plantation management. Depending on site condition, improper or unneeded fertilization may cause more problems than it solves. Too-fast growth leads to spindly trees. Weed responses may intensify an already difficult weed-control problem. For example, Thor (*1965*) found that N fertilizers had a detrimental effect on survival of Fraser fir and white pine seedlings (table 1). The fertilizer was added to the planting hole at time of planting. Thirty grams per seedling were used except for ammonium nitrate, which was applied at 15 grams per seedling. The weeds were intensified to a point of causing a moisture shortage for the seedlings.

Table 1.—Survival of fertilized Fraser fir and eastern white pine after two growing seasons

Treatment	Fraser fir	White pine
	Percent	*Percent*
1. 8-40-0	81	83
2. 7-35-0	77	83
3. 0-63-0	89	86
4. 35.5-0-0	20	76
5. 5-10-5	75	78
6. Check	89	91

Source: Thor (*1965*).

Also, fertilization is not retroactive. No amount of fertilizer can remedy previous neglect. It will not change the length of shoots nor the form of the older needles. Fertilizer applied in the final phase of production should be considered as a finishing touch in a program of intensive management.

The species most likely to benefit from fertilization are those that require good sites. For Christmas trees these are Douglas-fir, true firs, spruces, and eastern white pine (*Bell and White 1966*). Douglas-fir, spruces, and true firs generally grow slowly during the 2 or 3 years after planting. White (*1966*) indicated that the years of stagnation result to some degree from a combination of limited fertility, water availability, and weed competition.

In Ohio, Hacskaylo (*1964*) reported reducing the time required for producing salable spruce and fir Christmas trees from 10 to 14 years to 6 or 7 years through fertilization. He reported that "The spruce grew as well as did the pines, but the firs were somewhat slower." The economic advantage—reducing a crop rotation so that almost two rotations can be grown in the same length of time it formerly took for one—is tremendous.

The recommendation not to fertilize Scotch pine (*Pinus sylvestris* L.) is almost universal. The species is an excellent forager and will grow satisfactorily except on sites of exceptionally low fertility. Nor is it recommended to fertilize Scotch pine to correct yellowing in late fall. This change in color is an inherited characteristic related to the seed source and is a response to temperature changes and light quality (*White 1966*).

The harvest of any crop removes some of the available soil nutrients and may limit those available for following crops.

Successive Christmas tree rotations may reduce site productivity. Wilde (*1961*) noted that 95 percent of the nutrients in a tree are found in the foliage and young branches. These parts are removed by a Christmas tree harvest. By contrast, nutrient losses are small on most logging operations because the slash (foliage and young branches) is left on the site. Therefore nutrient loss due to successive Christmas tree harvesting may be considerable, and fertilization is necessary to maintain soil fertility.

Both soil tests and tissue tests can be used diagnostically to detect the need for fertilization, but neither have yet been calibrated and perfected for use with Christmas trees. Therefore visual symptoms are normally used to determine Christmas tree fertilizer needs. Poor color—particularly during the growing season—short needles and short growth, early needle drop, and decrease in the number of years the needles persist are general symptoms of low tree vigor. Site conditions such as sparse natural weed cover, presence of mosses, and patches of bare soil are also indicators of low nutrient availability (*White 1966*).

The nutrient most likely to improve growth and color of Christmas trees in the Northeast is N, except on the K-deficient outwash soils of northern New York, New England, and southern Canada. Urea and ammonium nitrate are excellent and inexpensive sources of N, while muriate of potash is a good source of K. These should not be applied to the soil surface without controlling the competing vegetation. To do so would stimulate weed growth and create unfavorable moisture stress and light conditions for the seedlings.

For general Christmas tree application, White (*1966*) recommended the use of complete fertilizers (N-P-K) if no specific deficiency is known. Granular material with an analysis similar to 12-12-12, 12-6-12, or 14-7-7 should be adequate. The 2-1-1 ratio is recommended for soils of sandy loam or loam texture where N is likely to be the limiting element.

The fertilizers should be placed on the ground in a band at about the edge of the crown but not closer than 8 inches to the central stem. Young trees, 2 to 3 years in the field, should get about 4 ounces. Large trees, 1 to 2 years before harvest, about ½ to 1 pound. White further stated that minor element deficiencies are uncommon in Christmas tree plantations. He suggests that field crop formulations that contain minor elements be avoided, because even very small quantities of boron or other minor elements may be harmful to evergreens.

Jablanczy (*1971*) urges greater use of lime in Christmas tree culture. Many of the areas used for Christmas trees are cutover areas and abandoned agriculture lands that are usually depleted of their calcium reserve. Liming would help remedy this situation. He cited observations of others as well as his own, made in the Canadian maritime provinces, describing how liming improved needle color and prevented early needle drop of balsam fir, spruce, and pines. M. L. McCormack of the Department of Forestry at the University of Vermont (*personal communication 1972*) has also observed a favorable response in balsam fir to liming in both plantations and natural stands when the soil was brought to a pH of about 6.7.

Turner (*1966, 1968, 1968a*) conducted fertilizer trials with varying amounts of N, P, K, and S. These were applied in a natural stand of chlorotic 15-year-old Douglas-fir growing on a glacial moraine soil in the Puget Sound Basin. He concluded that Douglas-fir Christmas tree color can be improved and growth controlled by the amount of fertilizer used. Rates of N from 0.125 pounds to 1.0 pounds per tree applied in May effectively improved color by November (fig. 1). Further, these trees exhibited a growth response the following season (fig. 2).

Figure 1.—Nitrogen makes yellow trees greener. November color after May application on Douglas-fir (Turner 1968).

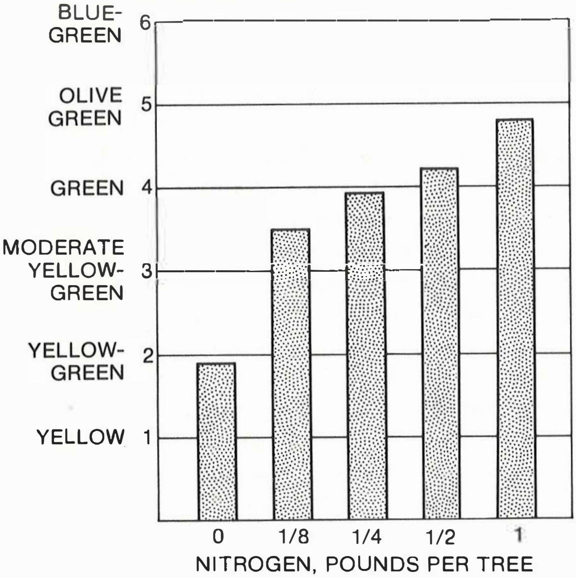
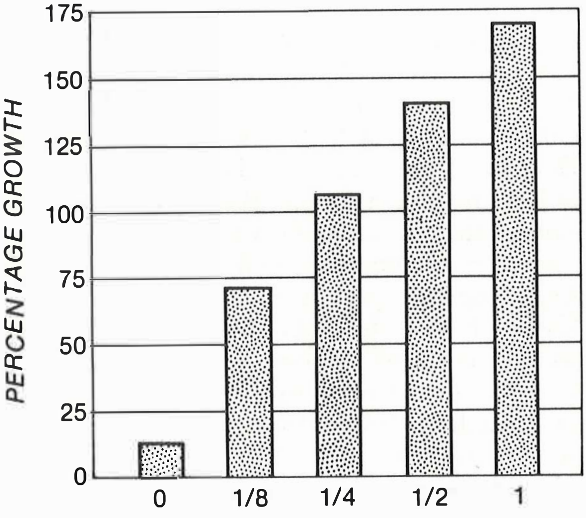


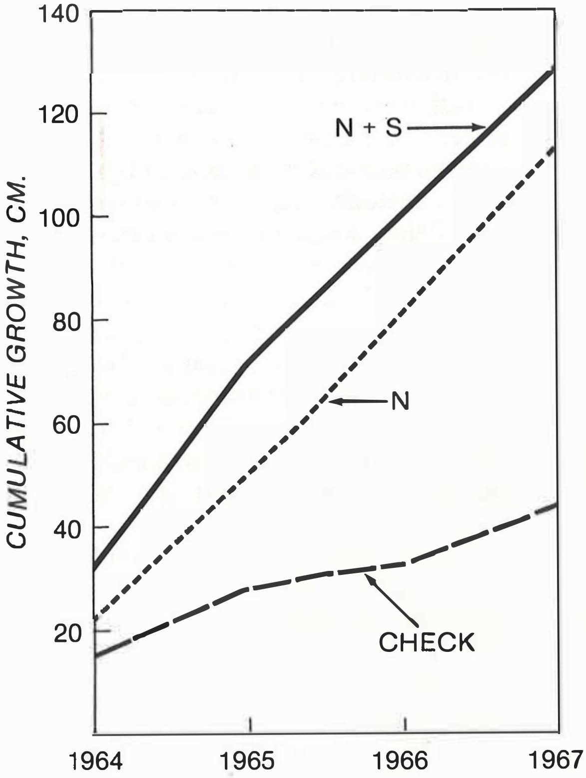
Figure 2.—Nitrogen stimulated leader growth. Percentage growth second season after application on Douglas-fir (Turner 1968).



However, N treatments of more than 0.125 pounds per tree may overextend leader growth. Treatment with P at 0.1 pounds, K at 0.2 pounds, or S at 0.125 pounds per tree had little effect on either color or growth. On the other hand, a treatment of 0.125 pounds of N plus 0.125 pounds of S per tree gave the greatest response in both color and growth rate (fig. 3). For maximum color Turner recommended an application of 0.25 pounds of N per tree in May for harvest in November. But if only growth stimulus is wanted, 0.125 pounds N can be used with safety.

In northern Vermont, fertilizer treatment effects were observed by Kinerson (*1967*) in three balsam fir plantations. The treatments were: no fertilizer, 1-½

Figure 3.—Cumulative growth of Douglas-fir following May 1964 fertilization (Turner 1968a).



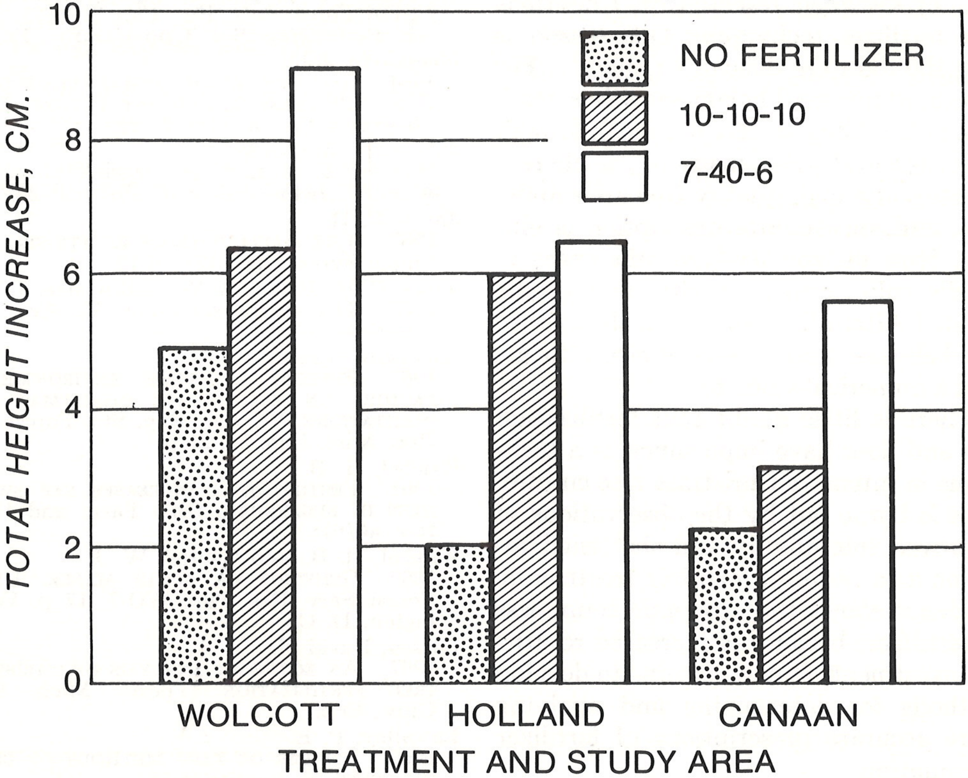
ounce per tree 10-10-10 applied to soil surface, and 2 ounces per tree of magnesium ammonium potassium phosphate (7-40-6) probed into the root zone. In two of the plantations, both fertilizer treatments resulted in significantly greater growth. In a third plantation, only the 7-40-6 applications resulted in a significant height growth increase (fig. 4). Generally, the fertilizer treatments increased internodal bud development, height growth, and needle length; in addition they also improved color and reduced winter burn. The root-zone application of slow-release 7-40-6 was judged to be superior to the surface application of granular 10-10-10.

McCormack (*personal communication 1972*) has worked with what he calls a typical Vermont hayfield site, generally heavy soils such as silt loam or clay loam. Because of past liming practices, their pH is high, averaging about 6.7. In addition, they have a very heavy herbaceous cover. He is attempting to develop cultural techniques specifically for growing balsam fir Christmas trees.

In one trial, he compared three treatments against an untreated control: band spray with simazine at the rate of 12 pounds per acre; 300 pounds each of elemental N-P-K per acre as a complete fertilizer, and a combination of the herbicide and fertilizer treatments. These were evaluated for response in terminal growth, needle color, needle length, and bud formation. The herbicide-only treatment was best, followed closely by the herbicide-fertilizer combination. Significantly poorer was the check, and the poorest was fertilizer only.

In other trials he used a slow-release

Figure 4.—Mean total height increase for 1966 expressed in centimeters per tree by fertilizer treatment and study area (Kinerson 1967).



formulation of 7-40-6. Two ounces per tree in the root zone at planting gave a 3- to 4-year benefit. Initial cost of 7-40-6 was higher than other formulations but the longer term benefits were greater.

Based on his own conclusions and on those of other researchers, McCormack made the following recommendations for growing balsam fir Christmas trees on a Vermont hayfield: (1) the year before planting, band-treat the site with 14 pounds simazine per acre ;(2) the following year plant big rugged 2-3 transplants in a big hole; (3) place 2 ounces of slow-release 7-40-6 in the planting hole; (4) about 2 years after planting, treat each tree with 4 ounces of 15-15-15; and (5) maintain weed control. He strongly emphasized that fertilizer without weed control is a total loss.

The published results of Christmas tree fertilization research are not very plentiful. Some of the general forest-fertilization results have application and give helpful data. But there is certainly a lack of designed research on Christmas tree fertilizer techniques. One reason is that the data are difficult to analyze. For instance, increased height growth is good, to a point; beyond that too much growth is detrimental. Also, many of the characteristics of a high-quality tree are subjective, and an accurate description is elusive. How do you analyze differences in needle color, crown density, and needle length? After all, beauty is in the eyes of the beholder and is very difficult to assign a numerical value to.

There is little doubt that fertilization can and does have importance as a technique in intensive Christmas tree culture. This is borne out by the observations of improved tree quality and shortened rotation as a result of fertilizer treatments. Evidence shows the economic soundness of fertilizers because of increased returns on investment. It now remains to develop methods for determining and applying more accurate prescriptions of fertilizer formulation.

REFERENCES

Anderson, W. R.
1951. OPEN CROWN MAPLES ARE BASIS FOR PROFITABLE SUGAR OPERATIONS. Ohio Farm and Home Res. 36(51):62-63.

Barraclough, K. E.
1947. MAPLE SYRUP AND SUGAR PRODUCTION IN NEW HAMPSHIRE. N. H. Ext. Bull. 79.

Bell, R. D.
1955. COST AND RETURNS IN PRODUCING AND MARKETING MAPLE PRODUCTS. Cornell Univ. Dep. Agr. Econ. AE 1016.

Bell, Lester E., and White, Donald P.
1966. TECHNICAL MANUAL FOR CHRISTMAS TREE FARMERS. Nitrogen Division, Allied Chemical Corporation, 128 p., illus.

Bramble, W. C.
1948. SWEETER SAP FROM MAPLE WITH FULL CROWNS. Pa. Agr. Exp. Sta. Bull. 502.

Collingwood, G. H., Cope, J. A., and Rasmussen, M. P
1928 THE PRODUCTION OF MAPLE SYRUP AND SUGAR IN NEW YORK STATE. N. Y. Agr. Ext. Bull. 167.

Foulds, R. T., and Reed, F. A.
1962. VERMONT'S MAPLE SYRUP AND SUGAR INDUSTRY. N. Logger, 10(10):12-15, 50-51.

Gabriel, W. J.
1964. SELECTION OF SUGAR MAPLES FOR HIGH SUGAR CONTENT IN SAP—DEVELOPMENT OF PROCEDURES. NE. Forest Tree Improv. Conf. Proc. 11:8-11.

Gabriel, W. J.
1972. PHENOTYPIC SELECTION IN SUGAR MAPLE FOR SUPERIOR SAP-SUGAR PRODUCTION. USDA Forest Serv. Res. Pap. NE-221, 12 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Hacskaylo, John.
1964. RESEARCH IN CHRISTMAS TREE PRODUCTION: THE PRESENT, PAST AND FUTURE. Amer. Christmas Tree J. 8(4):21-22.

Jablanczy, Alexander.
1971. USE OF LIME FOR TREE CULTIVATION. Amer. Christmas Tree J. 15(2):21-23.

Jones, C. H.
1967. THE MAPLE RULE OF EIGHTY-SIX. Nat. Maple Syrup Dig. 6(2):18-19.

Jones, C. H., Edson, A. W., and Morse, J. W.
1903. THE MAPLE SAP FLOW. Vt. Agr. Exp. Sta. Bull. 103.

Kinerson, Russell, S., Jr.
1967. EFFECTS OF SOME ENVIRONMENTAL FACTORS ON BALSAM FIR CHRISTMAS TREE PLANTATIONS. Vt. Agr. Exp. Sta. Forest Res. Rep. Misc. Pub. 50, 21 p.

Kriebel, H. B.
1961. FERTILIZATION INCREASES SAP SWEETNESS IN SUGARBUSH. Ohio Farm and Home Res. 46(6):

Kriebel, H. B., and Gabriel, W. J.
1969. GENETICS OF SUGAR MAPLE. USDA Forest Serv. Res. Pap. WO-7, 17 p. Washington, D. C.

Larsen, David N.
1967. AN ECONOMIC ANALYSIS OF CHRISTMAS TREE FERTILIZATION. Thesis, Mich. State Univ., 49 p.

LaValley, P. E.
1969. STUDIES OF FAST METHODS OF GROWING TREES. N. Logger: 24-25.

McIntyre, A. C.
1932. THE MAPLE PRODUCTS INDUSTRY OF PENNSYLVANIA. Pa. Agr. Exp. Sta. Bull. 280, 47 p.

Maki, T. E.
1958. FOREST FERTILIZATION POSSIBILITIES IN THE UNITED STATES. Better Crops with Plant Food: 16-25.

Marvin, J. W., Morselli, M., and Laing, F. M.
1957. A CORRELATION BETWEEN SUGAR CONCENTRATION AND VOLUME YIELDS IN SUGAR MAPLE—AN 18-YEAR STUDY. Forest Sci., 13: 346-351.

Moore, H. R., Anderson, W. R., and Baker, R. H.
1951. OHIO MAPLE SYRUP—SOME FACTORS INFLUENCING PRODUCTION. Ohio Agr. Exp. Sta. Res. Bull. 718.

Morrow, R. R.
1952. CONSISTENCY IN SWEETNESS AND FLOW OF MAPLE SAP. J. Forest. 50: 130-131.

Morrow, R. R.
1955. INFLUENCE OF TREE CROWNS ON MAPLE SAP PRODUCTION. N. Y. Agr. Exp. Sta. Bull. 916.

Richards, N. A., and Leaf, A. L.
1971. EFFICIENT CHRISTMAS TREE FERTILIZATION. Amer. Christmas Tree J. 15(2): 11-15.

Sowder, A. M.
1965. STATISTICS FOR THE U. S. CHRISTMAS TREE INDUSTRY. J. Forrest. 63: 876.

Taylor, F. H.
1956. VARIATION IN SUGAR CONTENT IN SAP. Vt. Agr. Exp. Sta. Bull. 587, 39 p.

Taylor, R. D., Pasto, J. K., and Southworth, H. M.
1967. PRODUCTION TRENDS AND PATTERNS OF THE MAPLE SYRUP INDUSTRY IN NORTH AMERICA. Pa. Agr. Exp. Sta. Bull. 742.

Thor, E.
1965. SHOULD YOU FERTILIZE WHEN PLANTING? Amer. Christmas Tree J.

Toma, A. K.
1961. CORRELATIONS BETWEEN SEVERAL TREE CHARACTERISTICS OF SUGAR MAPLE (*acer saccharum* Marsh.) AND MAPLE SAP AND SUGAR YIELDS. Thesis, Mich. State Univ.

Turner, Darrell O.
1966. COLOR AND GROWTH OF DOUGLAS-FIR CHRISTMAS TREES AS AFFECTED BY FERTILIZER APPLICATION. Soil Sci. Soc. Amer. Proc. 30: 792-795.

Turner, D. O.
1968a. SULPHUR RESPONSE OF DOUGLAS-FIR CHRISTMAS TREES. Sulphur Inst. J.

Turner, Darrell O., and Buhaly, Joseph.
1968. FERTILIZING NATURAL STAND DOUGLAS-FIR CHRISTMAS TREES. Wash. State Univ. Coll. Agr. Ext. Bull. 585, 14 p., illus.

U. S. Department of Agriculture.
1962. MAPLE PRODUCTS SUGAR AND SYRUP——TREES TAPPED, DISPOSITION PRICE VALUE BY STATES, 1916-1959. Statist. Rep. Serv. Crop Rep. Statist. Bull. 313.

U. S. Tariff Commission.
1930. MAPLE SUGAR AND MAPLE SYRUP REPORT OF THE UNITED STATES TARIFF COMMISSION TO THE PRESIDENT OF THE UNITED STATES. U. S. Govt. Printing Office, Washington, D. C.

Watterston, K. G., Leaf, A. L., and Engelken, J. H.
1963. EFFECT OF N, P, AND K FERTILIZATION ON YIELD AND SUGAR CONTENT OF SAP OF SUGAR MAPLE TREES. Soil Sci. Soc. Amer. Proc. 27(2): 236-238.

White, Donald P.
1966. FERTILIZATION FOR IMPROVED CHRISTMAS TREE QUALITY. Amer. Christmas Tree J. 10(1): 20-22.

Wilde, S. A.
1961. COMMENTS ON TREE NUTRITION AND USE OF FERTILIZERS IN FORESTRY PRACTICES. J. Forest. 59: 364-368.

Willits, C. O.
1965. MAPLE SIRUP PRODUCERS MANUAL. USDA Agr. Handbk. 134 (rev.), 112 p.

Winch, F. E., Jr., and Morrow, R. R.
1962. PRODUCTION OF MAPLE SYRUP AND OTHER MAPLE PRODUCTS. N. Y. Agr. Exp. Sta. Bull. 974.

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ESTABLISHING FOREST ON SURFACE-MINED LAND AS RELATED TO FERTILITY AND FERTILIZATION

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ABSTRACT. Studies on establishing forest on strip-mined lands show that most spoils are not hostile to planted trees. Nearly all essential elements for plant growth were found in the spoils; their concentrations depend on lithology, acidity, and the rate and degree of spoil weathering. Planted and seeded forest trees respond strongly to application of N and P both singly and in combination. Certain spoils will respond to K application. Extreme acidity and high concentrations of Mn, Fe, Zn, S, and Al are major factors limiting plant growth on coal-breaker refuse; but such areas are a small portion of the total area of disturbed land. Application of lime alleviates these problems.

ON LAND that has been drastically disturbed by mining coal, iron ore, clay, sand, and other natural resources, natural vegetation comes back very slowly—if at all. To create a new forest on these lands means planting forest tree seedlings or sowing the seeds. In our search for ways to establish a forest, we are concerned with the natural supply of nutrients essential to plant growth, and with the possibilities of applying lime, fertilizers, and other amendments.

BACKGROUND

Disturbance of land by strip and surface mining of natural resources has become common worldwide. Because strip-mined lands contribute to an overall degradation of the environment, they have become a matter of great concern in many countries and states.

Eastern North America is fortunate in having a wealth of natural resources. The Atlantic Seaboard has extensive deposits of gravel and fine sand, the latter essential in the glass industry. Other regions are rich in iron ore, phosphates, and kaoline clay deposits. Interspersed within the massive rock formations of the Appalachian Mountain chain are the world's finest deposits of coal.

From Florida to Maine, these resources have been mined. Now the drastically disturbed lands are a significant component of the landscape. Perhaps the most significant of all is the Appalachian Mountain region, which has had more than its share of surface-mining operations.

As of 1965, there were 3,357 square miles of strip-minded lands in 26 states east of the Mississippi River. Seventy percent of these lands were disturbed by strip-mining for coal, and an area approximately the size of the State of Delaware now needs rehabilitation (*USDI 1967*).

On the spoil material, re-establishment of natural vegetation is a very slow process. The bare spoils in many places cause serious environmental problems—and in some places ecological disasters. Adjacent land, water, forests, and aesthetics are drastically affected.

Although tree planting on strip-mined lands is as old as strip-mining itself, it was not until after World War II that a number of experimental tree plantings and pastures were established on those lands throughout the East. Now tree planting is required by law in each state.

The majority of studies on establishment of new forests on disturbed lands can be grouped as follows: (1) suitability of the tree species to the site; (2) planting seasons and methods; (3) effects of grading on tree performance; (4) seeding —direct, aerial, and hydroseeding; (5) performance of grasses and legumes as nurse crops for trees; and (6) performance of trees as related to fertilization, liming, and mulches.

Future reclamation and rehabilitation practices on disturbed lands will be geared toward diversified land use, including agricultural, horticultural, industrial, commercial and residential development, and recreation. However, the establishment of new forests will remain the major reclamation practice.

STRIP-MINED LANDS AS SITES FOR NEW FORESTS

Strip-mine spoils are composed of unstable debris in a heterogeneous mixture from all strata that were present in the overburden. This material exhibits great diversity in its physical, mineralogical, and biological characteristics and differs in the supply of mineral nutrients needed to sustain plant life.

Studies show that nearly all essential elements are found in most of the overburden. Concentrations are variable, depending on the lithology, spoil age, degree and rate of weathering, and erosion processes. Unfortunately, organic matter is practically nonexistent.

Results from many studies conducted in the bituminous and anthracite coal regions (*Hart and Byrnes 1960*, *Limstrom 1960*, *Chapman 1967, and Czapowskyj 1970*) indicate that certain spoils will support excellent forest plantations without any site preparation or soil ameliorants. On the other hand, some spoils may require site preparation such as grading, terracing, and harrowing. Obviously the effects of grading vary with the spoils. Limstrom (*1952, 1960*) and Chapman (*1967*) reported that in the Central States compaction resulting from spoil grading has adverse effects on tree establishment on spoils derived from limestone and having high content of clay. Compaction of spoils, besides reducing air and water infiltration, results in a less available supply of essential elements and a reduced biotic life.

However, Finn (*1952*) reported that white ash (*Fraxinus americana* L.) and yellow-poplar (*Liriodendron tulipifera* L.) grew equally well on graded and ungraded spoils in Ohio derived from sandstone and shales, and that growth was significantly better only on ungraded spoils derived from limestone. No marked differences in foliar N, P, and Ca between graded and ungraded spoils were noted.

Studies in Pennsylvania (*Czapowskyj 1970*) indicated that coarse-textured anthracite spoils were improved by the degree of compaction from grading operations. There is evidence that the Ca, Mg, and K in graded spoils in three of four spoil types were considerably higher than in their ungraded counterparts.

Other spoils in this region are plantable; but soil amendments such as lime, fertilizer, mulch, or seeding nurse crops are prerequisite for successful plantations.

Finally, considerable acreage is unsuitable for tree growth because of stoniness, texture, and stability of slope. These conditions cannot be corrected by liming, fertilizing, or mulching. Such spoils are unique problems.

Considerable work has been done on evaluating the performance of established plantations as related to spoil characteristics. Although past research has had some impact in generating interest in spoil classification, fertility, acidity, and nutrient availability to plants, the disturbed lands have in general received little attention by soil scientists.

STATUS OF NUTRIENTS AND RESPONSES TO FERTILIZERS

In a number of reports dealing with establishment of forests on strip-minded land, estimates have been made of natural fertility and nutrient availability to plants. These have been related to spoils of different physical, chemical, and biological characteristics in various states and climatological regions. Consequently, workers differ in their evaluation of plant nutrient status from one area to another.

In studying these reports, I found that N, P, and K are the most frequently mentioned limiting elements for plant growth. Table 1 shows examples of the supply of natural nutrients in selected spoils. The data were compiled from reports of several investigators (*Barnhisel and Massey 1969, Stiver 1949, and Czapowskyj 1969 and 1970*). Unfortunately, literature on the responses due to added fertilizers is meager, and the responses are expressed primarily in early survival and height growth.

Macronutrients

Many investigators (*Schramm 1966, Struthers 1960, Stiver 1949*) and others have concluded that coal-mine spoils are deficient in N. The fact that the spoil in many places will support an excellent growth without adding N is attributed to the N supplied by rainfall and biological fixation. On the other hand, Cornwell and Stone (*1968*) said that the N levels in certain anthracite spoils are not critical, at least in black shale spoils.

Cummings et al (*1965*) reported that certain Kentucky spoils have low concentrations of soluble salts and organic matter, abundant Mg, but low exchangeable

Table 1.—Main nutrient contents of some coal-mine spoils

Spoil	pH	N	P	K	Ca	Mg
		pct.	*p.p.m.*		*m.e./100 gm.*	
		KENTUCKY—BITUMINOUS				
Shale—black	2.2	—	—	<0.1	1.0	2.3
Shale—gray	5.0	—	—	0.8	5.5	4.8
Shale—gray	6.2	—	—	0.6	8.6	4.2
		INDIANA—BITUMINOUS				
Sandstone	4.0	<0.1	16.6	<0.1	1.8	0.6
Shale—gray	4.7	<0.2	6.6	<0.1	3.5	1.5
Glacial till	7.3	<0.1	15.6	0.1	17.5	3.5
		PENNSYLVANIA—ANTHRACITE				
Breaker refuse	2.9	<0.1	10.7	0.4	3.2	0.3
Sandstone	6.3	0.1	41.9	0.2	2.9	0.3
Glacial till	7.1	<0.1	64.2	0.2	2.4	0.4

Ca. Available K and P are low to adequate. Low to moderate concentrations of available P in extremely acid strata in Kentucky were reported by Berg and May *(1969)*. But Grandt and Lang *(1958)* found available P to be very high and K high in many spoils in Illinois.

May et al. (*1969*) observed that within a small segment of kaolin-mining spoils there are extreme variations in physical characteristics and concentrations of nutrient elements. The spoil may contain from 0 to 100 percent of sand or 0 to 85 percent of clay. Available P and exchangeable K, Ca, and Mg range from 2 to 160, 4 to 110, 6 to 600, and 2 to 600 p.p.m., respectively. Ca and Mg are generally low except where lime material is present. P and K are low in all strata. Mn and Fe are most abundant in the upper strata.

May et al. (*1969*) conducted greenhouse and field fertility experiments on kaolin-mine spoils in Georgia and South Carolina and found that by using 810 pounds of lime, 12 pounds of N, 28 pounds of P, and 20 pounds of K per acre, an excellent cover of grasses and lespedezas was established. Most promising tree species were loblolly pine (*Pinus taeda* L.), Virginia pine (*Pinus virginiana* Mill.), sycamore (*Platanus occidentalis* L.), sawtooth oak (*Quercus accutissima* Carr.), and black alder (*Alnus glutinosa* L.) Gaertn.). It was observed that initial growth was poor and foliar symptoms of nutrient deficiencies were very evident when N and P were not applied at time of planting. Lime and K did not produce a measurable response the first year. Without fertilization, even first-year mortality was high.

Troth (*1971*) studied the concentration of several essential elements in foliage of young sycamore, loblolly pine, and slash pine (*Pinus elliottii* Engelm.) after these trees had received a variety of N, P, and K fertilizer treatments. It was suggested that application of N, P, and K each improved early growth of slash pine where spoil nutrient levels were low. The best growth of sycamore and loblolly pine was associated with N concentrations of 1.6 and 1.4 percent, respectively, in September foliage. Evidently on many sites P and K do not limit tree survival and growth in the early stages.

Certain reports show that in applying fertilizers on strip-mined lands, one is not free from the risk of reducing germination or tree survival.

A study by Thomas *(1966)* suggested that survival of tree species was generally better on unfertilized plots than on fertilized plots and that the best height growth was obtained where N-P-K or N-P-K + Ca was applied.

Bengtson et al. (*1969*) conducted greenhouse experiments in northeastern Alabama, using spoils as media for seeding loblolly pine. They found that the seedlings responded dramatically to complete fertilizer and that the response was enhanced when microbial inoculum of fresh pine duff was added. N and P were found to be the only inorganic nutrients (macro or micro) limiting pine growth.

A further evaluation was made of the effects of concentrated superphosphate and several N-P fertilizer mixtures applied at time of seeding. Concentrated superphosphate, 50 pounds P per acre, when broadcast with the seed on the spoil surface, had no significant effect on germination or early seedling growth. On the other hand, the application of uncoated urea and diamonium phosphate greatly reduced germination even at the rate of 50 pounds N per acre. At this rate sulfur-coated urea ammonium polyphosphate, monoammonium phosphate, ammonium nitrate, and ammonium nitrate phosphate did not reduce germination. All N-P combinations increased early growth of seedlings.

Zarger et al. (*1969*) suggested that nitrogen and phosphorus are the main elements limiting growth of loblolly pine on coal mine spoils in Alabama. Early results showed a significant increase in seedling height when P was applied at 100 pounds per acre. Additional growth and improvement in seedling color and vigor were noted when N was applied with P and N rates of 25 and 100 pounds.

Seeded pines also responded strongly to N-P fertilizer applied at rates of about 100 pounds per acre of each element. Fewer seedlings were killed by frost-heaving when the spoils were fertilized.

Funk and Krause *(1965)* reported on 11 species of trees planted on Ohio strip-mine spoils with pH 5-7. Some were fertilized with pellets containing 28 percent N and 5 percent P_2O_5. After 2 years the fertilized American sycamore, European alder, and yellow-poplar were significantly taller than those that were not fertilized. However, fertilization significantly reduced yellow-poplar survival. Seven other species in the planting were less affected by fertilization. The authors concluded that properly timed applications of appropriate N-P fertilizers to planted or seeded pine or pine-grass mixtures are the key to rapid establishment of productive vegetation on this and similar sites.

Vogel and Berg (*1969*) showed that phosphorus is a limiting element in many coal mine spoils in eastern Kentucky for the early growth of direct-seeded black locust (*Robinia pseudoaccacia* L.). By fertilizing with 44 pounds per acre of P, the first year's height of seedlings was increased fourfold, and higher P rates produced even greater growth. Adding N with the P also caused some additional increase in height. Warm-season herbaceous species seeded with the locust were less competitive with the locust seedlings than were cool-season species.

Micronutrients

The status of micronutrients in spoil materials has been reported by numerous workers. However, they were studies primarily in connection with spoils of high acidity and phytotoxicity. Barnhisel and Massey (*1969*) pointed out that contents of available Fe, Mn, and Zn in eastern Kentucky spoils approach toxic levels and pose a serious problem in the establishment of vegetation. Berg and Vogel (*1968*) reported the occurrence of Mn toxicity on six legumes grown in 46 acid strip-mine spoils from Kentucky. Toxicity was characterized by a distinct paling (chlorosis) on the leaf margins, which was readily seen on young leaves of all the species except Kobe lespedeza (*Lespedeza striate*) (Thunb.) H. & A.). It was pointed out that spoil pH was useful in prediction of Mn toxicity on these legumes and that the water-soluble Mn extracted from the spoil was not.

Cornwell and Stone (*1969*) studied the availability of plant nutrients for five spoil types in the Anthracite Region of Pennsylvania. Eleven elements, including certain micronutrients, were determined. It was observed that foliar concentrations of all elements except Cu differed significantly among spoil types. Gray birch (*Betula populifolia* Marsh.) accumulated Zn to 400 p.p.m. and Mn to 1,500 p.p.m. without evidence of Zn, Mn, B or Al toxicity. Gray birch is exceptionally tolerant to acidity and to high concentration of these elements.

LIME—RATES AND RESPONSES

Acidity and phytotoxicity are probably the major causes of mortality or poor survival and growth of vegetation. Toxic conditions are due primarily to high concentrations of sulfur present in pyritic shales and rejected coal. Fortunately, except for coal-breaker refuse, toxic strip-mine spoils are not widespread. The applications of lime or lime materials would alleviate most exceptional cases.

Lime and lime materials are the oldest and the cheapest soil amendments. The benefits of lime in agriculture and in intensively managed forest has been adequately documented in scientific literature.

Lime has many functions in soil. It is used primarily to adjust the base saturation on the exchangeable complex of soil colloids, neutralizing the excess acidity and inhibiting the availability of elements present at toxic concentrations. It supplies the elemental Ca and Mg, the latter present in dolomitic limestone. Changes in soil acidity, brought about by liming the spoil, affect the availability of P and of micronutrients in the soil and create a better environment for microorganism activity. Lime is naturally the most logical amendment to be added to coal-mine spoils, especially those of extremely low reactions, if the establishment of suitable vegetation for forest, pasture, lawn, or golf green is to be accomplished.

Grandt and Lang (*1958*), while studying the neutralization of acidity of certain spoils in Illinois, found that some spoils required 40 to 70 tons of limestone per acre to bring the pH of the yellow shale spoils up to and above neutrality.

Tyner et al. (*1948*) and Tyner and Smith (*1945*) reported that 5.0 tons per acre of $CaCO_3$ added to strongly acid spoils in West Virginia was all that was necessary to establish legumes and grasses on this media. However, on certain spoils the acidity reverted to toxic levels (pH 3.0) within 60 days.

Ramsey (*1970*) reported an excellent stand of grass on highly acidic bituminous coal-breaker refuse after adding and incorporating agricultural lime equivalent to 40 tons per acre along with 1,500 pounds per acre of 6–24–24 fertilizer.

There is recent evidence that lime is an essential amendment in the establishment and improved growth of tree seedlings. Plass (*1969*) concluded from greenhouse trials that liming extremely acid strip-mine spoils at the rate of 5.0 tons per acre-foot significantly increased the growth of pine seedlings. Apparently growth rate may be related to the reduction in concentration of metallic ions of Mn, Fe, Cu, and Zn.

In the Anthracite Region of Pennsylvania, lime was applied at the rate of 2.5 and 5.0 tons per acre to coal-breaker refuse, and crownvetch (*Coronilla varia*, L.), red pine (*Pinus resinosa*, Ait.), and Japanese larch (*Larix leptolepis*, Sieb and Zucc, Gord.) were planted. It was found that lime applications were essential for adequate survival and establishment of crownvetch (*Czapowskyj et al. 1968*) and both forest species.

Since the question arose as to the duration of lime effect, it was decided to study this aspect also. It was found that the lime brought the surface layer—0 to 3 inches—to near neutral pH within a year. This surface layer was still neutral 7 years after liming. The effects of lime were detectable to a depth of 9 to 12 inches only about 6 years after lime application, and the lower liming rate—2.5 tons per acre—was as beneficial as the higher rate—5.0 tons per acre (*Czapowskyj and Sowa 1972*). Evidently 2.5 tons is adequate to neutralize the refuse to establish vegetation.

CONCLUSIONS

In the reclamation of strip-mine spoils for the establishment of forest as related to natural fertility and the responses to fertilization, the following generalizations can be made:

- Establishment of a forest, as in the past, will remain the major reclamation practice of strip-mined lands.
- Establishment of natural vegetation is a slow process, and tree plantings and seeding are the major forest-establishing practices.
- Most strip-mine spoils are not hostile to planted trees. Areas of extreme acidity and acid-related phytotoxicities are not widespread except on coal-breaker refuse.

- Nearly all essential nutrients are present in most of the spoils. Their concentrations vary, depending on the lithology and the weathering rate.
- Strip-mine spoils are practically devoid of organic matter, the major nutrient supplier, especially N.
- Nitrogen and phosphorus are the main elements deficient for plant growth. Magnesium and potassium content is usually adequate.
- Supply of micronutrient Mn, Zn, Cu, and S range from toxic levels in extremely acid spoils to adequate in moderately acid spoils.
- Plantations fertilized with N, P, and K fertilizers on kaoline spoils and with N and P on coal-mine spoils—singly or in combinations—show a definite positive response in height growth, vigor, and color.
- The effects of fertilization are not entirely free from the risk of reducing tree survival. It depends on tree species, timing of application, fertilizer formula, and the degree of nutrient release. Slow-release fertilizers have a special place in fertilizing surface-mined lands.
- Liming of extremely acid spoils to supply elemental Ca, to reduce and alleviate the toxicity of micronutrients and A1 present, has a definite place in forest establishment.

REFERENCES

Barnhisel, R. I., and H. F. Massey.
1969. Chemical, mineralogical and physical properties of eastern Kentucky acid-forming coal spoil materials. Soil Sci. 108: 367-372.

Bengtson, G. W., S. E. Allen, D. A. Mays, and T. G. Zarger.
1969. The use of fertilizers to speed pine establishment on reclaimed coal mine spoil in northeastern Alabama: I. Greenhouse experiments. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Berg, W. A., and W. G. Vogel.
1968. Manganese toxicity of legumes seeded in Kentucky strip-mine spoils. USDA Forest Serv. Res. Pap. NE-119. 12 p., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Berg, W. A., and R. F. May.
1969. Acidity and plant-available phosphorus in strata overlying coal seams. Mining Congr. J. 55 (3): 31-34, illus.

Chapman, A. G.
1967. How strip-land grading affects tree survival and growth. S. Ill. Univ. School Agr. Publ. 29, 34 p., illus.

Cornwell, S. M., and E. L. Stone.
1968. Availability of nitrogen to plants in acid coal mine spoils. Nature 217:768-769.

Cornwell, S. M., and E. L. Stone.
1969. Plant availability of nutrient and toxic elements in anthracite mining spoils. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Cummings, David C., William T. Plass, and Claude E. Gentry.
1965. Chemical and physical properties of spoil banks in eastern Kentucky coal fields. USDA Forest Serv. Res. Pap. CS-17. 12 p. Cent. States Forest Exp. Sta., Columbus, Ohio.

Czapowskyj, Miroslaw M.
1969. Performance of red pine and Japanese larch planted on anthracite coal-breaker refuse. Int. Symp. Ecol. and Reveg. Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Czapowskyj, Miroslaw, M.
1970. Experimental planting of 14 tree species on Pennsylvania's anthracite strip-mine spoils. USDA Forest Serv. Res. Pap. NE-155. 18 p., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Czapowskyj, Miroslaw M., John P. Mikulecky, and Edward A. Sowa.
1968. Response of crownvetch planted on anthracite breaker refuse. USDA Forest Serv. Res. Note NE-78. 7 p., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Czapowskyj, Miroslaw M., and Edward A. Sowa.
1972. Lime retention in anthracite coal breaker refuse. USDA Forest Serv. Res. Note NE-154. 4 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Finn, Raymond F.
1952. The nutrient content of leaves and tree growth as affected by grading on three strip-mined areas. USDA Forest Serv. Sta. Note 70. 2 p., illus. Cent. States Forest Exp. Sta., Columbus, Ohio.

Funk, David T., and Rodney R. Krause.
1965. Fertilizing strip-mine plantings benefits some hardwoods. Tree Planters' Notes 71:21-22.

Grandt, A. F., and A. L. Lang.
1958. Reclaiming Illinois strip coal land with legumes and grasses. Univ. Ill. Agr. Exp. Sta. Bull. 628. 64 p., illus.

Hart, George, and William R. Byrnes.
1960. Trees for strip-mined lands. USDA

Forest Serv. NE. Forest Exp. Sta., Sta. Pap. 136. 36 p., illus. Upper Darby, Pa.

Limstrom, G. A.
1952. Effects of grading strip-mine lands on the early survival and growth of planted trees. USDA Forest Serv. Cent. States Forest Exp. Sta. Tech. Pap. 130. 35 p., illus., Columbus, Ohio.

Limstrom, G. A.
1960. Forestation of strip-mined land in the Central States. USDA Handbook 166, 74 p., illus.

May, Jack T., C. L. Parks, and H. F. Perkins.
1969. Establishment of grasses and tree vegetation on spoil from kaolin strip mining. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

May, J. T., H. H. Johnson, H. F. Perkins, and R. A. McCreery.
1969. Characteristics of spoil material from kaolin strip mining. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Plass, William T.
1969. Pine seedlings respond to liming of acid strip-mine spoil. USDA Forest Serv. Res. Note NE-103. 8 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Ramsey, John P.
1970. Control of acid pollution from coal refuse piles and slurry lagoons. Coal Mine Drainage Res. Symp. 3: 138-143. Coal Ind. Adv. Com. Ohio River Valley Sanit. Comn., Pittsburgh, Pa.

Schramm, J. R.
1966. Plant colonization studies on black wastes from anthracite mining in Pennsylvania. Amer. Phil. Soc. Trans. New Ser. 56(1) Part 1. 194 p.

Stiver, Edward N.
1949. Revegetation of strip coal spoil banks in Indiana. Thesis, Purdue Univ.

Struthers, Paul H.
1960. Forage seedlings help reclaim acres of spoil banks. Ohio Farm and Home Res. 45: 12-13, illus.

Thomas, James Pevey, Jr.
1971. Survival and growth of selected tree species on kaolin mining spoil. Univ. Ga. Spec. Problem Pap. 54 p.

Troth, John L.
1971. Evaluation of movement and effectiveness of lime and fertilizer materials on kaolin spoil sites. Thesis, Univ. Ga. 74 p.

Tyner, E. H., and R. M. Smith.
1945. The reclamation of the strip-mine coal lands of West Virginia with forage species. Soil Sci. Soc. Amer. Proc. 10: 429-436, illus.

Tyner, E. H., R. M. Smith, and S. L. Galpin.
1948. Reclamation of strip-mine areas in West Virginia. J. Amer. Soc. Agron. 40: 313-323, illus.

U. S. Dept. Interior.
1967. Surface mining and our environment. 124 p. Washington, D. C.

Vogel, Willis G., and William A. Berg.
1969. Fertilizer and herbaceous cover influence establishment of direct seeded black locust on coal mine spoils. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Zarger, T. G., G. W. Bengtson, J. C. Allen, and D. A. Mays.
1969. The use of fertilizers to speed pine establishment on reclaimed coal mine spoil in northeastern Alabama: II. Field experiments. Int. Symp. Ecology and Revegetation of Drastically Disturbed Areas. In press. Pa. State Univ., University Park, Pa.

Wilde, S. A.
1961. Comments on tree nutrition and use of fertilizers in forestry practices. J. Forest. 59: 364-368.

Willits, C. O.
1965. Maple sirup producers manual. USDA Agr. Handbk. 134 (rev.), 112 p.

Winch, F. E., Jr., and Morrow, R. R.
1962. Production of maple syrup and other maple products. N. Y. Agr. Exp. Sta. Bull. 974.

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FERTILIZER NEEDS AND TREATMENT RESPONSES FOR WOOD FIBER PRODUCTION: FIELD ASSESSMENT

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ABSTRACT.–Successful use of fertilizers depends on (1) accurate assessment of inherent productivity potential of the site, (2) determination of nutrient status and needs on the site, and (3) accurate prediction of response to increments of fertilizer added. Site potential can be determined by site index or other stand measures, or by soil-site studies. Nutrient status and needs can be assessed by visual symptoms, foliar analysis, or soil analysis. Visual symptoms coupled with foliar analysis have been effective in identifying severe deficiencies, but ability to diagnose needs on better sites or predict response on any site is lacking. Soil analysis has not been developed successfully for diagnosis of needs or responses. Extensive test-plot studies for various sites are needed to provide information for developing foliar or soil-based diagnostic systems.

IT IS EASY to talk in glowing generalities about forest fertilization, to point with pride to the successes of experiments in the South, the Northwest, and Canada, and to give the practising forester visions of highly fertilized supertrees producing wood fiber and profits like some fabled horn of plenty. Alas, the forester must deal not with visions, but with real stands of trees. They are not about to tell him that their mineral nutrition is sub-par and that a good dose of salts would make them perform better. So it is the forester or consulting forest-soils specialist who must ask the questions, do the probing, diagnose whether treatment is advisable, prescribe the treatment, predict the results, and take the credit or blame for what happens.

In the simplest terms, a diagnostic system to assess fertilizer needs for wood-fiber production requires three things:

- A means of assessing inherent growth potential of various sites.
- A means of assessing fertilizer needs versus other limiting growth factors.
- A prediction system for estimating growth response to a particular increment of added fertilizer.

If we can measure the growth or potential growth accurately, *if* we can assess the nutrient status effectively, and *if* we can predict the response to fertilizer treatment, then, and only then, can we analyze whether the economic or other benefits are sufficient to justify the treatment. So the questions are: What is the best way to put such a diagnostic system together for field operation? Do we have the information for diagnostic systems for various species and sites? If not, what are we lacking, and what should we be doing about it?

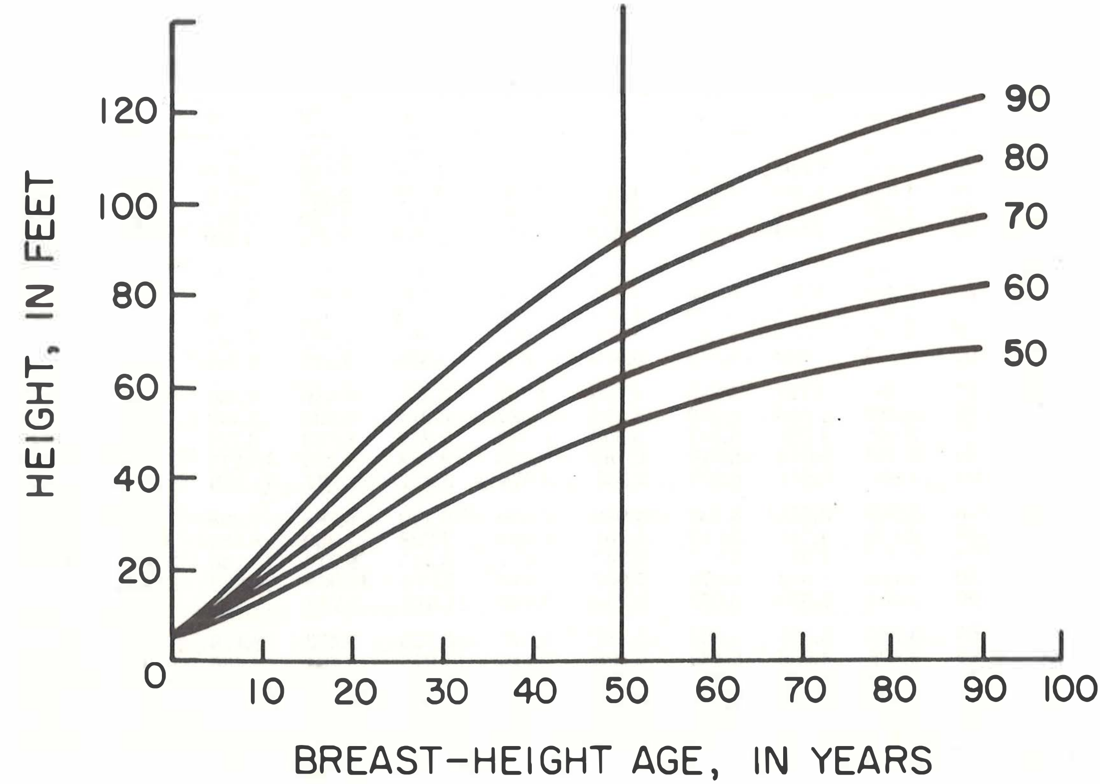
We are fortunate in having several models of diagnostic systems for fertilization that are used in agriculture, and we can draw on considerable information about their good and bad points seen over long periods of time.

TO ASSESS GROWTH POTENTIAL

The first problem, to assess growth potential within a site-classification system, is certainly not new to the forester. It is one of his basic steps in timber management. Anyone growing a longterm crop such as trees needs to know at what rate he is producing or could produce on a particular site. Field observation of poor growth rates often is the first clue that tree nutrition is not adequate.

Growth rates can be measured and evaluated in several ways. (*Gessel et al. 1960*). Determining of the site index for a stand is the most common method of estimating relative productivity for different sites. Site index for a species is the average height of dominant and codominant trees, not suppressed during their

Figure 1.—Site-index curves for eastern white pine in New England (breast-height age 50) based on Frothingham's site-index curves corrected to a breast-height age of 50. (*Leak et al. 1970.*)



growth, at a standard age—usually 50 years in the East. In actual practice, heights of about 10 dominants and codominants are measured, their ages are determined, and average values are computed. Then the age and height intersect is plotted on a standard set of site-index curves such as those for white pine (fig. 1), which are average curves of heights at different ages for the different site-index values (*Leak et al. 1970*). Thus the site-index value for the site can be determined by the plotted position in relation to the standard curve.

For the site-index curves, we generally also have sets of curves or tables giving cubic-volume growth for the site-index levels, as in table 1 (*Leak et al. 1970*). In general we do have good site-index curves and associated cubic-volume productivity tables for most of our species in the Northeast.

Sites with very low-productivity potential can be identified as possible candidates for improvement through fertilization. Unfortunately sites that may respond to fertilization are not limited to low-productivity areas; in fact, absolute response and profitability are often greater on better sites (*Baule and Fricker 1970*), so some other method of identifying such areas is needed.

A 5-year intercept, proposed by Wakeley and Marrero (*1958*) and Ferree et al. (*1958*), is a second method of using height to evaluate growth and site productivity. Average 5-year height growth from breast height upward is determined and can be related to conventional site-index values (fig. 2) (*Richards et al.*

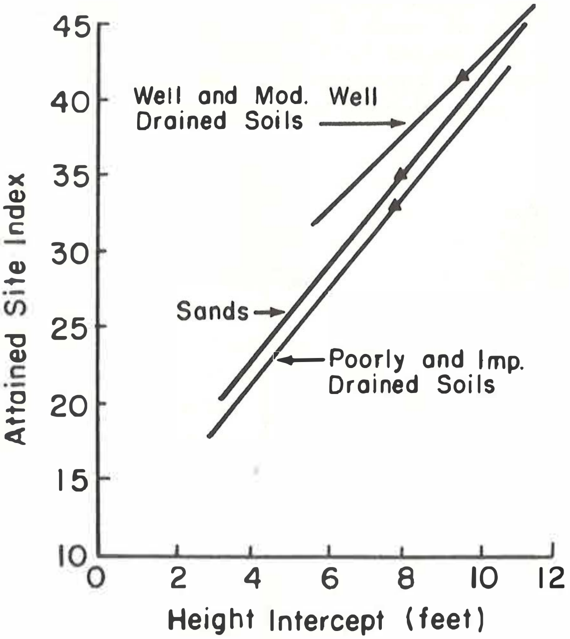
Table 1.—Cubic-foot yields per acre to a 3.0-inch i.b. top in Maine, Massachusetts, and New Hampshire, by age, site index (b.h. page 50), and stocking percent.

[Applies to overstory pine trees 3.0 inches d.b.h. and over.]

Age (yrs)	Site index	Stocking percent									
		40	50	60	70	80	90	100	110	120	130
20	50	761	931	1,098	1,262	1,423	1,583	1,741	1,897	2,052	2,206
	60	892	1,090	1,286	1,477	1,667	1,854	2,039	2,222	2,403	2,583
	70	1,044	1,277	1,506	1,730	1,952	2,171	2,387	2,602	2,814	3,025
	80	1,223	1,496	1,763	2,026	2,286	2,542	2,796	3,047	3,296	3,543
	90	1,432	1,752	2,065	2,373	2,677	2,977	3,274	3,569	3,860	4,149
40	50	1,886	2,307	2,719	3,125	3,526	3,921	4,313	4,700	5,084	5,465
	60	2,209	2,702	3,185	3,660	4,129	4,592	5,051	5,504	5,954	6,400
	70	2,587	3,164	3,730	4,287	4,836	5,378	5,915	6,446	6,973	7,495
	80	3,029	3,075	4,368	5,020	5,663	6,298	6,927	7,549	8,166	8,778
	90	3,548	4,339	5,115	5,879	6,632	7,376	8,112	8,841	9,563	10,280
60	50	2,552	3,121	3,680	4,229	4,771	5,306	5,836	6,360	6,879	7,395
	60	2,989	3,656	4,309	4,953	5,587	6,214	6,834	7,448	8,057	8,660
	70	3,500	4,281	5,047	5,800	6,543	7,277	8,003	8,722	9,435	10,142
	80	4,099	5,014	5,910	6,793	7,663	8,523	9,373	10,215	11,050	11,878
	90	4,800	5,871	6,922	7,955	8,974	9,981	10,977	11,963	12,940	——
80	50	2,968	3,631	4,280	4,919	5,550	6,172	6,788	7,398	8,002	8,602
	60	3,476	4,252	5,013	5,761	6,499	7,228	7,950	8,664	9,372	10,074
	70	4,071	4,980	5,871	6,747	7,611	8,465	9,310	10,146	10,975	11,798
	80	4,768	5,832	6,875	7,902	8,914	9,914	10,903	11,882	12,853	——
	90	5,584	6,830	8,052	9,254	10,439	11,610	12,769	——	——	——
100	50	3,250	3,976	4,687	5,387	6,077	6,758	7,433	8,100	8,762	9,419
	60	3,806	4,656	5,489	6,308	7,116	7,915	8,704	9,486	10,262	11,031
	70	4,458	5,453	6,428	7,388	8,334	9,269	10,194	11,110	12,018	12,918
	80	5,221	6,386	7,528	8,652	9,760	10,855	11,938	——	——	——
	90	6,114	7,478	8,816	10,133	11,431	12,713	——	——	——	——

Source: Leak et al. (*1970*).

Figure 2.—Relation of attained site index to height intercept for 112 plots. (*Richards et al. 1962.*)



1962), or directly to productivity. Wilde (*1964*) proposed an H/I ratio, consisting of the average yearly tree-height growth divided by the average yearly growth of the 5-year intercept, to assess growth patterns (fig. 3). He suggested that a very low value for stands 20 to 40 years old usually indicates a need for fertilization or other site improvement.

These intercept methods are applicable only to trees with identifiable yearly internodes, particularly pines; and site-index curves and associated cubic volume based on them are available for only a few species in the Northeast, red pine being one of them (*Richards et al. 1962*).

Cubic volume production in fully stocked stands can be measured directly with varying degrees of accuracy, depending on whether stem analyses or standard volume tables are used. My own work suggests that a 5-year volume growth period may be a suitable, though certainly more difficult, means of evaluating cubic-volume productivity than site index (*Mader 1963*).

The concept of current site index (*Heiberg and White 1956*) may be an important one for fertilization problems, because the state of nutrition and growth may change considerably over the long-term age span of stand development. Measurement of recent periodic height or volume growth can be used to assess this; however, as yet the normal changes in both of these variables in relation to age are not well documented or available for making comparisons.

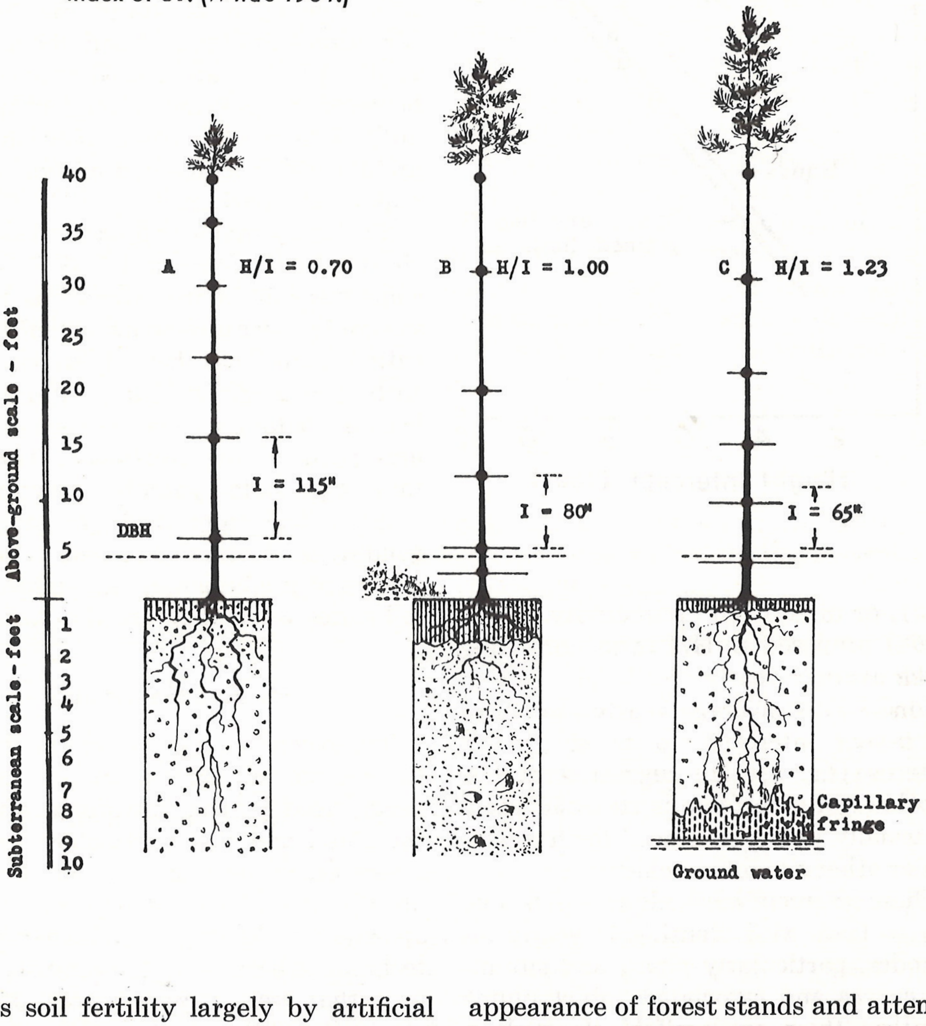
The other major approach to assessing site-productivity potential, as opposed to some measure of tree growth, is through site-factor measurements or soil-classification units that have been correlated with productivity. Such studies have been made for a number of species in various parts of the Northeast. The accuracy of predicted potential growth varies a great deal from study to study, depending on factors measured to serve as a basis of prediction or the uniformity of soil series when they are the basis.

TO ASSESS NEEDS

The second component of the diagnostic system is assessment of fertilizer needs; that is, the nutritional status of the stand and site, particularly whether severe deficiencies are present. Foresters until recently have suffered in the development of diagnostic information and techniques because of the prevailing attitude that trees required small amounts of nutrients, that such supplies could be developed and maintained by careful management of the vegetation, and that fertilization as a general practice was uneconomic.

Toumey and Korstian (*1947*) said, "The amounts of essential mineral constituents in the soil and the amounts used by forest vegetation are such that even soils low in them contain an excess. . . . He (a farmer) maintains and in-

Figure 3.—Growth patterns of red pine plantations imparted by environmental conditions. A, Progressively declining height growth retarded by inadequate supply of water and nutrients in a soil with an infertile substratum. B, Progressively accelerated growth on a fertile soil resulting from a suppression of weeds by the closed canopy. C, Explosively increasing growth caused by a contact of roots with ground water. Horizontal lines mark 5-year growth periods. All three plantations at the age of 30 years exhibited the same site index of 59. (*Wilde 1964.*)



creases soil fertility largely by artificial means, a forester through the medium of his crop of trees." Similar thoughts that physical properties of soils are of paramount importance compared to nutrients are expressed by Lutz and Chandler (*1946*) and by Coile (*1952*).

Historically, most of the cases of successful diagnosis and treatment of nutrient deficiency in forestry resulted from observation of poor growth, vigor, and appearance of forest stands and attempts to find out why the stands were in such debilitated condition. Here we had the emergence of the simplest diagnostic system, one that will function where severe deficiencies prevent normal healthy growth. Identification of the problem as a nutrient deficiency involves one or all of the following:

- Abnormally slow growth compared to other stands or site-index tables.

- Abnormal appearance of foliage, often coupled with twig dieback, etc.
- Lack of other evident problems such as insects or disease.

Fertilizer test plots including all major elements or selected ones based on interpretation of the foliage symptoms are then set up and the trees are observed to see if color, vigor, and growth are improved by any particular nutrient element. Once a deficiency of an element is identified, test plots can be set up to see how much fertilizer is needed to get maximum response on that site.

Unfortunately, this system, though sufficient for solving a particular problem, does not provide a general frame of reference. The nutrient status or potential responses of stands of normal growth and appearance are ignored, even though they may be economically more feasible to fertilize (*Baule and Fricker 1970*). No mechanism for predicting response on other sites is developed, and even the possibility of response to other nutrients after correction of the primary deficiency may be overlooked without extensive well-designed plot tests.

A more general and precise diagnostic system can be developed through foliar analysis or soil analysis, or a combination of the two, the techniques of which are discussed in another paper. The general assumption in foliar analysis is that, below a critical value or range, as the nutrient concentration in the sensitive plant tissue decreases, a progressively more severe deficiency develops, with accompanying greater reductions in growth. Above the critical levels, it is assumed that supplies of the element are sufficient and that no growth response to additions will occur although tissue concentration may increase (*Stelly 1967*).

An idealized diagnostic system based on foliar analysis would operate as follows. We would first measure foliar nutrient concentrations on a wide range of stand productivity and nutrient status to develop a curve of the type in figure 4 to identify the critical levels. Stone *et al.* (*1958*) presented a curve of this type relating foliar K and current site index. Then through a series of fertilizer test plots we would determine the growth response and foliar nutrient change after additions of a particular nutrient at several rates, enabling us to develop a set of curves relating fertilizer application to foliar content (fig. 5).

Figure 4.—Hypothetical curve relating foliar nutrient concentration to forest stand productivity potential.

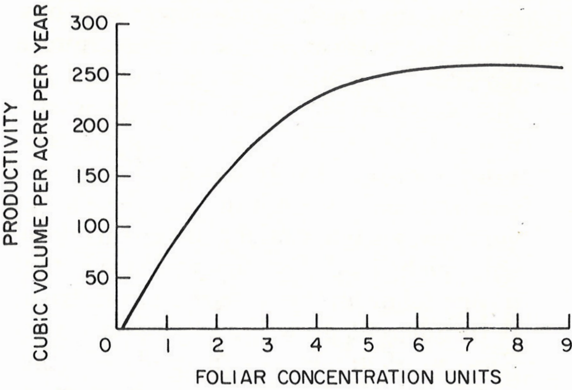
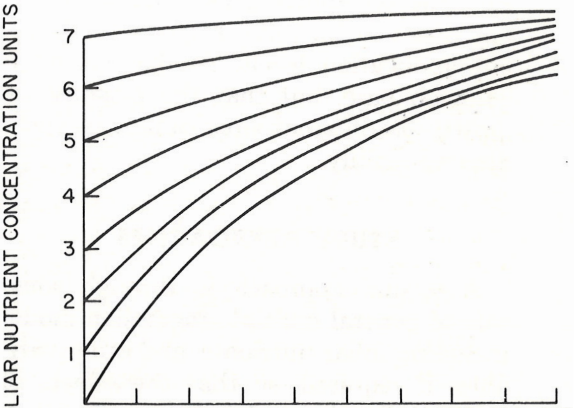


Figure 5.—Hypothetical curves relating fertilizer application rates to foliar nutrient response.



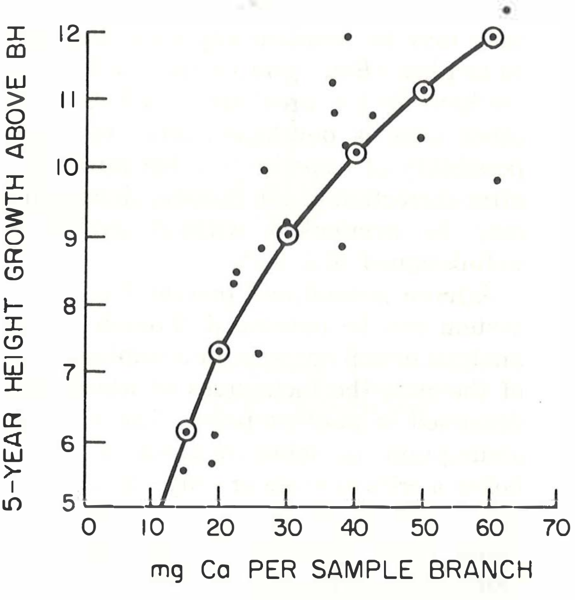
At this point such a theoretical system would become operative. We could analyse foliage from a stand, see where it falls on the productivity curve and how much increase we could achieve from a particular fertilizer application, and decide whether the application is worthwhile. Unfortunately, in reality the relationships are not that simple. Where only one nutrient is limiting and levels are very low, such a straightforward relationship might hold. But the evidence is that at one foliar level of a particular nutrient both inherent growth and response vary because of differences in levels of other nutrients or other factors such as moisture. That is, we are dealing with a multiple limiting factor system rather than a single limiting factor.

We have barely scratched the surface of this problem. One approach to a solution would be to segregate sites into several classes on the basis of foliar nutrient regime similarities or soil type similarities and then study productivity and growth responses of the subgroups. As yet we have not had extensive enough site investigations or fertilizer plot studies to predict the success of this approach; however, it seems likely that such narrowing of the variation of initial units would greatly enhance prediction of response. Mitchell and Chandler's (*1939*) early work on N fertilization of hardwoods in the Northeast indicates that the N-supplying capacity of different sites and the foliar response to different application levels can be put on a common base, but that the response in growth on different sites cannot be coordinated readily.

STUDY APPROACHES

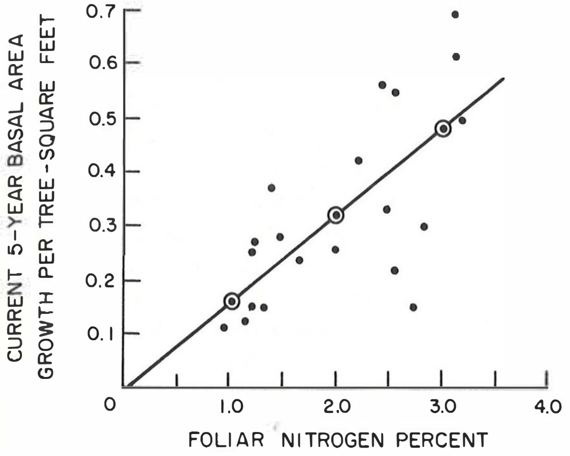
A second approach is through some sort of general multiple-regression model including foliar nutrients, and other variables if required, so that the effects of multiple limiting nutrients or other factors can be taken into account at the same time. The feasibility of this system is uncertain, but it has some promise. We have carried out two studies in which we have made multiple-regression analyses of different growth measures relating to foliar nutrient measures. In one study (*Hoyle and Mader 1964*) 5-year intercept site-index values were found closely related to either total Ca in the needles of the sampled branch or percent Ca in the foliage (fig. 6). Addition of other nutrients increased the effectiveness of prediction only slightly.

Figure 6.—Relationship between mg Ca per sample branch and 5-year height growth intercept above breast height in red pine. Equation: HT = 5.33 + 9.69 Log_{10} mg Ca, $R^2 = 0.73$.



In another study (*Thompson 1969*) in which foliar nutrients of sugar maple were studied, the results showed a significant correlation between N content of leaves and basal-area growth rate (fig. 7), accounting for about 50 percent of the variation in growth. A multiple-regression equation including Ca, K, and

Figure 7.—Relationship between foliar N and basal-area growth rate in sugar maple. Equation: BA = — .00017 + .01616 (% N), $R^2 = 0.49$.



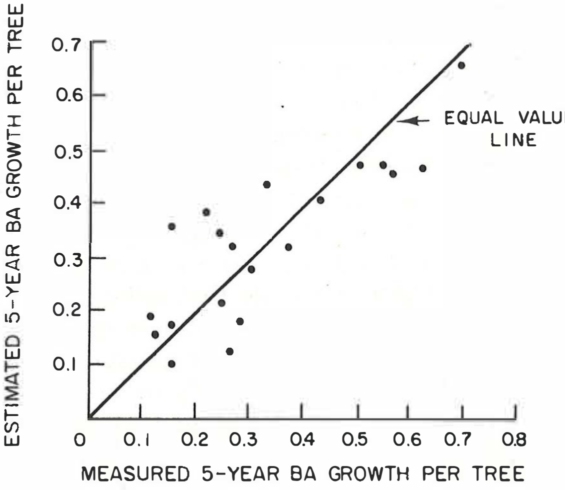
Mg accounted for almost 70 percent of the variation in growth (fig. 8). It appears that a reasonably satisfactory general model may be possible for some species, which, of course, would greatly simplify the diagnostic system. A wide range of studies of foliar nutrient variations from site to site for various species, analyzed by regression studies, and then followed up by fertilizer test-plot studies will be required before we have effective systems; but the studies to date indicate that such foliar diagnostic systems can work. Other parts of the country, particularly the Southeast (*Pritchett and Smith 1971*), are ahead of us in this, and we could learn a great deal from their methods and results.

Soil analysis systems for diagnosing nutritional needs and predicting responses have been the primary foundation of fertilization practice in agriculture. They have a number of advantages over foliar-diagnosis systems, most important that they evaluate the nutrient-supplying medium; it is not necessary to have the crop present to predict needs or responses. The results can be interpreted for a wide variety of species and, if necessary, corrective measures can be applied. Also, the soil is more stable and less affected by other environmental factors.

What are the prospects for soil analysis in forestry? The ideal situation would be a standardized soil-sampling and analysis system, a set of prediction equations for estimating inherent productivity, and an additional set or sets for estimating nutritional status and response. So far soil analyses have not seemed to function as well nor to have been developed to the extent that might have been expected. In many studies in the Northeast and elsewhere we find published foliar criteria for different levels of nutritional status for certain species (*Stone and Leaf 1967*; *Gessel et al. 1960; Wells and Crutchfield 1969*), but in few cases do we find soil criteria. Although soil tests were run, they were found to be not well correlated with growth or responses to fertilization.

Several factors probably contribute to this lack of success: the soil-testing methods may not be the most suitable ones, as suggested by Voigt (*1958*) and the work of White and Leaf (*1964*); the

Figure 8.—Relationship of average measured and predicted basal area per tree growth. Equation BA = .01710 + .0161 (% N) — .0177 (% Ca) — .0371 (% K) + .2766 (% Mg), $R^2 = 0.68$.



mode of expression of nutrients may not be suitable; or the evaluation of nutrient status may be so intertwined with other site factors that these must be taken into account at the same time, or success is precluded.

Site-index values alone probably will not serve as an effective guide to response (*Heilman 1971*). Although a considerable number of site studies have been carried out in the Northeast to relate soil and other factors to productivity, very few of these have identified significant soil-fertility factors, in spite of the fact that various foliar-diagnosis studies strongly suggest that relationships exist. However, these site studies form a valuable base of information about site productivity and the factors controlling or associated with it, a base that can be used in developing soil-based diagnostic systems for fertilization.

The problems of developing soil-based diagnostic systems seem to be much farther from solution and to require a much greater input of research as compared to foliar systems, but in the long run such systems would probably be preferable. The first problem to be faced is development of soil-testing methods. This will require extensive greenhouse and field tests of fertilizer levels, growth responses, and foliar-nutrient levels to provide a basis of correlating soil-test results with fertility levels and responses on a wide variety of soils, preferably where other environmental factors can be controlled to some extent. After this phase some sort of broad-based field-fertilization and soil-testing experiments will be required to establish response curves for soil groups and fertility levels.

Diagnostic systems combining both foliar and soil analyses are possible, and it is almost inevitable that foliar diagnosis will play a considerable part in the development of soil-testing systems and that foliar analysis is likely to be used as a supplemental or confirming information system. If foliar- or soil-diagnosis systems are refined sufficiently, each may function without the other; but generally feedback from both is essential to improvement of the accuracy and understanding of the factors controlling nutrient availability and response. However, there is no reason why elements of the two systems could not be combined. For instance, we might find that a foliar-deficiency level of K on a sandy, unbuffered soil might require one level of fertilization, a similar foliar level on a heavy texture soil might require a different level of fertilization, and the diagnosis might be better by using the combination of soil and foliar levels than with either separately. As yet we have little experience on which to judge the possibilities or desirabilities of such systems.

THE URGENT NEED

Perhaps the most urgent need in the Northeast is a wide range of fertilizer test plots for our key sites and species. There is no substitute for field tests to accurately determine responses to fertilization. Successful soil-testing and interpretation in agriculture stem from the wide-spread formal and informal testing of rates, kinds, and methods of application and the rapid feedback of this information through extension specialists and agronomists to the soil scientists, resulting in refinement and improvement of the testing system.

Field tests in forestry, to be of much value, require a considerable amount of planning and effort. Some important considerations include:

- Important soil-site types and species.
- Site and stand uniformity.
- Plots large enough (1/10 to 1/5 acre) and buffer strips provided so that treatments are effectively isolated.

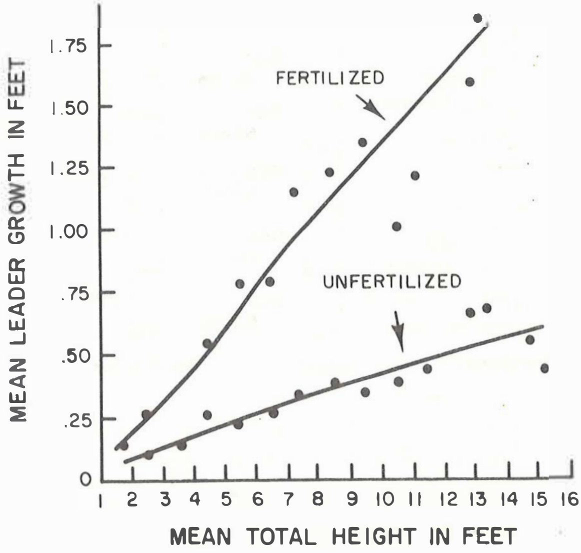
- A good statistical design for the layout to get maximum benefit. Good control and replication are especially desirable. Several application rates to establish response curves, and combinations of nutrients to establish if simple or complex responses occur. Designs that omit certain nutrients from combinations are supposed to be more efficient than testing of all levels of individual nutrients or combinations. Factorial designs in randomized complete blocks have been suggested by Turnbull et al. (*1970*) and response surface designs have been suggested by Clutter (*1968*).

- Accurate evaluation of growth responses.

This last item needs further elucidation. A wide variety of measures have been used by researchers, and the choice of the most suitable one is important. Accuracy and sensitivity of the response measure is of prime importance, but the difficulty and expense involved may also influence choice. Responses can be measured both relative to past growth or in relation to control plots; the latter is preferable because effects of other factors, especially climate, are constant. Height-growth response has been widely used to evaluate fertilization of conifers and is particularly suitable to excurrent tree form. Height poles are good for measuring young trees; Haga altimeters or other types of hypsometers may be accurate enough in some cases; but for tall trees and short periods, transits or other precise optical instruments will be required.

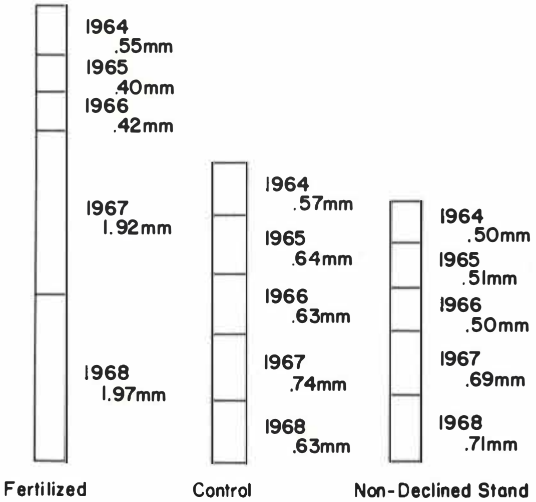
Particularly in younger stands, height growth tends to be related to the size of the tree, so it may be necessary to express this as a percent of previous growth or to segregate height classes to assess response differences. An example of this is shown in figure 9 from Gessel et al. (*1960*). In older stands, height growth tends to slow down, so total height or age of the stand may need to be considered.

Figure 9.—Effect of fertilization on height growth of Douglas-fir is illustrated by these curves. The upper curve shows leader growth of fertilized 15- to 20-year-old trees of various heights during 1953, and the lower curve compares leader growth of unfertilized check trees in the same height classes. (*Gessel, Turnbull, and Tremblay 1960.*)



The main problem in using height growth is to translate the response into cubic volume units; for instance, a 50-percent increase in height growth from site index 60 to 90 in white pine at breast-height age 60 results in an increase in cubic volume from 6,800 to 11,000 cubic feet per acre at full stocking —approximately a 62-percent increase. Rates of volume increase relative to height increase differ with age because height growth usually tapers off sooner than gross volume increment (*Mader 1968*). Conversion estimates can be made by using tree and stand volume tables, but the accuracy is always open to question; so height-growth measurements are good for relative assessment of general magnitude of response, but they leave something to be desired for total volume figures, especially on a short-term basis.

Figure 10.—Mean annual ring width based upon one core from each of six sample sugar maple trees within a plot. (*Mader, Thompson, and Wells 1969.*)



Measurement of diameter or basal-area growth response also has been used widely and successfully. This is necessary in situations where accurate height measurement is not possible, such as in many hardwood types. The growth responses Mitchell and Chandler (*1939*) found were based entirely on diameter growth, and diameter growth was effective in assessing growth responses in slow-growing declined maple stands (fig. 10) (*Mader et al. 1969*). Changes in diameter growth can be measured with a diameter tape or calipers, but these devices are of limited accuracy as ordinarily used and would be suitable only if large responses took place. Dendrometer bands are more accurate and are suitable in most cases, but are tedious to make. Dial-gage dendrometers are good for intensive seasonal-response studies, but are too expensive for general use. Measurement of ring growth on increment cores or tree sections is more precise than the other methods for comparing ring width and is one of the best and simplest methods for evaluating diameter growth rates.

In some cases diameter or basal-area growth is compared on a single-tree basis; for instance, Mitchell and Chandler's (*1939*) data were expressed as an average radial increment in millimeters for dominant and codominant trees in the stand and served as an effective base even though they were dealing with mixed stands and, presumably, a considerable range of tree size where absolute diameter growth values could vary greatly. Extrapolation of such values to other stands of different tree size, age, and density seems very likely to lead to serious errors. Comparisons on a relative basis (*Heilman 1971*) avoid some of these problems.

Again, we have the problem of converting to cubic-volume equivalent growth increases, which require some height data and use of tree-volume tables. Increases in basal area at different sizes, ages, and densities may not be equal on a percentage basis nor have a constant relationship to volume increases, complicating such projections; however, they may be somewhat better and more consistent than height-volume change relationships. Basal-area response is most logically applied on an area basis rather than on a single-tree basis. If data are taken carefully on the whole plot or a good subsample so that basal-area increase comparisons can be made on an area basis, variations in stand density and tree size are less important; and either relative or absolute comparisons are more precise and more safely extrapolated to other stands. Conversion to volume-response estimates can probably be reasonably good with some height data and use of the equations from yield-table studies to compute volumes. These are generally based on basal area, height, and form-class functions.

The current ultimate measure of response in respect to fiber production is actual cubic-volume increase in the stems. If both height and diameter increases are measured carefully, plus form class, quite accurate volume increase for each stem can be calculated from standard tables, and both absolute and relative volume increase of the stand can be determined. Even more precise estimates can be obtained by stem analysis from increment cores or sectioning, and calculating volume increases by sections of the stem for each tree or selected representative sample trees. This latter process is a tedious one and feasible only on small and intensively studied aeras.

To get good volume-increase data at a reasonable cost, breast-height increment-core analysis for several sample trees from each diameter class is probably sufficient. Those data can be used to project diameter increase for all the trees in the stand. Sample-tree height measurements can be used to construct a height-diameter curve, and form class can be determined for different diameter classes. Form-class tree-volume tables or equations can then be used to compute stand volume per plot and the change in volume. The other alternative is to take one or two trees from each diameter class and do a total stem analysis on them, projecting volume and volume change for the remainder of the stand from curves or equations based on the sample trees. In any case good volume response data per acre are not easy to obtain.

The problem of length of response period to fertilization is another important aspect of plot fertilizer trials. This must also be obtained from good experimental plots established for long periods of time. Responses from nutrients that cycle rapidly may be long-lived, as reported for K with red pine by Heiberg et al. (*1964*). Or they may be more short-lived for those that are tied up in large amounts in plant tissues and cycle slowly, as reported for N by Heilman (*1971*). Growth response often does not occur until the second growing season after treatment, may peak for a few years, and then gradually decline.

To summarize the current situation in terms of assessing fertilizer needs for managing foresters in the Northeast, we have very limited tools. Foliar diagnosis can be used to identify some severe deficiencies where good response to fertilization is highly probable; where severe deficiencies do not exist, foliar diagnosis is not very helpful, and we cannot predict either the direction or magnitude of response to fertilizers. Soil analysis or just identification and classification is presently even less helpful than foliar analysis. It will help us identify very infertile sites but will not tell us the need for fertilization or the response to expect.

The most immediate prospects for successful diagnostic systems seem to be with foliar analysis. They probably can be developed faster, easier, and more cheaply than soil-based systems where testing methods present a formidable development task. I think these foliar systems can be developed successfully in the near future with moderate research inputs and cooperative effort in the region.

Perhaps the most urgent need is for a cooperative effort to install well-designed fertilizer test-plot studies over a wide range of sites for several of our key species. This type of program is under way in the Southeast, such as the CRIFF (Cooperative Research in Forest Fertilization) program in Florida (*Pritchett and Smith 1971*). Such fertilizer test-plot programs are essential as a basis for either foliar- or soil-diagnosis systems to obtain data for development of response curves, to segregate different kinds of sites if necessary, and to provide feedback for improvement and development of prototype systems.

As for the future, what is really going to happen? If the companies and agencies interested in wood-fiber production are willing to support and cooperate in the research, the research necessary to put forest fertilization on a sound basis in the Northeast can and will happen over the next 10 to 20 years. I am not fully convinced that companies feel their fiber needs are critical enough now or will be in the near future to make them want to support the research.

In spite of preliminary favorable results from other regions, the economics of fertilization in the Northeast for the future is an open question, and industry is not prone to gamble too much on open questions. However, it is fairly obvious that the universities and federal agencies in forestry research are in a period where problems other than wood-fiber production in the Northeast get highest priority, and the allocation of funds and effort from these sources toward solving the problems is apt to be less, rather than more. Research related to fertilization is apt to be directed more toward health and vigor problems rather than wood-fiber production. Naturally, such studies will produce information about nutrient demands and productivity, but that will not be the main objective, and progress will be slower.

REFERENCES

Baule, H., and C. Fricker.
1970. The fertilizer treatment of forest trees. (Translated by C. L. Whittles). BLV, Munich. 259 p.

Berglund, J. V.
1964. The relationship of site factors to site index and the occurence and severity of sugar maple canker in Pennsylvania. M. S. thesis, Pa. State Univ., University Park, Pa.

Berglund, J. V.
1968. The use of modal soil taxonomic units for the prediction of sugar maple site productivity in southern New York. Ph.D. dissertation, State Univ. N. Y. Coll. Forest., Syracuse.

Clutter, J. L.
1968. Design and analysis of forest fertilization experiments. *In* Forest fertilization . . . theory and practice: 281-288. TVA, Muscle Shoals, Ala.

Coile, T. S.
1952. Soil and the growth of forests. Advance. Agron. 4:329-398. Academic Press, Inc., New York.

Czapowskyj, M., and R. A. Struchtemeyer.
1958. A soil profile can help you predict the growth of white pine. Maine Farm Res. 6 (1): 27-29.

Donahue, R. L.
1940. Forest site quality studies in the Adirondacks. I. Tree growth as related to soil morphology. Cornell Univ. Agr. Exp. Sta. Mem. 229. Ithaca, N. Y.

Farnsworth, C. E., and A. L. Leaf.
1963. An approach to soil-site problems: sugar maple-soil relations in New York. *In* Forest soil relationships in North America: 279-298. Oreg. State Univ. Press, Corvallis.

Farrington, R. A., and M. Howard, Jr.
1958. Soil productivity for hardwood forests of Vermont. N. Amer. Forest Soils Conf. Proc. 1: 102-109. Mich. State Univ. Agr. Exp. Sta., East Lansing.

Ferree, M. J., T. D. Shearer, and E. L. Stone, Jr.
1958. A method of evaluating site quality in young red pine plantations. J. Forest. 56: 328-332.

Finn, R. F.
1953. Mineral content of leaves clue to white oak site quality. USDA Forest Serv. Cent. States Forest Exp. Sta. Tech. Paper 135. 12 p.

Gessel, S. P., K. J. Turnbull, and F. T. Tremblay.
1960. How to fertilize trees and measure response. Nat. Plant Food Inst. 67 p. Washington, D. C.

Haig, I. T.
1929. Colloidal content and related soil factors as indicators of site quality. Yale Univ. School Forest. Bull. 24, 33 p. New Haven, Conn.

Heiberg, S. O., and H. Loewenstein.
1958. Depletion and rehabilitation of a sandy outwash plain in northern New York. N. Amer. Forest Soils Conf. Proc. 1: 172-180. Mich. State Univ. Agr. Exp. Sta., East Lansing.

Heiberg, S. O., H. A. I. Madgwick, and A. L. Leaf.
1964. Some long-time effects of fertilization on red pine plantations. Forest Sci. 10: 17-23.

Heiberg, S. O., and D. P. White.
1956. A site evaluation concept. J. Forest. 54: 7-10.

Heilman, Paul.
1971. Effects of fertilization on Douglas-fir in southwestern Washington. Wash. State Univ. Agr. Exp. Sta. Circ. 535. 23 p. Pullman.

Hicock, H. W., M. F. Morgan, H. J. Lutz, Henry Bull, and H. A. Lunt.
1931. The relation of forest composition and rate of growth to certain soil characters. Conn. Agr. Exp. Sta. Bull. 330: 673-750.

Hoyle, M. C., and D. L. Mader.
1964. Relationships of foliar nutrients to growth of red pine in western Massachusetts. Forest Sci. 10: 337-347.

Husch, B., and W. H. Lyford.
1956. White pine growth and soil relationship in southeastern New Hampshire. Univ. N. H. Agr. Exp. Sta. Tech. Bull. 95. 29 p., Durham.

Leak, W. B., and others.
1970. Yields of eastern white pine in New England related to age, site, and stocking. USDA Forest Serv. Res. Pap. NE-176. 15 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Lewis, R. A.
1967. Site quality evaluation for white ash (*Fraxinus americana* L.). M. S. thesis, Pa. State Univ., University Park.

Lutz, H. J., and R. F. Chandler, Jr.
1946. Forest soils. 514 p. John Wiley and Sons, Inc., New York.

Mader, D. L.
1963. Volume growth measurement—an analysis of function and characteristics in site evaluation. J. Forest. 61: 193-198.

Mader, D. L.
1968. Soil, a guide to forest growth patterns and maximum productivity. Univ. Mass. Agr. Exp. Sta. Bull. 570, Amherst.

Mader, D. L., and D. F. Owen.
1961. Relationships between soil properties and red pine growth in Massachusetts. Soil Sci. Soc. Amer. Proc. 25: 62-65.

Mader, D. L., Bruce W. Thompson, and Jan P. Wells.
1969. Influence of nitrogen on sugar maple decline. Univ. Mass. Agr. Exp. Sta. Bull. 582. 24 p. Amherst.

McClintock, T. F.
1957. Physical properties of the soils of the spruce-fir region of Maine on their relation to site index of red spruce. Doctoral dissertation, Yale Univ., New Haven Conn.

Mitchell, H. L., and R. F. Chandler, Jr.
1939. The nitrogen nutrition and growth of certain deciduous trees of northeastern United States. Black Rock Forest Bull. 11. 94 p.

Paine, L. A.
1960. Nutrient deficiencies and climatic factors causing low volume production and active deterioration in white spruce. Can. Dep. Agr. Forest Biol. Div. Publ. 1067. 29 p. Ottawa.

Phillips, John J.
1966a. Site index of Delaware-Maryland sweetgum stands in relation to soil characteristics. USDA Forest Serv. Res. Note NE-48. 5 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Phillips, John J.
1966b. Site index of yellow poplar related to soil and topography in southern New Jersey. USDA Forest Serv. Res. Pap. NE-52. 10 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Phillips, John J., and M. L. Markley.
1963. Site index of New Jersey sweetgum stands related to soil and water-table characteristics. USDA Forest Serv. Res. Pap. NE-6. 25 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Post, B. W., and R. O. Curtis.
1970. Estimation of northern hardwood site index from soils and topography in the Green Mountains of Vermont. Univ. Vt. Agr. Exp. Sta. Bull. 664. 17 p. Burlington.

Pritchett, W. L., and W. H. Smith.
1970. Fertilizing slash pine on sandy soils of the lower coastal plain. *In* Tree growth and forest soils: 19-41. Oreg. State Univ. Press, Corvallis.

Pritchett, W. L., and W. H. Smith.
1971. Annual report cooperative research in forest fertilization. Univ. Fla. Inst. Food Agr. Sci., Gainesville.

Richards, N. A., R. R. Morrow, and E. L. Stone.
1962. Influence of soil and site conditions on red pine plantations in New York. 1. Stand development and site index curves. Cornell Univ. Agr. Exp. Sta. Bull. 977. 24 p., Ithaca, N. Y.

Stelly, M. (Ed.).
1967. Soil testing and plant analysis, Part II, Plant analysis. Soil Sci. Soc. Amer. Spec. Publ. Ser. 2. Madison, Wis.

Stone, E. L., and A. L. Leaf.
1967. Potassium deficiency and response in young conifer forests in eastern North America. Colloq. Forest Fert. Jyvaskjla, Finland Proc. 1967: 217-229.

Stone, E. L., G. Taylor, N. Richards, and J. DeMent.
1958. Soil and species adaptation: red pine plantations in New York. N. Amer. Forest Soils Conf. Proc. 1: 181-184. Mich. State Univ. Agr. Exp. Sta., E. Lansing.

Stratton, K. G., and R. A. Struchtemeyer.
1968. Evaluation of soil sites for white pine in Maine. Univ. of Maine Agr. Exp. Sta. Tech. Bull. 32. 17 p. Orono.

Thompson, B. W.
1969. Relationships of soil and foliar analyses to decline symptoms and growth rates of sugar maple. M. S. thesis, Univ. Mass., Amherst.

Toumey, J. W., and C. F. Korstian.
1947. Foundations of silviculture upon an ecological basis. 2d. ed., 468 p. John Wiley and Sons, Inc., New York.

Turnbull, K. J., S. P. Gessel, and T. N. Stoate.
1970. Growth response analysis for fertilizer experiments. *In* Tree growth and forest soils: 119-126. Oreg. State Univ. Press, Corvallis.

Voigt, G. K.
1958. Plant-soil factors in chemical soil analysis. N. Amer. Forest Soils Conf. Proc. 1: 31-41. Mich. State Univ. Agr. Exp. Sta., E. Lansing.

Wakeley, P. C., and J. Marrero.
1958. Five-year intercept as site index in southern pine plantations. J. Forest. 56: 332-336.

Ward, W. W., P. W. Fletcher, and M. M. Armstrong.
1965. Site index determination for black cherry. J. Forest. 63: 15-16.

Wells, C. G., and D. M. Crutchfield.
1969. Foliar analysis for predicting loblolly pine response to phosphorus fertilization on wet sites. USDA Forest Serv. Res. Note SE-128. 4 p. SE. Forest Exp. Sta., Asheville, N. C.

White, E. H., and A. L. Leaf.
1964. Soil and tree potassium contents

related to tree growth. I. HNO^{3} — extractable soil K. Soil Sci. 98: 395-402.

Wilde, S. A.
1964. Relationship between the height growth, the 5-year intercept, and site conditions of red pine plantations. J. Forest. 62: 245-248.

Young, H. E.
1954. Forest soils-site index studies in Maine. Soil Sci. Soc. Amer. Proc. 18: 85-87.

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SOIL AND PLANT ANALYSIS TECHNIQUES AS DIAGNOSTIC CRITERIA FOR EVALUATING FERTILIZER NEEDS AND TREATMENT RESPONSE

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ABSTRACT. Use of soil and plant analysis techniques must take into account both stage of development and rate of growth of the tree crop, and the environmental conditions under which the crop exists. The principles and relationships between plant growth, plant nutrients, and soil nutrients are illustrated. Soil and plant analyses have been used both comparatively and mathematically. The precautions necessary in sampling and use of chemical procedures applied to plots and soils are discussed briefly.

THERE IS a voluminous literature dealing with the soil and plant analysis techniques used to evaluate the nutritional status of plants. Here I will place the major emphasis on the principles employed and their application to forest trees, especially those of eastern North America.

Much of the background for studies of forest soils and trees has, as might be expected, come from earlier work in agriculture, and this is especially true for the analytical techniques. Within the past few decades, however, there has been developing within forestry an expertise specifically related to the diagnostic use of soil and plant analyses. That this proficiency has not been developed more is a reflection of the general low level of intensity of forestry practices, particularly those of silviculture.

The use of soil and plant analytical techniques for diagnostic purposes must be viewed in the context of the crop and the environmental conditions under which it exists. A diagnosis involves the interpretation of quantitative information about soils and plants. If the diagnosis is to be meaningful, it must take into account both the stage of development and the rate of growth of the crop either for an individual tree or on a per unit area basis. Too often there is a tendency to consider the application of an analytical technique in isolation. There are, I believe, two main reasons for this: one is the human urge to simplify, to search for a single index or yardstick; the other is the specialization associated with the elaborate and sophisticated techniques that develops in any area of knowledge.

BASIC RELATIONSHIPS

Analyses of soils or plants usually are considered in relation to the size or growth of the plant, and there have been developed certain principles and relationships between two or more of these parameters (soil nutrients, plant nutrients, and plant size or growth) that are useful for diagnostic purposes. Figure 1 illustrates certain simple relationships; thus when a nutrient limits growth, an increase in supply of nutrient is associated with increase in plant absorption and a concomitant increase in plant size. The growth-response curve is curvilinear, as is the increase in nutrient concentration with increase in supply; but when the concentration of nutrient in the plant increases beyond the level of supply at which there is any plant growth increase, then there is said to be *luxury consumption* of the nutrient.

In some instances the nutrient present in limiting amount in the plant may show first a decrease and then an increase in percentage concentration with increase in plant size (fig. 2.). This, termed a *Steenbjerg effect,* is associated usually with certain micronutrients such as copper (*Steenbjerg 1954*). Such an effect can sometimes be observed over a short period of time when there is a large growth response to addition of a major nutrient.

Figure 1.—Increase in white pine seedling dry weight in relation to nitrogen concentration in the plant (dash line) and nitrogen supply in rooting medium (solid line). Source: Mitchell (*1939*).

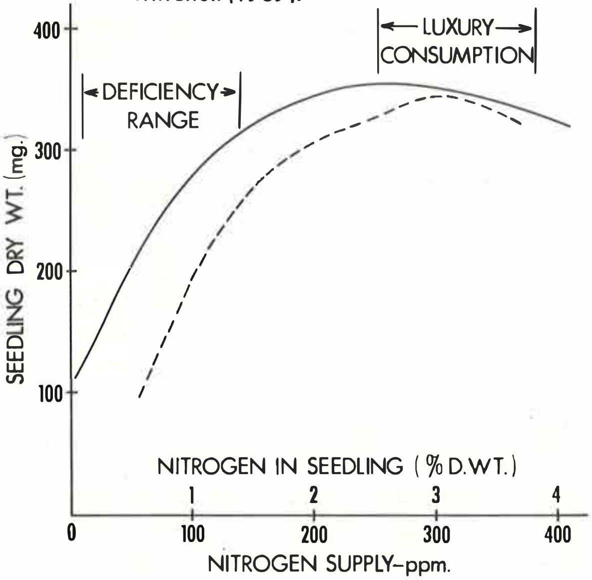
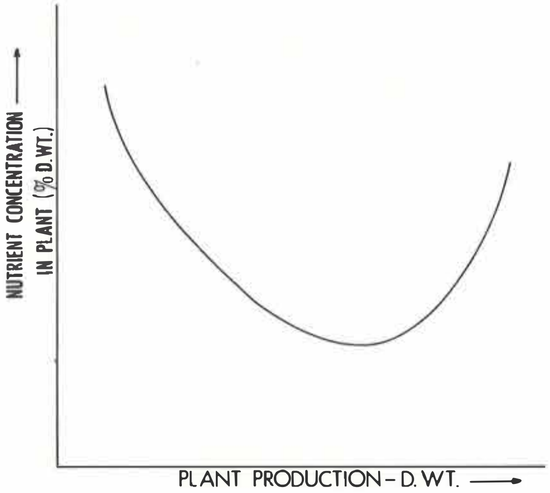


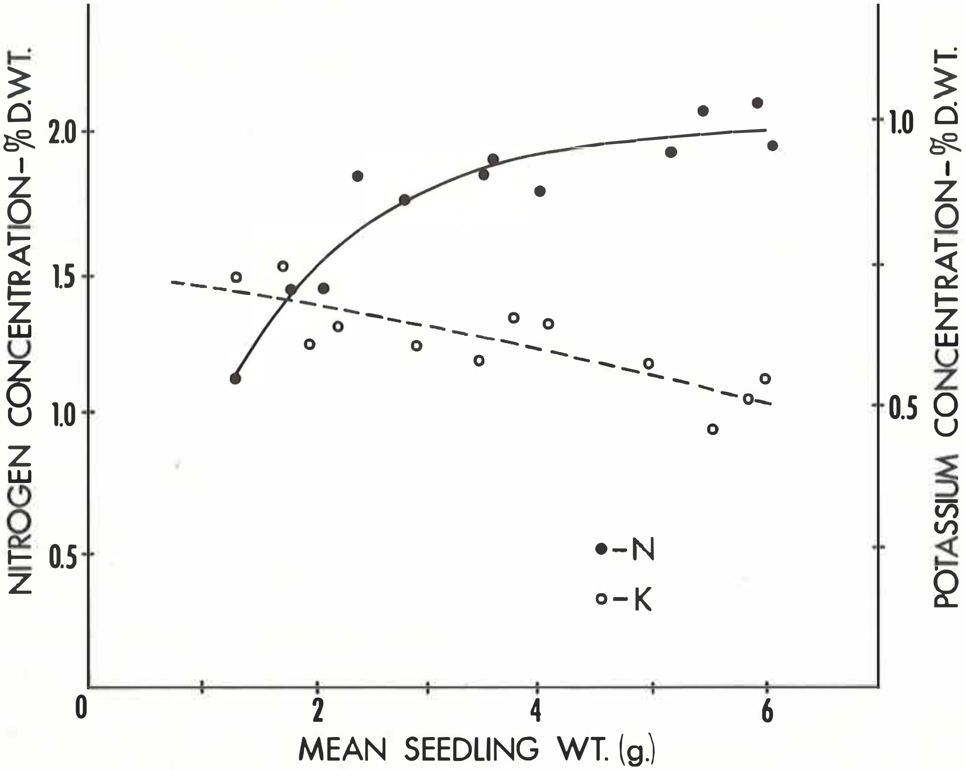
Figure 2.—Relation between nutrient concentration in plant and plant production to illustrate Steenbjerg Effect.



Frequently, when plant analyses are employed, the level of more than one nutrient element is determined. An increase in the supply of a limiting nutrient that results in increased growth may result in a decrease in the concentration of other non-limiting elements (fig. 3). This is termed a *dilution effect.* As the dilution progresses, the level of the nutrient may become low enough that it in turn limits growth, and a stage is reached at which the increase in supply of one nutrient may induce a deficiency of another element.

Generally, when plant analyses are undertaken for diagnostic purposes, only a

Figure 3.—Relationships between foliar nitrogen and potassium concentrations and associated mean seedling dry weights. 2 + 0 white spruce. Source: Armson (*1968*).



portion of the plant is sampled, and the level of the nutrient is expressed as a concentration (dry-weight basis). This value usually does not reflect the content or uptake, which refers to the absolute amount of the element within the plant or plant organ. It is unfortunate that in much of the literature the terms *concentration, content,* and *uptake* have been used synonymously.

Plant and soil analytical data have been used either diagnostically or as guides to adequate levels in soils and/or plants in two main ways, comparative and mathematical.

Comparative Analyses

Samples from trees or stands that are considered to exhibit satisfactory growth and corresponding samples from the soils in which the trees are growing may be analysed, and the levels of nutrients in these samples have been used as standards to compare other stands of trees and soils. At best, comparative analyses serve to provide ranges of values, and where the comparisons are between individuals of the same species, of the same age, and growing in the same location on the same soil materials, the data may be of value (*Madgwick 1964*), especially where nutritional differences may be related to some aspect of soil use (*Armson 1959; Heiberg and Loewenstein 1958*). The greatest unreliability of comparative values may be expected when values are extrapolated from one growing location to another or from a tree or stand at one stage of development to another of a different age class or stage of development.

Mathematical Relationships

The curvilinear relationships that are often found to exist (fig. 1) between plant growth, nutrient content or concentration in the plant, and nutrient supply from the soil, have been used to detect nutrient deficiencies and also to predict possible growth response. Often, for simplification—and based on the reasoning that over the most deficient part of the curve it approximates a straight line—linear regressions have been widely used.

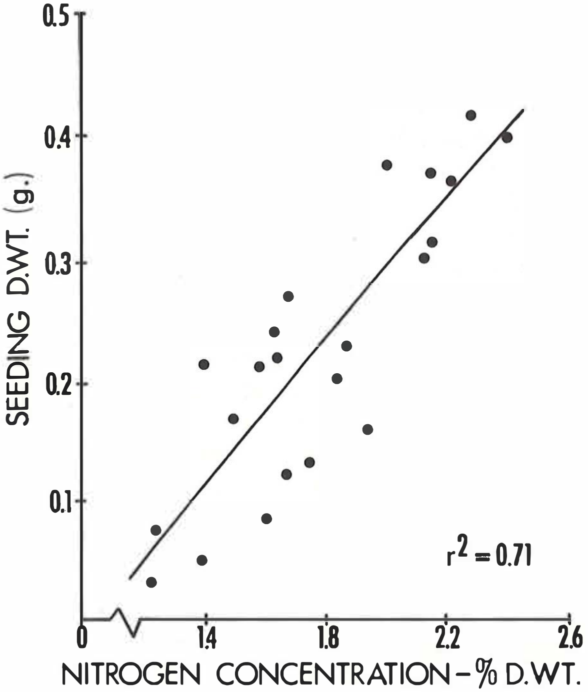
Plant growth—plant nutrient relation. —An example of a simple relationship is shown in figure 4. The seedlings were growing in a nursery seedbed under uniform conditions, and the highly significant linear correlation between growth and N concentration indicates that the supply of N was limiting and variable. A more sophisticated multiple regression was developed by Leyton and Armson (*1955*) and used to determine, tentatively, that N and K were most likely limiting the height and dry-weight growth of the Scots pine (*Pinus sylvestris* L.) trees studied. Later, Leyton (*1956*), used the same technique on a plantation of Japanese larch (*Larix leptolepsis*, Murr.) and determined the following regression:

$$Y/(\text{Ht.} - \text{cm}) = 123.3\ \text{N}\% + 188.7\ \text{K}\% - 180.9$$

S.E. of estimate = ± 41 cm.
and R = 0.916.

Subsequently (*Leyton 1957*) a fertilizer trial using N and K was set out in a similar-aged plantation of the same species a short distance from the one previously studied; and growth responses, primarily to N and to a much lesser degree K, were obtained. Although the quantitative relationship between tree height and foliar concentrations of N and K were substantially different than formerly, the general value of the technique was demonstrated.

Figure 4.—Relationship between mean seedling dry weights of 2 + 0 red pine seedlings and seedling foliar nitrogen concentrations.



Hoyle and Mader (*1964*) undertook a comprehensive study of the relationships of foliar nutrients to growth of red pine (*Pinus resinosa* Ait.) and found that in nearly all instances higher correlation coefficients were achieved by using total foliar nutrient contents rather than percent concentrations. The choice of growth parameters was important because foliar Ca was related to height, foliar K to basal area, and soil moisture to volume.

The interpretation of such mathematical relationships must take into account the fact that the growth parameter chosen may be important, as Hoyle and Mader (*1964*) demonstrated. In addition, other factors both external and internal to the plant may affect the relationship. Supply of soil moisture may vary from one growing season to the next and so alter growth-nutrient relationships. An increase in uptake of a limiting nutrient will often change the balance of other nutrient elements. For example, Leyton (*1957*) found that N/P and N/K ratios were related to growth and suggested that the ratios might have a value for diagnostic purposes.

Another procedure to establish plant growth-soil nutrient relations involves sampling a species population and attempting to correlate some measure of growth with one or more plant nutrient levels, as for example in a study by Stone *et al.* (*1958*).

Plant growth—soil nutrient relations. Attempts to relate plant growth to soil-nutrient analyses have been generally less productive in terms of diagnostic use than those employing plant-growth/plant-nutrient values. There are two prime reasons for this. One is the difficulty in determining meaningful values for availability of a particular nutrient to a plant; thus any method of extracting an element from the soil is arbitrary and its applicability to a particular tree must be previously established. Many, if not all, chemical extractions will give different values, depending on the soil properties.

The second reason is the variability in the distribution of tree roots. For tree nurseries where the plow layer is relatively homogeneous and is also the prime zone for rooting, the use of soil analyses is most useful. In forest soils where there is not only considerable variety between the major horizons (O, A, B, C), but also often within horizons of a profile, and also major differences in rooting intensity within the soil profile, adequate sampling techniques have yet to be established. Leaf and Madgwick (*1960*) have also stressed that results of soil analyses for forest soils must be expressed on a soil volume basis, and for this to be done, bulk density and stoniness must be measured.

In eastern North America, the major attempts to relate soil nutrient levels to plant growth have been in the Northeast, where soil K and red pine growth have received attention, and the Southeast, where soil P has been studied. For red pine, White and Leaf (*1964, 1965*) found that none of the extraction values for potassium were significantly related to tree height when *only the solum was sampled,* but that nitric acid extractable K, from materials towards the bottom of the solum and just below it, was highly correlated with total tree height. Pritchett and Llewellyn (*1966*) studied the response of slash pine (*Pinus elliottii* Engelm. var. *elliottii*) to phosphate additions in sandy soil and, although there was a growth response to fertilizer addition, total soil P values were not correlated with increase in growth and ammonium acetate extractable P values were negatively correlated with tree height growth the third year following treatment.

Certain studies have involved the sampling of a species over a geographic range and making graphical or mathematical comparisons of the variation in growth with various soil properties. Wilde *et al.* (*1964*) and De Ment and Stone (*1968*) have used this technique for red pine plantations. Such studies have value in the management of a species in the area in which they are conducted, but must be used with caution when applied to other areas.

Plant nutrient—soil nutrient relations. —In certain instances, relationships between plant nutrient and soil nutrient levels have been established. Walker (*1955*), for example, demonstrated that strong correlations existed between exchangeable K levels in the soil and K concentrations in the foliage of white pine (*Pinus strobus* L.), choke cherry (*Prunus virginiana* L.) and certain herbaceous species in New York. One of the objectives in determining such correlations, particularly for native vegetation, is to develop a useful diagnostic technique for selecting tree species for planting.

Thus, if white pine is known to be susceptible to K deficiency, and it can be established that some commonly occurring native plant exhibits a relationship between soil K supply and plant K supply over the range of deficiency to nondeficiency in white pine, then sampling of the native plant will provide prior information useful in making a planting decision for the pine. Obviously, this application suffers from the limitations related to soil heterogeneity, rooting distributions, and plant-sampling variation. Often no clear-cut relationships exist; Gagnon *et al.* (*1958*) found no relation between the levels of nutrients in a number of species of lesser vegetation and nutrient content of the humus, although the levels in the humus (H) horizons did show a consistent increase with site class.

Our information and understanding of soil-plant nutrient relations is ultimately based on experimental studies in which one or more species are subjected to fertilizer additions on different soils. Usually, only stands of uniform density are considered, yet in natural stands where the information is most likely to be applied, stand density is often quite variable. Further, even in stands such as plantations, which may be initially of uniform density, there is inevitably a change in density as the trees develop. Surprisingly then, diagnostic studies in which variations in stand density are employed are uncommon.

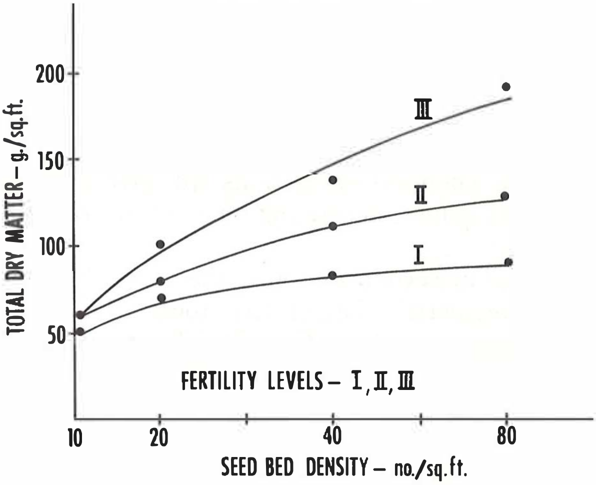
In a study of white spruce (*Picea glauca* (Moench) Voss.) and red pine, Armson (*1968*) showed that seedling density would profoundly affect both individual seedling size and foliar N concentration (table 1). Total dry-matter production per unit area also will reflect nutrient supply and stand density (fig. 5), and thus any interpretation of plant growth and plant N concentration, or a decision to alter production on an area basis by changing nutrient supply levels must take such density factors into consideration.

Table 1.—Mean seedling dry weights and foliar N concentration for 2-year white spruce seedlings grown at four densities (10, 20, 40, and 80 per square foot) and three levels of soil fertility (increasing I → III)

Fertility level	Seedling density—No./sq. ft.							
	10		20		40		80	
	Dry wt.	N	Dry wt.	N	Dry wt.	N	Dry wt.	N
	g.	*pct.*	*g.*	*pct.*	*g.*	*pct.*	*g.*	*pct.*
I	5.2	1.8	3.6	1.9	2.1	1.4	1.3	1.1
II	6.1	1.8	4.0	1.7	2.8	1.7	1.8	1.4
III	6.0	2.0	5.5	1.9	3.5	1.8	2.4	1.8

Source: Armson (*1968*).

Figure 5.—Total dry-matter production in relation to seedbed density and increasing soil-fertility levels—I, II and III 2 + 0 white spruce. Source: Armson (*1968*).



Heiberg *et al.* (*1959*) presented data on the response of red pine plantations to various levels of K fertilizer additions. Height growth of pine at a spacing of 6 x 6 feet, and addition of 50 lb./acre of K fertilizer was slightly greater than that achieved by pine at 4 x 4 spacing and a fertilizer addition of 150 lb./acre. Although individual tree size was greater at the lower density, on a per-acre basis volume growth increased curvilinearly with increase in K supply.

DIAGNOSTIC OBJECTIVES

There are three major objectives, one or more of which may be considered when soil and plant analysis techniques are employed diagnostically. To some degree the analytical techniques may vary with the objective.

(1) *To determine why a tree or stand exhibits poor growth and/or foliage or other organ abnormalities such as discoloration or unusual development*

Most frequently the symptom observed is foliage discoloration, and studies such as those of Swan (*1960, 1966, and 1970*) for conifer seedlings and Hacskaylo *et al.* (*1969*) for deciduous species provide not only pictorial records of visual symptoms but also associated foliar concentrations for several nutrient elements. Sometimes the identification of the nutrient element involved in the abnormal condition is only part of the diagnosis.

For example, in conifers the uptake of N may be highly correlated with increase in growth, and any factor that will reduce the ability of the tree to absorb N will also reduce growth and result in symptoms of deficiency. One of the symptoms of littleleaf disease (*Phytophthora cinnamomi* Rands.) is chlorosis and reduced N concentrations in the foliage of shortleaf (*Pinus echinata* Mill.) and loblolly (*Pinus taeda* L.) pines, yet the cause is the reduction in absorbing roots due to their mortality caused by the disease organism (*Campbell 1954*).

The stage of development of the tree may be important for diagnostic purposes. K deficiency symptoms in red pine, in outwash sandy old-field soils, occur 5 to 6 years after planting (*Heiberg and White 1950*); and typically the foliar discolorations appear in the 1- and 2-year-old foliage in June at the time of main height growth and current-year-needle development. Purpling in new needle tissue in white spruce seedlings, which is a symptom of P deficiency, develops typically about 35 days after germination or in mid-summer when, although overall growth rate may be high, root elongation is normally at a minimum.

(2) *To determine the occurrence of nutrient deficiencies that inhibit growth in a tree or stand.*

These conditions would primarily be in trees for which growth might be restricted by one or more deficiencies, but visual symptoms or abnormal growth would not be apparent. It is in such situations that plant analysis, particularly of foliage, has been most widely used. Frequently the concept of critical concentration has been employed. Critical concentration has been defined as "that concentration of a given form of a specific nutrient within a specific plant part at which plant growth begins to decline" (*Ulrich and Hills 1967*).

Although the diagnostic use of nutrient concentration has found certain uses in agriculture, it must be emphasized that if more than one nutrient limits growth, the estimation of a critical concentration for each one is usually invalidated. Use of plant concentrations can only be applied when the variation in nutrient levels is well known, as for example in black spruce (*Picea mariana* Mill. B.S.P.) and jack pine (*Pinus banksiana* Lamb.) (*Lowry and Avard 1965, 1968a, 1968b*), loblolly pine (*Wells and Metz 1963*), and white and red pine (*White 1954*).

Multiple-regression techniques (*Leyton and Armson 1965; Leyton 1956, 1957; Hoyle and Mader 1964*;, such as have already been described, would appear to have considerable application in the detection of nutrient deficiencies. Factors other than soil fertility may have to be taken into account when plant-analysis techniques are used diagnostically. The moisture-supplying ability of a soil is one of the most common factors to affect tree growth and interact with nutrient levels. Jurgensen and Leaf (*1965*) described a red pine stand in which the depth to water table varied from 0.61 m. to 4.9 m. Growth in terms of height and dry weight increased with increase in depth to the water table. At 26 years of age, the stand was fertilized with K and some 10 years later plant analysis indicated that the foliar K concentrations were related to depth to water table—decreasing concentration associated with decreased depth to water table—but the relationship held only in the oldest (4- and 5-year-old) needles.

The use of plant-tissue analysis in relation to a stand growth parameter such as site index is exemplified by the relationship between foliar K (1-year-old needles) and site index for red pine (*Stone et al. 1958*). Soil analyses have generally been of less utility in prognosis. One of the few areas where soil techniques may be used is in tree nurseries where, on an empirical basis, levels of such elements as P and K may be established for a particular crop.

The principal difficulties in using plant, and particularly soil, analyses for the determination of nutrient deficiencies are those related to sampling procedures.

(3) *To control and regulate the nutrient supply to a tree or crop in order to produce a crop to meet specific objectives of management.*

The specific objectives may be various, ranging from the production of a large vigorous crown for aesthetic purposes, seed production, specific diameter increment for sawlog or veneer utilization, maple sap yield, to maximum cellulose production per acre. For these purposes, plant and soil analytical techniques may be used primarily to monitor the nutrient status rather than detect deficiencies. Nutrient additions may be made in relation not only to growth of the trees but to their stage of development. In such instances the physiological development of the tree or stand becomes an item of major importance. Thus, in order to induce increased female conelet production in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), both the form of N and the time of application are critical (*Ebell 1962*).

An example of patterns of stand growth and development that may have relevance is provided for loblolly pine by Switzer *et al.* (*1968*). Figure 6 illustrates the trend in production of bolewood dry matter and foliage. Note that the current annual increment of the foliage is at a maximum at about 25 years, whereas stem increment peaks at 30 years. However, the stand foliage N content is at maximum at about 15 years. Thus the procession of maximum foliage N content in the stand crown, followed by foliage dry weight and then stem weight, suggests that the photosynthetic activity of the stand may be capable of some manipulation by regulating the N inputs. N additions would have greatest effect if made at the time of inflexion of the curve of N foliage content at stand age of 8 years; this should enhance bolewood increment in the following decade or two. The delayed response of trees to changes in soil fertility has already been demonstrated in red pine by Heiberg *et al.* (*1964*).

In any sophisticated, responsible form of forest management in which considerations of soil fertility and its manipulation are considered, the context in which treatments may be applied takes on importance. Although the objective may be to produce more fibre per acre or more maple sap yield, the stands themselves interact with their environment so that the possible effect of nutrient additions to produce the desired objective not only in the crop but also in other vegetation, and the processes involved in cycling nutrients in the system, should be examined and assessed.

Any application of plant and soil analysis techniques must therefore be extended to other components of the sys-

Figure 6.—Left: current annual increment for stems and foliage of loblolly pine. Right: accumulation of nitrogen in stems and foliage of loblolly pine. Source: Switzer *et at*. (*1968*).

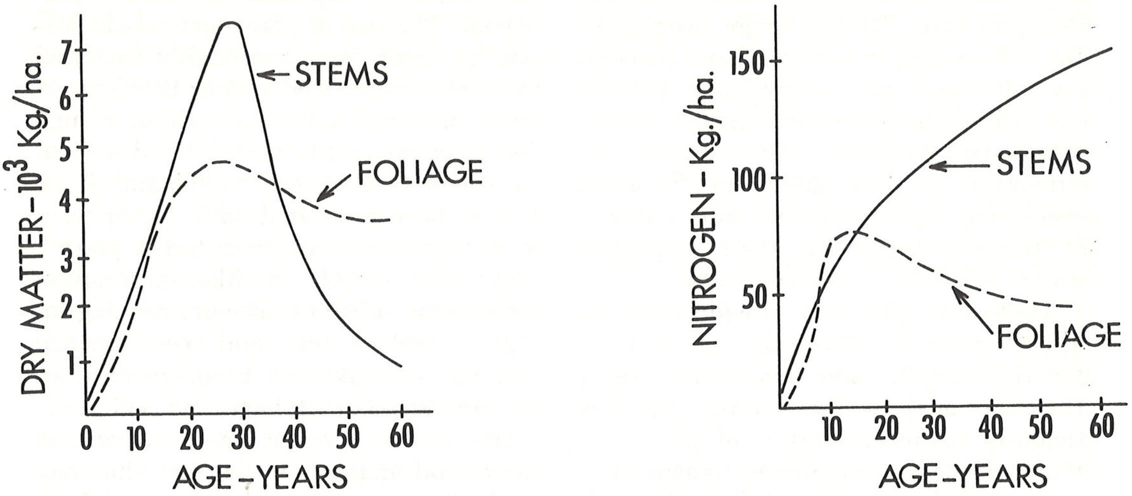
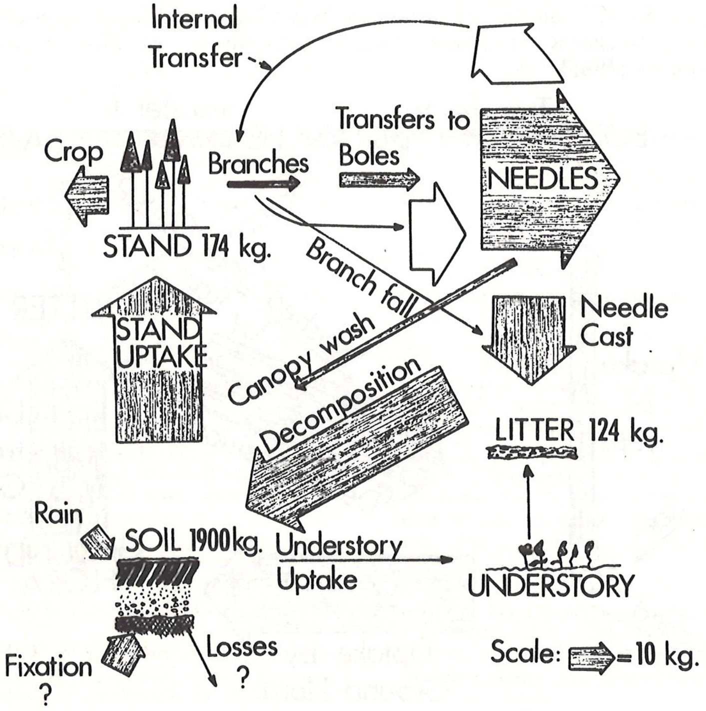


Figure 7.—Annual circulation of nitrogen in a 20-year-old old-field loblolly pine plantation. Thickness of arrow indicates magnitude of flow. Source: Switzer *et al.* (*1968*).



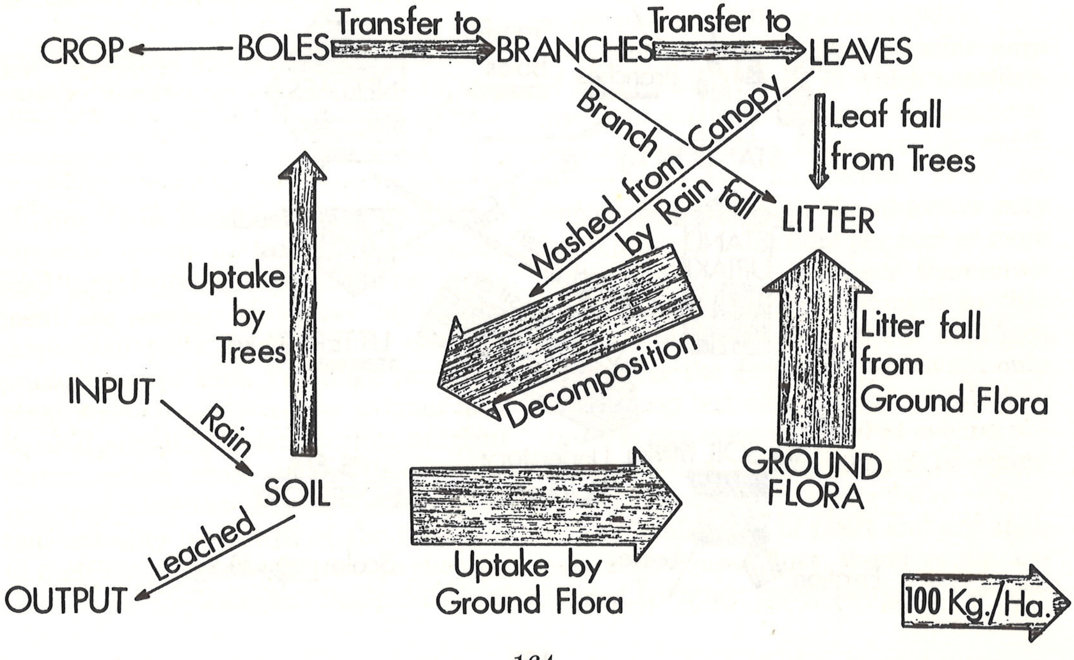
tem. As an example of such an approach, figures 7 and 8 illustrate the circulation of N and K in two conifer stands. In loblolly pine (fig. 7) the major portion of the N is cycling in the stand and its components, and an insignificant portion enters into the understory or lesser vegetation. In the Scots pine, however, the circulation of K is mainly in the lesser vegetation (ground flora); hence inputs of these nutrients to their respective stands will follow different paths.

These examples also provide evidence of the importance that other silvicultural practices might have that could affect the use of analytical techniques, and particularly the interpretation of such data. For example, in figure 8 any treatment to remove the lesser vegetation would block the major cycling of K in the system.

Finally, it must be stressed that the use of soil and plant analytical techniques can produce data of significance for diagnostic use only when the variables are known that affect the data, such as sampling and its associated variables, and the choice of sample treatment, extraction, and chemical procedures employed. The use of plant analysis in forests has been very thoroughly reviewed by Leaf (*1972*). The serious problems in sampling forest soils that exhibit a high degree of variability have been discussed by Mader (*1963*), and McFee and Stone (*1965*) have presented data on variation in nutrient contents in a forest podzol. Metz *et al.* (*1963*) provided information not only on soils but also on sampling foliage in loblolly pine and recommended numbers of plots and numbers of trees for sampling both foliage and soil.

One of the greatest handicaps in the use of soil analyses is the fact that any method of extraction of a nutrient from the soil must necessarily be arbitrary, and whether it approximates the availability to a particular crop tree can be fully established only by rather time-consuming studies. Voigt (*1966*) has shown that P taken up by pitch pine (*Pinus rig-*

Figure 8.—Circulation of potassium in a 47-year-old Scots pine plantation. Thickness of arrow indicates magnitude of flow. Source: Ovington (*1965*).



ida Mill) was related to water-soluble P, and P extracted by 0.002N H_2SO_4, HOAc-NaOAc, and NH_4F-HC1 in the rooting zone of the soil. Only the last three extractions yielded values of P that approximated the tree's annual uptake.

The employment of soil and plant analytical techniques for diagnostic purposes will undoubtedly increase as forest-management practices develop and become refined. The use of such techniques not only involves greater skill and knowledge associated with the analytical procedures themselves, but presents a challenge to professional forestry because the intelligent use of these techniques will demand a more complete knowledge and understanding not only of the trees and forest stands themselves but also of the ecological systems of which they are a part.

LITERATURE CITED

Armson, K. A.
1959. AN EXAMPLE OF THE EFFECT OF PAST USE OF LAND ON FERTILITY LEVELS AND GROWTH OF NORWAY SPRUCE (*PICEA ABIES* L. KARST.). Univ. Toronto Fac. Forest. Tech. Rep. p. 1.

Armson, K. A.
1965. SEASONAL PATTERNS OF NUTRIENT ABSORPTION BY FOREST TREES. *In* FOREST-SOIL RELATIONS IN NORTH AMERICA: 65-76. Ore. State Univ. Press, Corvallis.

Armson, K. A.
1968. THE EFFECTS OF FERTILIZATION AND SEEDBED DENSITY ON THE GROWTH AND NUTRIENT CONTENT OF WHITE SPRUCE AND RED PINE SEEDLINGS. Univ. Toronto Fac. Forest., Tech. Rep. p. 10.

Campbell, W. A., and O. L. Copeland Jr.
1954. LITTLELEAF DISEASE OF SHORTLEAF AND LOBLOLLY PINES. U.S. Dep. Agr. Circ. p. 940.

De Ment, J. A., and E. L. Stone.
1968 INFLUENCE OF SOIL AND SITE ON RED PINE PLANTATIONS IN NEW YORK. II. SOIL TYPE AND PHYSICAL PROPERTIES. Cornell Agr. Exp. Sta. Bull. 1020.

Ebell, L.
1962. GROWTH AND CONE PRODUCTION RESPONSES OF DOUGLAS FIR TO CHEMICAL FERTILIZATION. Can. Dep. Forest. Res. Branch Memo B.C. 62-8.

Gagnon, D, A. Lafond, and L. P. Amiot.
1958. MINERAL NUTRIENT CONTENT OF SOME FOREST PLANT LEAVES AND THE HUMUS LAYER AS RELATED TO SITE QUALITY. Can. J. Bot. 36: 209-220.

Hacskaylo, J., R. F. Finn, and J. P. Vimmerstedt.
1969. DEFICIENCY SYMPTOMS OF SOME FOREST TREES. Ohio Agr. Res. and Develop. Cent. Res. Bull. 1015.

Heiberg, S. O., and D. P. White.
1950. POTASSIUM DEFICIENCY OF REFORESTED PINE AND SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15: 369-376.

Heiberg, S. O., and H. Loewenstein.
1958. DEPLETION AND REHABILITATION OF A SANDY OUTWASH PLAIN IN NORTHERN NEW YORK. N. Amer. Forest Soils Conf. Proc. 1: 172-180. East Lansing, Mich.

Heiberg, S. O., L. Leyton, and H. Loewenstein.
1959. INFLUENCE OF POTASSIUM FERTILIZER LEVEL ON RED PINE PLANTED AT VARIOUS SPACINGS ON A POTASSIUM DEFICIENT SITE. Forest Sci. 5: 142-153.

Heiberg, S. O., H. A. I. Madgwick, and A. L. Leaf.
1964. SOME LONG-TIME EFFECTS OF FERTILIZATION ON RED PINE PLANTATIONS. Forest Sci. 10: 17-23.

Hoyle, M. C., and D. L. Mader.
1964. RELATIONSHIPS OF FOLIAR NUTRIENTS TO GROWTH OF RED PINE IN WESTERN MASSACHUETTS. Forest Sci. 10: 337-347.

Jurgensen, M. F., and A. L. Leaf.
1965. SOIL MOISTURE-FERTILITY INTERACTIONS RELATED TO GROWTH AND NUTRIENT UPTAKE OF RED PINE. Soil Sci. Soc. Amer. Proc. 29: 294-299.

Leaf, A. L.
1972. PLANT ANALYSIS AS AN AID IN FERTILIZING FORESTS, *In*: Soil Testing and Plant Analysis. Soil Sci. Soc. Amer. Spec. Publ. 2.

Leaf, A. L., and H. A. I. Madgwick.
1960. EVALUATION OF CHEMICAL ANALYSIS OF SOILS AND PLANTS AS AIDS IN INTENSIVE SOIL MANAGEMENT. 5th World Forest Congr. Proc. 1: 554-556.

Leyton, L.
1956. THE RELATIONSHIP BETWEEN THE GROWTH AND MINERAL COMPOSITION OF THE FOLIAGE OF JAPANESE LARCH (*Larix Leptolepis* Murr.) Plant and Soil 7: 167-177.

Leyton, L.
1957. THE RELATIONSHIP BETWEEN THE GROWTH AND MINERAL COMPOSITION OF JAPANESE LARCH. II. EVIDENCE FROM MANURIAL TRIALS. Plant and Soil 9: 31-48.

Leyton, L., and K. A. Armson.
1955. MINERAL COMPOSITION OF THE FOLIAGE IN RELATION TO THE GROWTH OF SCOTS PINE. Forest Sci. 1: 210-218.

Lowry, G. L., and P. M. Avard.
1965. NUTRIENT CONTENT OF BLACK SPRUCE NEEDLES. I. VARIATIONS DUE TO CROWN POSITION AND NEEDLE AGE. Pulp and Pap. Res. Inst. Can. Woodlands Res. Index, 171.

Lowry, G. L., and P. M. Avard.
1968a. NUTRIENT CONTENT OF BLACK SPRUCE NEEDLES. II. VARIATION WITH CROWN CLASS AND CLASS AND RELATIONSHIPS TO GROWTH AND YIELD. Pulp and Pap. Res. Inst. Can. Woodlands Pap. 3.

Lowry, G. L., and P. M. Avard.
1968b. NUTRIENT CONTENT OF BLACK SPRUCE AND JACK PINE NEEDLES. III. SEASONAL VARIATIONS AND RECOMMENDED SAMPLING PROCEDURES. Rep. 10, Woodlands Pulp and Pap. Res. Inst. Can.

Mader, D. L.
1963. Soil variability: a serious problem in soil site studies in the Northeast. Soil Sci. Soc. Amer. Proc. 27: 707-709.

Madgwick, H. A. I.
1964. Variations in the chemical composition of red pine (*Pinus resinosa* Ait.) leaves: a comparison of well-grown and poorly-grown trees. Forestry 37: 87-94.

McFee, W. W., and E. L. Stone.
1965. Quantity, distribution and variability of organic matter and nutrients in a forest podzol in New York. Soil Sci. Soc. Amer. Proc. 29: 432-436.

Metz, L. J., C. G. Wells, and B. F. Swindel.
1966. Sampling soil and foliage in a pine plantation. Soil Sci. Soc. Amer. Proc. 30: 397-399.

Mitchell, H. L.
1939. The growth and nutrition of white pine (*Pinus strobus* L.) seedlings in cultures with varying nitrogen, phosphorus and potassium and calcium. Black Rock Forest. Bull. 9. 135 p.

Ovington, J. D.
1965. Woodlands. English Universities Press, Ltd., London. 154 p., illus.

Pritchett, W. L., and W. R. Llewellyn.
1966. Response of slash pine (*Pinus elliottii* Engelm. var *elliottii*) to phosphorus in sandy soils. Soil Sci. Soc. Amer. Proc. 30: 509-512.

Steenbjerg, F.
1954. Manuring, plant production and the chemical composition of the plant. Plant and Soil 5: 226-242.

Stone, E. L., G. Taylor, N. A. Richards, and J. De Ment.
1958. Soil and species adaptation: red pine plantations in New York. N. Amer. Forest Soils Conf. Proc. 1: 181-184.

Swan, H. S. D.
1960. The mineral nutrition of Canadian pulpwood species. I. The influence of nitrogen, phosphorus, potassium and magnesium deficiencies on the growth and development of white spruce, black spruce, jack pine and western hemlock seedlings grown in a controlled environment. Pulp and Pap. Res. Inst. Can. Tech. Rep. 168.

Swan, H. S. D.
1966. Studies of the mineral nutrition of Canadian pulpwood species. The use of visual symptoms, soil and foliage analyses and soil bio-assays for the determination of the fertilizer requirements of forest soils. Pulp and Pap. Res. Inst. Can. 179. Woodlands Res. Index.

Swan, H. S. D.
1970. Relationship between nutrient supply, growth and nutrient concentrations in the foliage of black spruce and jack pine. Pulp and Pap. Res. Inst. Can. Woodlands pap. 19.

Switzer, G. L., L. E. Nelson, and W. H. Smith.
1968. The mineral cycle in forest stands. *In* Forest fertilization . . . theory and practice: 1-9. TVA, Muscle Shoals, Ala.

Ulrich, A., and F. J. Hills.
1967. Principles and practices of plant analysis. *In* Soil testing and plant analysis. II. Plant analysis. Soil Sci. Soc. Amer. Spec. Pub. 2.

Walker, L. C.
1955. Foliar analysis as a method of indicating potassium-deficient soils for reforestation. Soil Sci. Soc. Amer. Proc. 19: 233-236.

Wells, C. G., and L. J. Metz.
1963. Variation in nutrient content of loblolly pine needles with season, age, soil and position on the crown. Soil Sci. Soc. Amer. Proc. 27: 90-93.

White, D. P.
1954. Variation in nitrogen, phosphorus contents of pine needles with season, crown position and sample treatment. Soil Sci. Soc. Amer. Proc. 12: 326-330.

White, E. H., and A. L. Leaf.
1964. Soil and tree potassium contents related to tree growth. I. HNO^3 EXTRAC. Soil K. Soil Sci. 98: 395-402.

White, E. H., and A. L. Leaf.
1965. Soil and tree potassium contents related to tree growth. II. Tissue K as determined by total tree analysis techniques. Soil Sci. 99: 109-114.

Wilde, S. A., J. G. Iyer, Ch. Tanzer, W. L. Trautmann, K. G. Watterston.
1964. Growth of red pine plantations in relation to fertility of non-phreatic sandy soils. Forest Sci. 10: 463-470.

Voigt, G. K.
1966. Phosphorus uptake in young pitch pine (*Pinus rigida* Mill.). Soil Sci. Soc. Amer. Proc. 30: 403-405.

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EFFECTS OF FOREST FERTILIZATION ON WOOD QUALITY

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ABSTRACT. Recent studies demonstrate an increase in the uniformity of wood as a result of fertilization. An increase in cell-wall thickness of earlywood fibers and a simultaneous thinning of latewood fiber walls were induced in fertilized red pine and Douglas-fir. Wood quality, for the pulp and paper industry, is generally enhanced by such uniformity. Strength properties of pulps produced from fertilized trees are as good as or better than those of pulps from unfertilized trees.

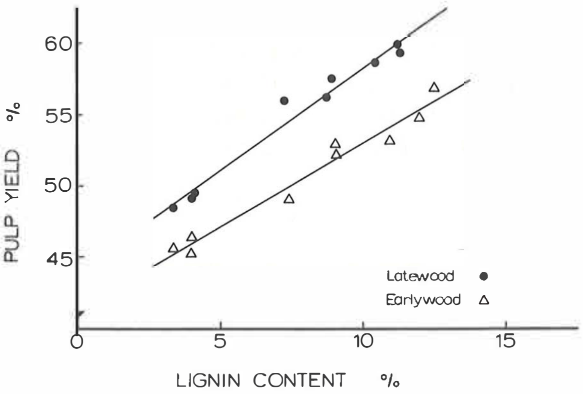
IN A REVIEW of the effects of fertilization on wood quality, Klem (*1968*) concluded that the results of forest-fertilization treatments depend to a great extent upon the condition of the trees before treatment. When differences in species, treatments, and other factors are superimposed on preconditioning, it is not surprising that a spectrum of responses is observed and that apparent inconsistencies are recorded.

It is not our intent to review this response spectrum nor to report on a specific investigation, but we do propose to tie together some recent research results that promise to assist in justifying certain forest fertilization efforts.

QUALITY RELATIONSHIPS: WOOD-PAPER

Wood specific gravity and the generally correlative parameter of mean cell-wall thickness are measures of wood quality that provide excellent predictions of the general suitability of wood as a raw material for papermaking. Obviously wood specific gravity (or wood density) and the yield of pulp per unit *volume of dry wood* are related. More digester capacity is required to produce a given daily tonnage of chemical pulp from wood of low specific gravity than from denser wood. Operating efficiencies are generally higher with wood of high specific gravity.

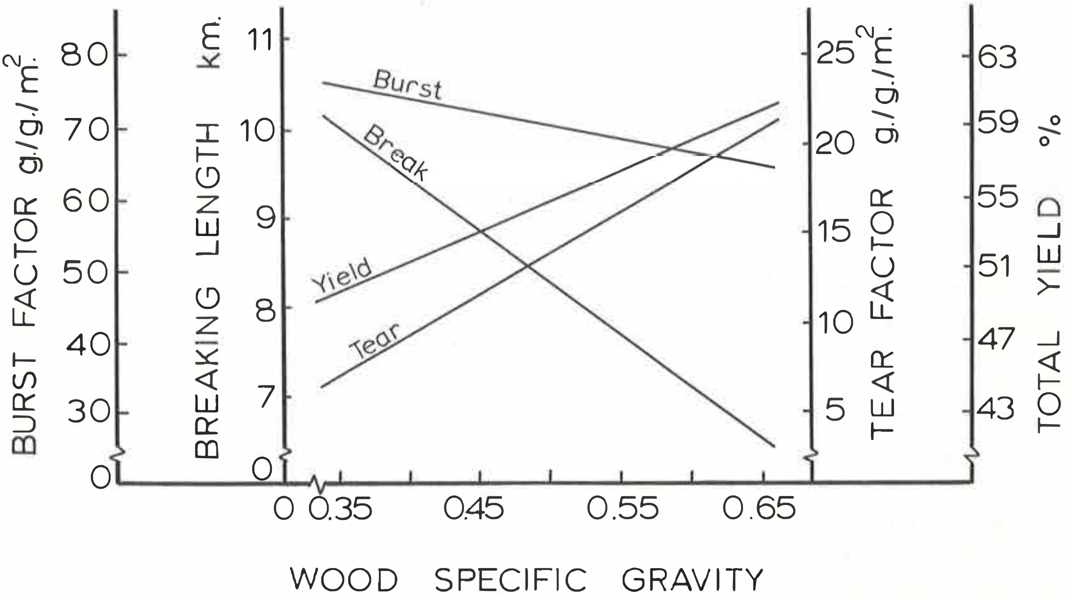
Figure 1.—Regressions of kraft pulp yields from earlywood and latewood (from a single loblolly pine) on lignin contents of the respective pulps. A range of pulp lignin contents was obtained by varying cooking time. Yields are expressed on an extracted wood weight basis. From Gladstone *et al.* (*1970*).



Somewhat more subtle is the emerging positive relationship between specific gravity and chemical pulp yield when yield is calculated on a *dry wood weight basis*. This relationship is particularly evident within a given tree and is probably applicable to those coniferous species that produce distinctive latewood.

A higher kraft pulp yield from loblolly pine latewood, relative to that from earlywood, was recorded by Gladstone *et al.* (*1970*) (fig. 1). Percent of latewood seemed to be the morphological feature that best established the total kraft pulp yield to be expected from a given lot of loblolly pine wood (*Barefoot et al. 1969*). A positive relationship between specific gravity and total yield established in that study (fig. 2) confirmed a well-established positive correlation between percent latewood and specific gravity. The demonstrated superiority of mature pine wood over juvenile wood (juvenile wood has less latewood) with respect to

Figure 2.—The effect of wood specific gravity on the properties of moderately refined kraft pulps prepared from loblolly pine wood. Yield is calculated on a wood weight basis. Adapted from Barefoot *et al.* (*1972*).



weight-based pulp yield supports these observations.

Regressions show the effects of loblolly wood specific gravity on three important strength properties of kraft pulp (fig. 2). Though these are exactly appropriate only for the material from which they were derived, they are indicative of the general relationships for coniferous wood and associated chemical pulps. Note that the measure of resistance to tearing, like yield, is positively related to specific gravity. However, bursting strength and breaking length (a measure of tensile strength) are related inversely to specific gravity, and the technologist is faced with expensive choices if either or both of these latter properties are essential to specific paper products.

In general, wood composed of fibers having the thick cell walls typical of latewood tends to produce high weight-based yields of pulps, while these same thick-walled fibers provide excellent resistance to tearing. However, their tendency to retain their tubular form and thus to minimize surface contact between fibers in a paper web results in lower burst and breaking-length properties than can be achieved with the thin-walled collapsible fibers characteristic of earlywood. Tearing resistance, of course, is lower in the earlywood, as is weight-based yield.

QUALITY RELATIONSHIPS: FERTILIZED-UNFERTILIZED WOOD

An increase in the rate of wood volume production is a desirable and frequent result of forest fertilization. Equally frequent, and often less desirable to fiber-using industries, are changes in the anatomy and anatomy-dependent physical characteristics of wood formed under various treatment regimes.

For example, fertilization often results in a decrease in wood specific gravity due to an increase in the proportions of thin-walled earlywood fibers in a given annual increment and to a concurrent decrease in the thickness of latewood fiber walls.

Such changes in wood quality will result in:

- A substantial loss in pulp yield per unit volume of wood–unfavorable.
- A moderate loss in pulp yield per unit weight of wood—unfavorable.
- A loss in tearing strength accompanied by increases in breaking length and bursting strength–desirable for some products, but not for others.

The net effect of these changes in wood quality must be offset by the value of additional wood volume beyond what is necessary to justify the cost of fertilization.

Other responses have been observed. Fertilization can also produce woods of specific gravities, proportions of latewood, and/or fiber wall thicknesses that are equal to or higher than those of associated unfertilized wood. In any instance, if pulp yields, both volume- and weight-based, and pulp properties, are *not* affected adversely by the treatments, then growth (volume) increases due to fertilization may be accepted at face value.

Several instances where fertilization has resulted in increased wood uniformity or in somewhat favorable pulping characteristics have been described recently. The parallel trends observed in Douglas-fir (*Megraw and Nearn 1972*; *Siddiqui et al. 1972*) *and red pine* (*Siddiqui 1970; Gray 1970*) should be of particular interest to persons involved with commercial forest fertilizer application.

WOOD UNIFORMITY: RED PINE

The red pine (*Pinus resinosa* Ait.) example involves wood formed after relatively slow-growing trees here at the Pack Demonstration Forest were treated with K at the rate of 200 pounds per acre. This treatment, though it resulted in substantial growth increases, was in fact remedial and was designed to overcome an extreme K deficiency. Our interest thus lies primarily in comparing the wood quality responses due to the K treatment with those resulting from the N fertilization of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco.] growing on a quality-3 site.

An examination of some gross wood properties in the course of a pulping study of the fertilized and unfertilized red pine indicated that, though the proportion of latewood was slightly lower in the wood from fertilized trees, there was essentially no difference in specific gravity between these two wood types (*Siddiqui 1970*). Kraft pulp yields, calculated on a weight basis, also remained constant, the mean yield values being 47.8 and 47.7 percent respectively for fertilized and unfertilized wood.

Since specific gravity and yield per unit weight of wood were unaffected by the increased diameter growth produced by fertilization, no effect on pulp yield, weight *or* volume basis, was observed. An examination of the papermaking properties of the fertilized and unfertilized pulps, however, indicated that the treatment *did* alter the characteristics of the wood fibers (table 1).

For clarification: the term *unrefined pulp* describes a mass of fibers essentially as they are when released from the original wood through chemical digestion. *Refining* implies a mechanical treatment of the fiber mass designed to collapse and fibrillate or fray the individual fibers and thus to increase their interfiber bonding potential when formed into a paper sheet.

The interaction of fertilizer treatment and pulp-refining produced results that seem anomalous. Considering that the percentage of latewood decreased somewhat with fertilization, we anticipated that burst factor and breaking length would be higher in fertilized wood than in unfertilized wood, and that the reverse would be true for tearing strength. With refined pulps, breaking length fulfilled this expectation while burst factor and tear were unaffected by fertilization (table 1). The net effect of rapid growth on refined pulp quality was favorable in that breaking length improved while tearing strength did not decrease.

Practically, the properties of unrefined pulps are of lesser significance, however in this instance they do provide insight to related wood and fiber characteristics. Strength properties of the unrefined pulps were not consistent with a decrease in the proportion of thick-walled latewood fibers. Burst factor and breaking length both decreased with fertilization while tearing strength increased, changes that would be expected to accompany an increase in latewood percentage rather than a decrease.

The data suggested that, though the fertilized wood contained more earlywood than its unfertilized counterpart, the walls of fertilized earlywood fibers

Table 1.—Mean strength properties of pulps produced from fertilized and unfertilized red pine wood

Property	Unrefined pulp			Refined pulp		
	Fertilized	Control	F minus C	Fertilized	Control	F minus C
Burst factor	32	44	− 12	70	70	± 0
Breaking length, m	5575	6573	−998	10,022	9538	+484
Tear factor	165	141	+ 24	62	63	− 1

Source: Siddiqui (*1970*).

were thicker than those of the controls. Apparently the thickening of earlywood fiber walls lowered the collapsibility of the unrefined pulps and thus caused a decrease in burst and breaking length. Concurrently, the thicker-walled fibers produced an improvement in tearing strength (table 1). Refining, however, overcame the increased collapse resistance of the fertilized pulps and the resultant strength properties were consistent with observed wood properties.

A detailed examination of the anatomical characteristics of wood taken from the same study plots, but from different trees, supports our explanation (*Gray 1970*). The mean double-wall thickness of earlywood fibers from fertilized material was approximately twice that from unfertilized material (fig. 3). The walls of latewood fibers from fertilized wood were 20 percent *thinner* than controls, however; and as a result the fertilized wood was much more homogeneous with respect to wall thickness than was unfertilized wood.

WOOD UNIFORMITY: DOUGLAS-FIR

A similar trend toward wood uniformity was observed in Douglas-fir that had been fertilized with 300, 150, and 100 pounds per acre of N, P, and K respectively (*Megraw and Nearn 1972*). Wood density profiles developed from X-ray

Figure 3.—Relationship between double-cell-wall thickness of red pine tracheids and distance from pith. All tracheids measured were extracted from stem intervals formed after the date of fertilization treatment. From Gray (*1970*).

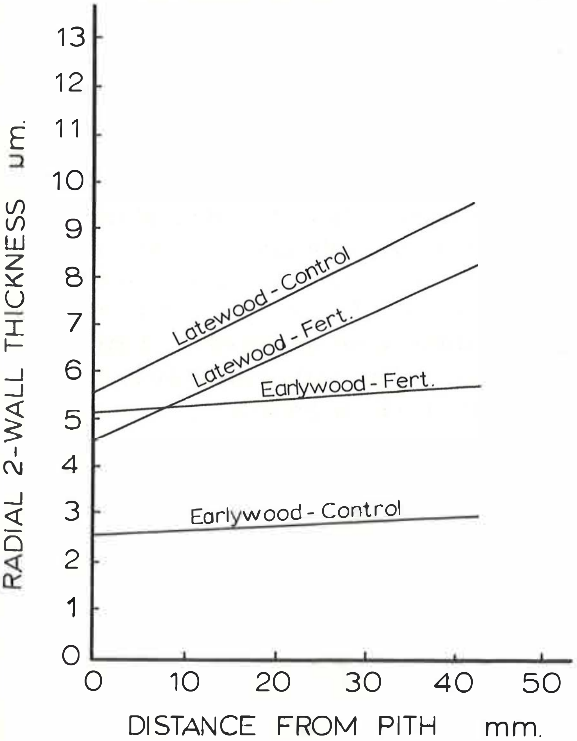
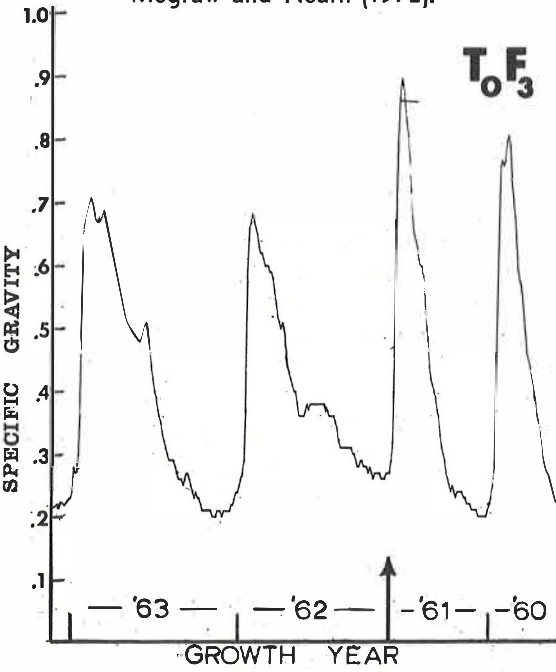


Figure 4.—Within-ring density profile of a Douglas-fir increment core, including two annual increments before and after treatment. T_0 F_3 signifies application of a calibration thinning and a fertilization treatment of 300, 150, and 100 pounds per acre of N, P, and K, respectively, in 1962. From Megraw and Nearn (*1972*).



analysis of increment cores demonstrated that fertilization resulted in increased homogeneity within annual increments. Lower maxima for latewood specific gravity and more wood of intermediate density are evident in figure 4. Composite wood specific gravity was not altered by fertilization, though it was noted that the normal upward trend in specific gravity for 16- to 18-year-old trees was not evident.

An independent but uniquely complementary study of the pulping characteristics of wood from older (45- to 52-year-old) Douglas-fir that had been fertilized with 400 pounds per acre of N reflected similar uniformity changes (*Siddiqui et al. 1972*). During the 7 years immediately following fertilization, a mean volume increase of 74 percent, relative to control trees, was accompanied by a specific gravity decrease of approximately 10 percent. However, the negative impact of this specific gravity decrease on volume-based pulp productivity was halved by an increase of about 2 percent in pulp yield per unit weight of wood.

Contrasts between strength properties of refined pulps from fertilized and unfertilized woods were strikingly similar to those of red pine (tables 1 and 2). Breaking lengths increased with fertilization and, though the specific gravity of fertilized wood was lower, no loss in tearing strength was evident. Collectively, these factors again suggested that fertilization had the effects of: (1) thickening earlywood fiber walls, (2) reducing the thickness of latewood fiber walls, and (3) increasing the proportion of earlywood (decreasing the proportion of latewood), all of which increased wood uniformity.

Limited confirmation of these trends was gained by measuring cell-wall components on electron micrographs. The mean secondary wall thickness of earlywood fibers increased approximately 20 percent in response to fertilization while the same characteristic in latewood decreased 6 percent. A net increase in the relative amount of cellulose-rich secondary wall present in the fertilized wood probably contributed to the higher pulp yield from that wood. Additional and more comprehensive confirmation is provided by the work of Megraw and Nearn (*1972*).

CONCLUSION

The trends toward wood uniformity are decidedly favorable for wood quality vis-a-vis the pulp and paper industry. Losses in specific gravity and concomitant losses in pulp yield per unit volume of wood can be minimized or offset by increases in the thickness of earlywood fiber walls. This same fertilizer-induced thickening process can also stabilize or increase pulp yield per unit weight of wood.

In both the red pine and Douglas-fir instances, tearing strength and burst factor levels were maintained while improvements in breaking length were realized as a result of fertilization. Fiber and paper qualities were improved by fertilization, coincident with substantial improvement in volume growth.

Table 2.—Mean strength properties of refined pulps produced from fertilized and unfertilized Douglas-fir wood

Property	Fertilized	Control	F minus C
Burst factor	75	75	± 0
Breaking length, m	10,430	10,105	+325
Tear factor	111	108	+ 3

Source: Siddiqui *et al.* (*1972*).

Though this uniformity trend is certainly not universal, the identification of species, site, and treatment combinations to which it does apply is desirable.

REFERENCES

Barefoot, A. C., R. G. Hitchings, E. H. Wilson, and R. C. Kellison.
1972. RELATED ASPECTS OF THE MORPHOLOGY OF LOBLOLLY PINE AND PAPERMAKING. USDA Forest Prod. Lab. Symp. Effect Growth Acceleration on Properties of Wood Proc.: Madison, Wis.

Gladstone, W. T., A. C. Barefoot, and B. J. Zobel.
1970. KRAFT PULPING OF EARLYWOOD AND LATEWOOD FROM LOBLOLLY PINE. Forest Prod. 20(2) :17-24.

Gray, R. L.
1970. EFFECTS OF POTASSIUM FERTILIZER ON THE WOOD DENSITY AND RELATED ANATOMICAL CHARACTERISTICS OF RED PINE. M. S. thesis, State Univ. N.Y. Coll. Forest., Syracuse, 123 pp.

Klem, G. S.
1968. QUALITY OF WOOD FROM FERTILIZED FORESTS. TAPPI 51(4) : 99A-103A.

Megraw, R. A., and W. T. Nearn.
1972. DETAILED DBH DENSITY PROFILES OF SEVERAL TREES FROM DOUGLAS-FIR FERTILIZER/THINNING PLOTS. USDA Forest Prod. Lab. Symp. Effect Growth Acceleration on Properties of Wood Proc.: Madison, Wis.

Siddiqui, K. M.
1970. SOME EFFECTS OF POTASSIUM FERTILIZATION ON THE PROPERTIES OF WOOD AND PULP FROM RED PINE. M.S. thesis, State Univ. N.Y. Coll. Forest., Syracuse. 102 p.

Siddiqui, K. M., W. T. Gladstone, and Renata Marton.
1972. INFLUENCE OF FERTILIZATION ON WOOD AND PULP PROPERTIES OF DOUGLAS-FIR. USDA Forest Prod. Lab. Symp. Effect Growth Acceleration on Properties of Wood Proc.: Madison, Wis.

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FERTILIZATION OF ADULT AND JUVENILE HARDWOODS IN ONTARIO

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FERTILIZATION OF ADULT HARDWOODS

by R. C. Ellis

ABSTRACT. Fertilization and thinning are being used to rehabilitate hardwood woodlots of southern Ontario for the production of high-grade hardwood lumber. Variable conditions of tree quality, species composition, and age necessitate that experimental treatments be evaluated on the basis of individual tree responses. A method is described for the selection of trees and their allocation to treatments according to a competition index. Soil perfusion techniques were used to assay the degree to which different levels of nitrogenous fertilizer might increase the amount of nitrogen available to the trees from forest soils with brown forest to gray-brown podzolic profiles.

INTRODUCTION

IN CANADA the heavy hardwoods exhibit their greatest variety and best growth in southern Ontario. This is near the centre of the range of sugar maple (*Acer saccharum* Marsh.) and in the northern ranges of white ash, (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), and black walnut (*Juglans nigra* L.).

As the result of a varied history of clearing and exploitation, the remaining stands of mature hardwoods are degraded, and most of the hardwood resource is in the form of regrowth stands that are less than 100 years old. In consequence the wood-using industries are becoming short of home-grown quality hardwoods.

The principal objective of the Canadian Forestry Service's program is to increase the supply of quality hardwoods: in the short term, by improving the growth of existing young stands; in the long term, by establishing desirable tree species, either in plantations or by enrichment planting beneath existing stands. A secondary objective, which is increasing in importance, is the growing of hardwoods for amenity purposes. Fertilization is being carried out in both aspects of this program.

THE PROBLEM

Growing heavy hardwoods differs from growing many other species in that one is concerned with quality rather than quantity. The amount of veneer or first-class lumber that is produced by a degraded stand may bear little or no relation to the gross weight of fiber contained in the stand; therefore one must consider the potential growth, and hence the response to treatment of individual trees.

The heterogeneous species composition and stocking of most stands in southern Ontario present problems in the evaluation of responses to treatments. One has to assess the effect of silvicultural treatments upon individual trees that are growing in stands where species composition and age-class distribution are largely the effect of a complex history: where the density of stand that represents full stocking varies from point to point, and is dependent upon additional factors such as soil depth, texture, stone content, position on slope, and bedrock configuration. The main problem is to relate response to the level of treatment and yet achieve a manageable number of replicates.

A fertilizer x thinning experiment was made in hardwood woodlots. In young stands a 3^2 factorial design was used that contained 5 trees per treatment combination, or 45 trees per block; it was repeated in six woodlots of varying age. In two older stands only the fertilizer treatment was carried out: 15 trees per treatment, for 45 trees per block, in each woodlot.

All the stands are in Grey County, Ontario, and are situated on soils formed from calcareous glacial till. The soil profiles are uniform and classified as brown forest or gray-brown podzolic intergrades in which the slightly acid A_1 horizon of about 10 cm. depth grades rapidly into a slightly alkaline B_1 horizon. They are well drained. The steps taken to overcome the variable conditions presented by the small privately owned woodlots are outlined in some detail below.

Characterization of the Sample Trees

Selection.—The individual tree was the unit of treatment. A tree was considered if an examination of its bole and crown indicated a high probability of its developing into a veneer log or first-class saw log.

Observations of hedgerow trees suggested that a tree had a depressing effect upon adjacent field crops that extended from the tree to a distance equal to 1½ times the radius of its crown. Therefore it appeared reasonable to assume conversely that a tree would be relatively unaffected by treatments that were applied at distances greater than 1½ crown radii from its stem. Measurements made upon more than 100 dominant and codominant trees revealed that for sugar maple the diameter at breast height in inches, within the range 5 to 13 inches, was almost equal to the radius of the crown in feet. In practice it was assumed that interaction between two trees would be negligible if they were separated by a distance equal to twice the sum of their crown radii; for example, two trees of 10 inches d.b.h. should be separated by at least 40 feet.

Upon these premises 45 trees were selected from each of 8 stands. Each stand was predominantly of one age class, and the mean d.b.h. of sample trees per stand varied from 6 to 14 inches (table 1).

Competition index.—In stands of heterogeneous structure and growing conditions, the release by thinning of individual trees to a uniform standard cannot be effected by a uniform reduction in basal area either on an absolute or on a percentage basis, or on the basis of thinning to a given radius. Thinning seeks to reduce competition to the

Table I.—Characteristics of the experimental stands

[All on well-drained, upland, calcareous soils]

Stand No.	Age	Species	Land form	Mean d.b.h. sample trees
	Years			*Inches*
1	30	Sugar maple	Till plain	6.2
2	35	Sugar maple	Till moraine	6.6
3	40	White ash (black cherry, sugar maple)	Drumlin	7.4
4	40	Black cherry (white ash, sugar maple)	Drumlin	7.6
5	65	Sugar maple (beech, elm)	Till plain	9.6
6	85	Sugar maple (white ash)	Till plain	12.5
7	(m)	Sugar maple	Till moraine	13.5
8	(m)	Sugar maple (red maple, basswood, black cherry)	Till plain	13.9

[m] Mature.

selected tree, a competition that depends upon the relative size and spatial distribution of the competitors and upon the density of stand that represents full stocking in the vicinity of the selected tree.

It was necessary to make several assumptions:

1. That in a more or less even-aged stand that had been undisturbed for at least 10 years, the level of effective competition was relatively uniform throughout.
2. That the competitive effect of a neighboring tree upon a sample tree was proportional to
$$\frac{(\text{D.b.h.})^2 \text{ of competing tree}}{(\text{D.b.h.})^2 \text{ of sample tree}} = \frac{d^2}{x^2}$$
3. That the extent to which the zones of influence of adjacent trees overlap is inversely related to the square of the distance between them $\frac{1}{D^2}$
4. That the effects of neighboring trees upon the sample tree are additive.

The competitive effect of a neighboring tree upon a sample tree was considered to be proportional to

$$\frac{d^2}{x^2 \text{ x } D^2}$$

and an index of the competition experienced by a sample tree is then given by

$$\Sigma_1^n \frac{d^2}{x^2 \text{ x } D^2}$$

To make these and subsequent calculations, each sample tree was made the center of a plot, and the position of each neighbor was mapped within a radius equal to twice the crown diameter of the sample tree. Beyond this distance a tree was included where its distance was less than the sum of the diameters of its own and the sample tree's crowns. From these plot maps a competition index was calculated for each sample tree.

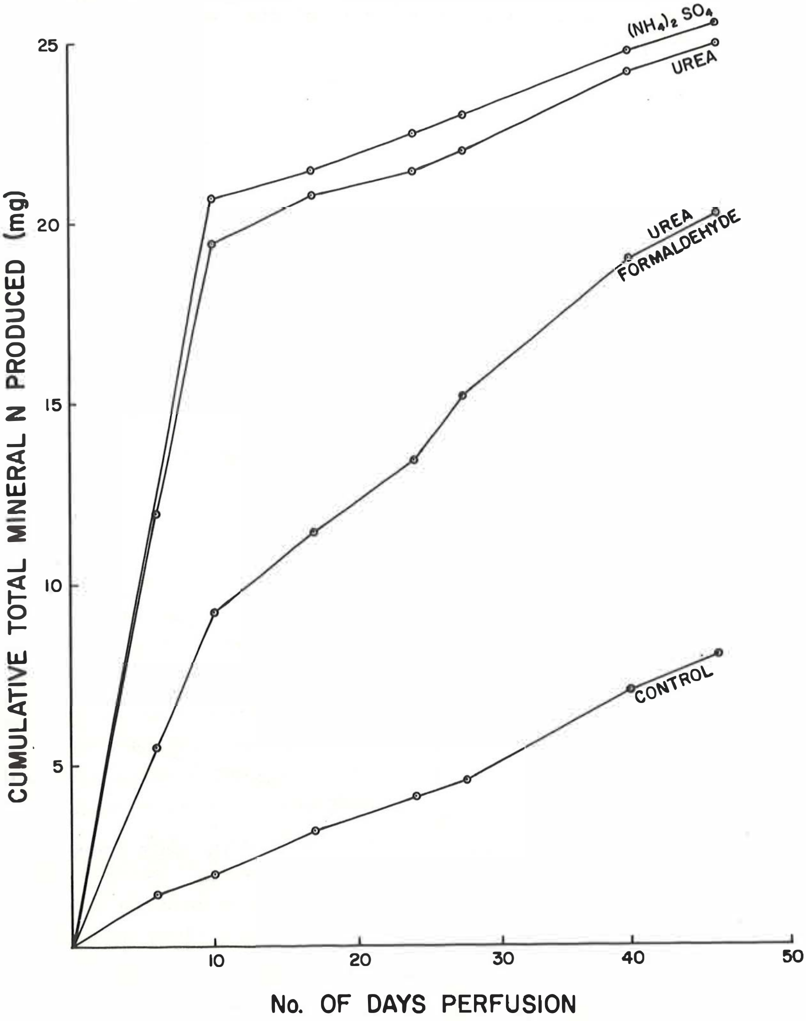
(It was realized that competitive effect does not increase indefinitely with diminution in D, because this would give undue weight to small suppressed trees growing very close to the sample tree. Therefore D (in feet) was assumed to diminish until it equalled x (in inches), and was then constant at this figure: for example, the competitive effect of a tree growing very close to the sample tree was considered to be no greater than it would have been had its axis been located directly beneath the periphery of the crown of the sample tree.)

Allocation to treatments.—In each replicate the 45 trees were arrayed by competition index. For thinning x fertilizing treatments, the array was divided into 5 groups of 9 trees each, and from each group a tree was assigned at random to each treatment. When fertilizing was the only treatment, each array was divided into 3 groups of 15 trees each, and 5 trees from each group were assigned at random to each treatment. Insofar as it was reflected in the competition index, variation in the conditions of growth of the trees was thus effectively distributed among the treatments.

Characterization of the Fertilizer

Choice of fertilizer.—In northern forest zones, responses to nitrogenous fertilizer are commonly reported. Mitchell and Chandler's (*1939*) oft-quoted study indicated a marked response by several hardwood species to nitrogenous fertilizer but

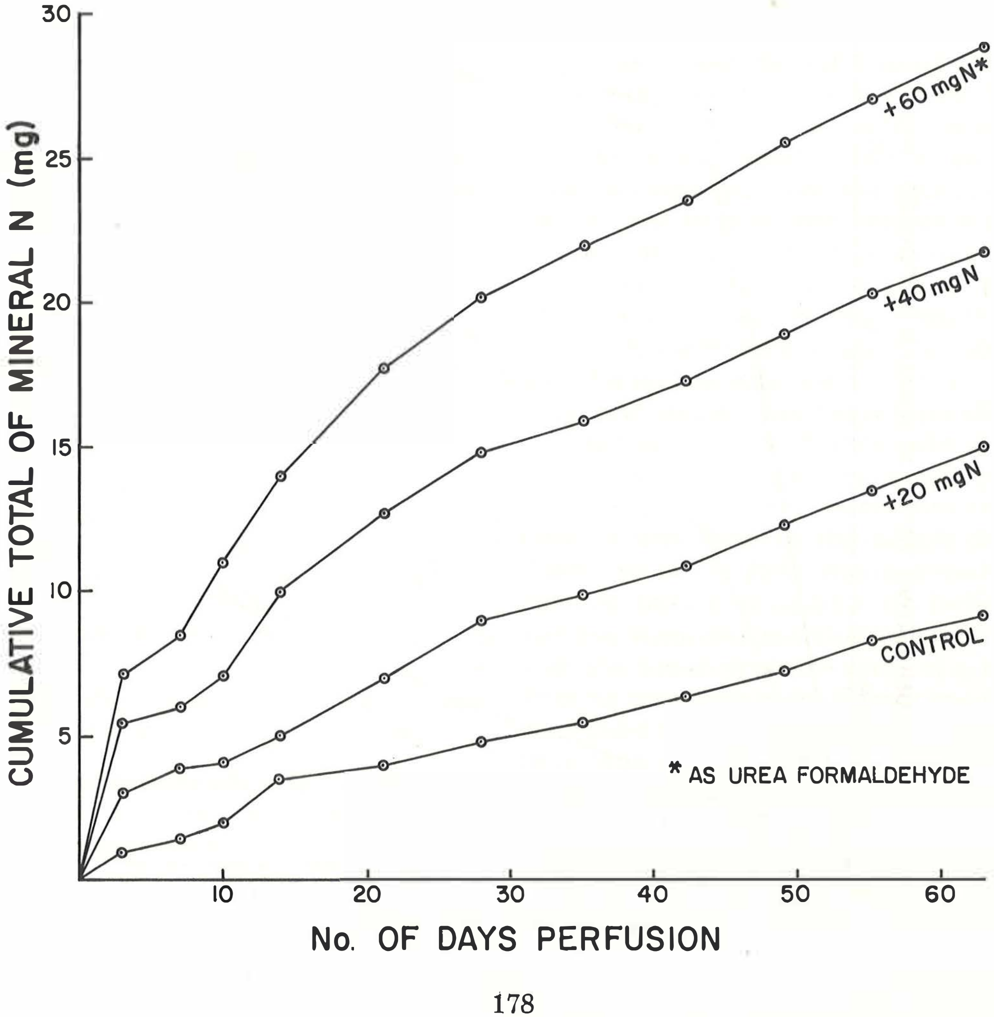
Figure 1.—Cumulative total of mineral nitrogen produced as NO_3 from maple woodlot soil amended with three nitrogenous fertilizers.
UREA FORMALDEHYDE: 30.0 mg. N added
$(NH_4)_2SO_4$: 21.0 mg. N added
UREA : 19.4 mg. N added



little response to phosphatic or other fertilizers. Neely, Himelick, and Crowley (*1970*) reached a similar conclusion and, further, found little difference in overall response to N applied either as ammonium nitrate, ammonium sulphate, urea, or urea formaldehyde. A preliminary sampling of foliage from five stands in southern Ontario indicated that the rate of growth of sugar maple was more closely related to the foliar concentrations of N and Mn than to those of P, K, Ca, Mg, Fe, or Zn. Therefore it was decided to investigate first the effect of adding nitrogenous fertilizer to the stands.

Perfusion experiments.—The interaction between A_1 horizon soil and three nitrogenous fertilizers was studied by means of a perfusion apparatus. Two hundred g. of a composite sample of moist soil from a mature stand of maple was put into each of eight tubes. (The soil had been frozen since its collection in September, 3 months before.) Ammonium sulphate, urea, and urea formaldehyde were each added to two tubes of the eight, and two served as control. Perfu-

Figure 2.—Cumulative production of mineral nitrogen as NO_3 from maple woodlot soil amended with three levels of urea formaldehyde.



sion with water was continued for 7 weeks. At intervals of a few days the perfusate was drained and analyzed, and replaced with fresh water. The net rate of formation of nitrate from the three fertilizers is shown in figure 1.

It was found that 90 percent of the N in ammonium sulphate and urea had been converted to nitrate after 10 days, as opposed to only 23 percent of that from urea formaldehyde. Nitrate formation from urea formaldehyde proceeded at a fairly uniform rate for the duration of the experiment, whereas after 10 days there was no further production of nitrate from the other two fertilizers. From this it was concluded that on these soils urea formaldehyde could be the most satisfactory compound to use. Leaching of nitrate during spring runoff would probably diminish the effectiveness of the more easily converted fertilizers, whereas, from urea formaldehyde, mineral nitrogen could be released continuously throughout at least the first growing season.

In a second perfusion experiment, three quantities of urea formaldehyde were added in duplicate to tubes of soil taken from a stand of mature maple. (This second sample of soil had also been kept frozen since its collection 4 months before.) The tubes were perfused for 63 days, during which time the perfusate was periodically drained and analyzed for nitrate. The pattern of net nitrification is shown in figure 2.

In each case a flush of activity during the first 3 days converted about one-tenth of the fertilizer N to nitrate. Over the 9 weeks of the experiment, nearly one-third of the N in the fertilizer appeared as nitrate, and the amount of nitrate produced in excess of that of the control was almost exactly proportional to the amount of fertilizer that was added (fig. 3). During the past 35 days of the experiment nitrate was produced at a constant rate in each tube: that rate, less the control rate, was again propor-

Figure 3.—Mineral nitrogen produced as NO_3 after 63 days perfusion of a maple woodlot soil with three levels of urea formaldehyde.

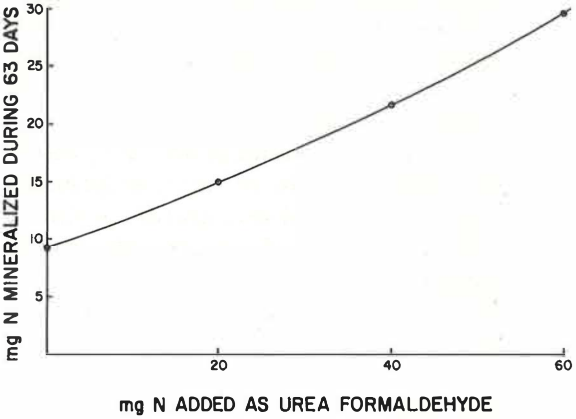
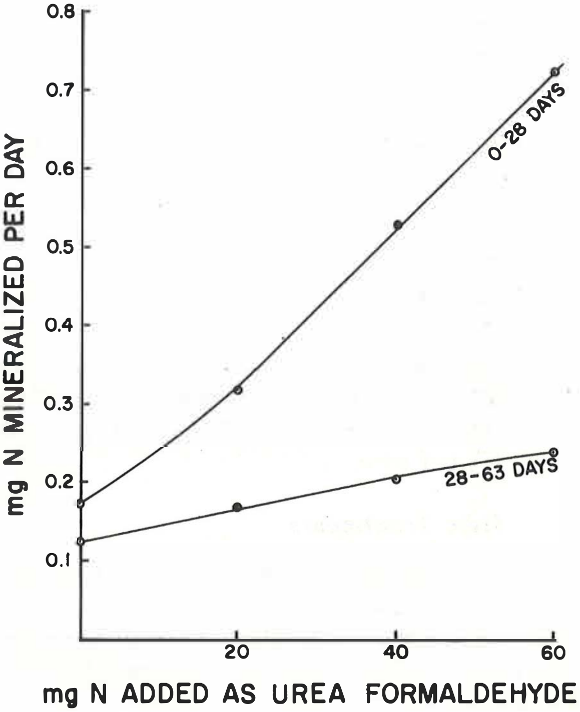


Figure 4.—Rate of production of mineral nitrogen as NO_3 in mg. per tube per day with three levels of urea formaldehyde.



tional to the amount of fertilizer added (fig. 4).

Rate of fertilizer application.—From the perfusion experiments it is possible to calculate the proportion by which a given amount of urea formaldehyde fertilizer should increase the net amount of nitrate produced in this soil. Implicit in this is the reasonable assumption that, though the absolute rate of nitrate formation will vary with soil temperature, soil moisture, and season of the year, the relative rates of net nitrate production in fertilized and unfertilized soils will remain fairly constant.

Each tube contained nearly 130 g. of soil (air-dry). The addition of 30 mg. of nitrogen as urea formaldehyde doubled the net amount of nitrate that was formed over an interval of 9 weeks, and at the end of this period the rate of net nitrate production was still 50 percent greater than that of the control. The depth of the active (A_1) horizon of the soil beneath these hardwood stands was about 10 cm.; bulk density of the horizon averaged 1.2; rock and cobble content was estimated at 15 percent of the volume. The weight of the active horizon of the soil was estimated to be almost 840,000 kg./ha., or 750,000 lb./acre. By proportion, it seemed possible that the addition of 520 lb./acre (590 kg./ha.) of urea formaldehyde could effect a doubling of the mineral N that was available to the trees during the ensuing 2 months and a 50-percent increase for some time thereafter. This distant extrapolation was accepted in the absence of any more reasonable basis of calculation. The rates of application adopted were 520 and 260 pounds of urea formaldehyde (33 percent N) per acre.

Field Treatments

Thinning.—Thinning consisted of felling or sap-ringing neighboring trees to reduce the competition index of the sample trees by a given percentage. Different degrees of thinning were first simulated on the plot maps. It was found that a 50-percent reduction in the competition index was usually achieved by the removal of three or four codominant near neighbors of the sample tree. A 75-percent reduction in the competition index left the sample tree with its crown virtually free of contact with those of its neighbors. A large number of simulations in each of the stands to be thinned indicated that, for silvicultural purposes, the approach was a realistic one and generated very few anomalies. The two thinning grades adopted were a 50-percent and a 75-percent reduction in the competition index.

Trees to be removed were selected initially on the plot map. If, later in the field, it was decided to retain a tree for silvicultural reasons, it was replaced on the condemned list with a tree, or trees, of similar competitive effect.

Thinning was completed by early August 1970. Most of the sap-rung trees were dead by July 1971, and those that still survived were then felled with a chainsaw. In stand 6, many trees were of a utilizable size, and these were felled and extracted in October 1970.

Fertilizing.—Urea formaldehyde fertilizer was applied by hand in early April 1971. At this time most of the snow had melted, but a light cover remained on 25 to 90 percent of the ground surface. This facilitated an even spread of fertilizer. It was placed on the surface of the ground around the tree on a radius equal to 1½ times the crown radius of the tree. Thus at a rate of application of 260 lb./acre a tree of 6 inches d.b.h. received 1.5 pounds, and a tree of 14 inches d.b.h. received 8.5 pounds.

Response to Treatment

Growth in diameter.—A dendrometer band was installed on each sample tree at the time of fertilizer application. Readings were taken at intervals of 3 weeks until October 1971 and were recommenced in early May 1972.

Although the treatments were not completed until April 1971, some trends became apparent within 5 months of applying the fertilizer. In stands 7 and 8 (unthinned), the growth of the heavily fertilized trees increased by 16 percent and 19 percent respectively over that of the control trees. However, variation was such that these differences did not reach a statistically significant level.

In the thinned x fertilized woodlots, no clear trends had appeared by the end of the first growing season. However, the ash in stand 6 showed a significant response to thinning (F = 5.10, cf. 4.11 for 2.5 percent probability), and the cherry of stand 4 showed a significant response to fertilizer (F = 3.61, cf. 3.26 for 5 percent probability).

Increase in leaf weight.—In stands 2 (maple), 3 (ash), and 4 (cherry) two branches of approximately ½ inch in diameter were collected from the upper half of the crown of each sample tree during late August 1970 and again in 1971. Successive groups of leaves from

Table 2.—Effect of treatment in increasing the weight of leaves in three hardwood species during the first season

Ratio of mean squares	Species			F(5%)
	Sugar maple	White ash	Black cherry	
Thinning (A) error	0.07	0.11	0.92	3.11
Fertilizing (B) error	.43	8.88[a]	.74	3.11
A + B error	2.41	.43	.17	2.48

[a]Significant at the 1-percent level of probability.

Table 3.—Effect of treatment in increasing the concentration of nitrogen in the leaves of three hardwood species during the first season

Ratio of mean squares	Species			F(5%)
	Sugar maple	White ash	Black cherry	
ANALYSIS OF DIFFERENCES AMONG 1971 CONCENTRATION LEVELS (2 BRANCHES PER TREE)				
Thinning (A) error	1.54	0.84	1.49	3.11
Fertilizing (B) error	2.50	.56	.95	3.11
A + B error	1.87	.54	1.03	2.48
ANALYSIS OF DIFFERENCES BETWEEN 1970 AND 1971 CONCENTRATION LEVELS (BY TREES)				
Thinning (A) error	1.01	1.81	1.65	3.26
Fertilizing (B) error	13.14[a]	4.02[b]	3.50[b]	3.26
A + B error	2.50	.91	.44	2.63

[a]Significant at the 1-percent level of probability.
[b]Significant at the 5-percent level of probability.

each branch were oven-dried at 105°C., and the mean oven-dry weight per leaf was then calculated for each branch. Subsamples were taken for chemical analysis.

The species differed among themselves in this reponse. The weight of both maple and cherry leaves appeared to be unaffected by either fertilizing or thinning, but ash showed a large and highly significant increase in the weight of its leaves after being fertilized (table 2).

Increase in Foliar Nitrogen levels

An analysis of variance of the simple 1971 data indicated only a slight and nonsignificant effect of the treatment for all species (table 3). The analysis of variance was performed on the differences effected in levels of N within trees by treatment in 1970 and 1971. The sensitivity of the analysis was thereby improved, and all three species showed significant increases in foliar concentration of N as a result of fertilizer treatment.

DISCUSSION

The main points of interest in this work lie in the attempt made to ensure that a treatment of uniform probable effect could be applied to single trees that differed appreciably in their conditions of growth. In terms of tree diameter growth, it is too soon to tell whether or not this was achieved. However, after one growing season, mean differences between treatments of as little as 5 percent in leaf size and 7 percent in foliar N level attained significance at the 5-percent level of probability. It may be anticipated that nitrogenous fertilizer, in increasing both the size of the leaves and their concentration of N, will effect an increased rate of growth in tree diameter in ensuing growing seasons.

FERTILIZATION OF JUVENILE HARDWOODS

by F. W. von Althen

ABSTRACT. In a series of studies, plowing and disking the planting site, followed by effective weed control for the first 3 years after planting, were found to be prerequisite to the successful establishment of hardwood plantations in southern Ontario. To increase seedling growth during the critical establishment phase, N-P-K fertilizers were applied to the soil surface at time of planting. However, these treatments failed to produce consistent increases in growth, and further studies are now under way. Until more promising results are obtained, fertilization of new hardwood plantations cannot be recommended.

BACKGROUND

During the last decade, interest in hardwood afforestation has greatly increased in southern Ontario because of a dwindling supply of high-quality timber and a growing appreciation of the environmental and aesthetic values of hardwood trees. Southern Ontario is a predominantly agricultural area, and forests are generally restricted to sites unsuited to agriculture. Although some clearing of woodlots is still under way in the most productive agricultural regions, larger farmland areas of marginal productivity and lands unsuited to the economic use of farm machinery are being removed from agriculture. This is the land that is generally available for afforestation. Though most of the available land will not support quality hardwood growth, many tracts contain small areas that are capable of growing good hardwood timber. These are the sites on which hardwood planting should be concentrated.

HARDWOOD PLANTATION SURVEY

To determine the relative importance of factors affecting hardwood establishment and growth in southern Ontario, in 1963-64 we sampled 296 plantations ranging in age from 10 to 85 years (*von Althen 1965*). The results of this survey showed that soil texture, depth to C-horizon, and drainage were the three most important factors affecting hardwood growth. Although plantation histories were difficult to verify, several owners distinctly recalled having fertilized their plantations at time of planting at the same intensity as their adjacent crops. Although each plantation received a uniform broadcast application of fertilizer, large variations in growth occurred in all plantations.

Close examination of soils nearly always revealed variations in growth caused by changes in either soil texture, depth to C-horizon, or drainage. In no instance could it be ascertained that fertilizer, applied at time of planting, had maintained growth on a site where one of these major soil factors was unfavorable to the growth of the planted species.

FIELD EXPERIMENTS

The hardwood species commonly planted in southern Ontario are white ash (*Fraxinus americana* L.), red oak (*Quercus rubra* L.), basswood (*Tilia americana* L.), silver maple (*Acer saccharinum* L.), black walnut (*Juglans nigra* L.), sugar maple (*Acer saccharum* Marsh.), and black locust (*Robinia pseudoacacia* L.). During the early years after planting, seedlings of most of these species are highly susceptible to damage from browsing by rabbits, stem girdling by mice, and damage by frosts as late as the beginning of June. Any treatment that increases growth will reduce the period during which a new plantation is vulnerable to such injuries, and this will increase the probability of successful establishment.

To determine the relative importance of site preparation, chemical weed control, and fertilization on the establishment and early growth of sugar maple, red oak, basswood, black locust, silver maple and white ash, seedlings were set out in a nonreplicated pilot experiment in the spring of 1964 near Richmond Hill, Ontario. The planting site was a former hayfield with a soil classified as Cashel clay (a uniform neutral clay over compact clay till at a depth of 2 feet). The pH of the plow layer was 7.2, and the organic matter content 3.5 percent. Site preparation consisted in either plowing and disking in autumn prior to spring planting or removing a scalp 18 inches in diameter at time of planting, at each prospective planting spot. Granular simazine was applied either alone or in combinaion with the fertilizer in dosages of 3, 6, or 12 lb./acre of active ingredient. Ammonium nitrate, triple superphosphate, and potassium sulphate were broadcast in combination with the herbicide on the soil surface shortly after planting in the following amounts (lb./acre of active ingredient): level A: N - 75, P - 40, K - 40; level B: N - 150, P - 80, K - 80; level C: N - 300, P - 160, K - 160.

The results of this study showed that no single treatment assured successful establishment (*von Althen 1970*). However, plowing and disking of the total plantation area proved to be prerequisite to the success of the herbicide and herbicide-plus-fertilization treatments. In all plots where site preparation was restricted to the removal of a scalp 18 inches in diameter, the herbicide and herbicide-plus-fertilization treatments failed to assure planting success. In the plowed and disked plots, fertilization at level C nearly doubled height growth of white ash during the first 3 years, and this advantage increased during the next 5 years (table 4).

Fertilization at level C also increased height growth of silver maple and black locust; but all sugar maple, basswood, and red oak seedlings were so severely browsed by rabbits that an assessment of growth responses was impossible.

The results of this preliminary trial were encouraging, and in the spring of 1969 we established two sets of 3^3 factorial fertilizer experiments near Parkhill, Ontario. In the first set, 972 seedlings each of 1+0 black walnut, 2+0 basswood, and 2+0 red oak were planted in an abandoned field with a soil of deep, well-drained, fine sandy loam (Fox fine sandy loam). The pH of the plow layer was 6.4, and the organic-matter content was 2.4 percent.

In the second set, 972 seedlings each of 1+0 walnut and 2+0 silver maple were planted in an abandoned field of slightly eroded, imperfectly drained loam (Parkhill loam). The pH of the plow layer was 7.2, and the organic-matter content was 3.2 percent.

Both fields were plowed and disked in the summer before spring planting.

Table 4.—Average 3- and 8-year height growth of three species planted in plowed and disked plots, in feet

Species	Three-year height growth					Eight-year height growth				
	Control	Herbicide only	Herbicide plus fertilization[a]			Control	Herbicide only	Herbicide plus fertilization[a]		
			Level A	Level B	Level C			Level A	Level B	Level C
Black locust	3.4	8.1	7.5	7.4	8.5	10.0	15.5	15.5	13.5	18.5
Silver maple	.5	4.1	4.5	5.3	5.2	1.5	9.0	10.5	12.0	12.0
White ash	.7	2.4	3.5	3.5	4.4	3.5	6.5	12.5	10.0	13.0

[a] Fertilization (lb./acre of active ingredient):

Level	N	P	K
A	75	40	40
B	150	80	80
C	300	160	160

Shortly after planting, ammonium nitrate, triple superphosphate, and potassium sulphate were broadcast singly and in combination in the following amounts (lb./acre of active ingredient): N - 0, 100, 200; P - 0, 50, 100; K - 0, 50, 100. Simazine 50W was sprayed over the total area shortly after planting and in early spring of the second and third growing seasons in the following dosages (lb./acre of active ingredient): walnut 8, 4, 4; silver maple 6, 3, 3; red oak and basswood 4, 4, 4.

After three growing seasons, average height growth on the fine sandy loam was 3, 2.9, and 3.1 feet respectively for walnut, basswood, and oak. On the loam the average height growth was 3.1 feet for walnut and 6.7 feet for silver maple. Differences in height growth between treatments within individual species were nonsignificant on both soils, indicating failure of all fertilizer treatments to improve height growth. The results of foliar analyses of samples collected on both soils in late summer of the first and second growing seasons also showed no significant differences in N, P, or K concentrations between treatments within individual species on the same soil (table 5).

Failure of the fertilization treatments to improve growth cannot be fully explained. However, the low concentrations of P in all leaf samples and K in all but the basswood leaves indicate possible P and K deficiencies (*Finn 1966*). Since only N, P, and K were examined, limited availability of other minerals might have prevented or retarded P and K uptake. It is also possible that the small root systems of the newly planted seedlings were unable to utilize the fertilizer until most of the nutrients were lost by conversion into insoluble form, gaseous exchange, or leaching.

Table 5.—Average foliar N, P, and K by site, species, and year of sampling

Site	Species	N 1st year	N 2nd year	P 1st year	P 2nd year	K 1st year	K 2nd year
Sandy loam	Black walnut	3.14	3.12	0.117	0.095	0.997	1.25
	Basswood	2.51	2.81	.112	.070	1.19	1.94
	Red oak	2.38	2.47	.091	.102	.747	.710
Loam	Black walnut	2.97	2.91	.103	.097	.803	.744
	Silver maple	2.91	2.73	.088	.086	.628	.677

DISCUSSION

Haley (*1966*) stated that it is most unlikely that the returns from fertilization at time of planting will cover the high costs involved, except in those instances where the establishment of a crop would be impossible without fertilization. If hardwood planting is restricted to good planting sites with deep, moist, but well-drained soils, there is little need for fertilization, because site preparation and weed control, properly applied, will generally guarantee successful establishment and satisfactory early growth (*von Althen 1971*). However, interest in hardwood planting has increased greatly during the last decade, and hardwoods are often planted on sites that do not meet the foregoing criteria. Fertilization may be necessary on these marginal sites.

To date, the results of our fertilization experiments have not been encouraging. We strongly suspect the main reason is that the fertilizers were applied to the soil surface at time of planting to minimize treatment costs. However, newly planted seedlings—with their small, bunched, and often mutilated root systems—seem poorly equipped to utilize the fertilizer before the nutrients are either converted into insoluble form or lost by gaseous exchange or leaching. The favorable results obtained in sand culture studies (*Broadfoot and Ike 1968*) and soil-pot tests (*Dickson 1971; Phares 1971*) as compared to less successful field experiments (*McComb 1949*) seem to support this hypothesis.

We have found that white ash responds more readily to surface-applied fertilization than any of the other species tested. Presumably this is due primarily to the high N requirement of the species (*Mitchell and Chandler 1939*); but the relatively large, fibrous root system of white ash seedlings may be a contributing factor.

Mixing fertilizer with the soil appears to be economically feasible as plowing and disking of the total plantation area are essential, and fertilizer could be incorporated during the disking operation. We are presently investigating this approach as well as testing the effects of time of fertilizer application on nutrient uptake and seedling growth.

Until more promising results are obtained, fertilization of new plantations will remain economically unattractive, and it is recommended that planting be restricted to sites of proven productivity.

REFERENCES

Broadfoot, W. M., and A. F. Ike.
1968. RESEARCH PROGRESS IN FERTILIZING SOUTHERN HARDWOODS. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 180-184. TVA, Muscle Shoals, Ala.

Dickson, R. E.
1971. THE EFFECTS OF SOIL MOISTURE, TEXTURE, AND NUTRIENT LEVELS ON THE GROWTH OF BLACK WALNUT. USDA Forest Serv. N. Cent. Forest. Exp. Sta. Res. Paper NC-66, 6 p.

Finn, R. F.
1966. MINERAL NUTRITION OF WALNUT TREES. USDA Forest Serv. N. Cent. Forest Exp. Sta. Walnut Workshop Proc.: 35-41. Carbondale, Ill.

Haley, D.
1966. THE ECONOMICS OF FOREST FERTILIZATION. Forest. Chron. 42(4): 390-394.

McComb, A. L.
1949. SOME FERTILIZER EXPERIMENTS WITH DECIDUOUS FOREST TREE SEEDLINGS ON SEVERAL IOWA SOILS. Iowa Agr. Exp. Sta. Res. Bull. 369: 405-448.

Mitchell, H. L., and R. F. Chandler.
1939. THE NITROGEN NUTRITION AND GROWTH OF CERTAIN DECIDUOUS TREES OF NORTHEASTERN UNITED STATES. Black Rock Forest Bull. 11, 94 p.

Neely, D., E. B. Himelick, and W. R. Crowley.
1970. FERTILIZATION OF ESTABLISHED TREES. Ill. Natur. Hist. Surv. Bull. 30(4): 235-266.

Phares, R. E.
1971. FERTILIZATION TESTS WITH POTTED RED OAK SEEDLINGS. USDA Forest Serv. N. Cent. Forest. Exp. Sta. Res. Note NC-114, 4 p.

von Althen, F. W.
1965. HARDWOOD PLANTATIONS OF SOUTHERN ONTARIO. Can. Forest. Serv. Inform. Rep. O-X-2, 34 p. Sault Ste. Marie.

von Althen, F. W.
1970. METHODS FOR THE SUCCESSFUL AFFORESTATION OF A WEED-INFESTED CLAY SOIL. Forest. Chron. 46(2): 139-143.

von Althen, F. W.
1971. SITE PREPARATION AND WEED CONTROL IN WHITE ASH AND BLACK WALNUT AFFORESTATION. Can. Forest. Serv. Inform. Rep. 0-X-153, 13 p. Sault Ste. Marie.

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ACKNOWLEDGMENTS

The authors acknowledge the technical assistance of R. Brettschneider and E. Mitchell.

FOREST FERTILIZATION IN EASTERN CANADA, WITH EMPHASIS ON NEW BRUNSWICK STUDIES

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ABSTRACT. Although the allowable cut is far in excess of wood consumption in eastern Canada, a strong interest in forest fertilization developed during the 1960's. Main emphasis was placed on experimentation with fertilizers on small experimental plots, and major research programs were developed by the Pulp and Paper Research Institute of Canada, the Canadian Forestry Service, provincial governments, and universities. Although few results have been published, it has become clear that N shortage is commonly limiting growth in pole-size and maturing conifer stands, and that substantial growth increases can be obtained with addition of fertilizer N. Under certain site conditions tree growth may also be improved by addition of K or P.

PHYSIOGRAPHIC AND FOREST REGIONS OF EASTERN CANADA

THE TERRAIN now being found suitable for industrial forestry is located within four physiographic regions: (1) the Appalachian Region, including the Atlantic provinces and the Gaspé Peninsula of Quebec; (2) the St. Lawrence Lowlands; (3) the rugged Laurentian Highlands at the southeastern fringe of the Canadian Shield; and (4) the Abitibi and Severn Uplands, which are a part of the interior portion of the Canadian Shield. The Shield area is characterized by thin surficial deposits consisting of glacial drift derived mainly from granite bedrock. The Abitibi Uplands include the well-known clay belts, which represent glacial lake bottoms.

The prominent soils of eastern Canada belong to the podzolic (Spodosol) and luvisolic (Alfisol) orders. Within the Appalachian and Laurentian Highland regions, characteristic great groups are humo-ferric and ferro-humic podzols (Orthods). Soils developed from granite till and outwash in the Abitibi and Severn Uplands also belong to the great groups of ferro-humic and humo-ferric podzols. In the clay belt area of the Abitibi Uplands and on lake-bottom deposits of the Severn Uplands, grey luvisols or grey wooded soils (Typaltalfs) have developed. Soils characteristic of the St. Lawrence Lowlands are grey-brown luvisols (Typudalfs).

The forest vegetation of primary interest to industrial forestry may be subdivided into three types: (1) the Acadian forest; (2) the Great Lakes-St. Lawrence forest; and (3) the boreal forest, which forms a continuous band from Newfoundland through Quebec and Ontario (*Rowe 1959*).

Best known probably is the Great Lakes-St. Lawrence forest type with its mixed stands of white pine (*Pinus strobus* (L.), hemlock (*Tsuga canadensis* (L.) Carr.), white spruce (*Picea glauca* (Moench) Voss), yellow birch (*Betula alleghaniensis Britton*), maples (*Acer saccharum* Marsh. and *A. rubrum* L.), beech (*Fagus grandifolia* Ehrh.), and other species. Red pine (*Pinus resionsa* Ait.) is widely distributed on well and excessively drained sites.

The Acadian forest resembles the Great Lakes-St. Lawrence forest. Its main characteristic is the wide occurrence of red spruce (*Picea rubens* Sarg.) usually in association with balsam fir (*Abies balsamea* (L.) Mill.). Most of the northern hardwoods are found in this region. Red pine is less frequent than in the Great Lakes-St. Lawrence region.

The characteristic species of the boreal forest are black spruce (*Picea mariana* (Mill.) B.S.P.) and white spruce. Other common conifer species are jack pine, tamarrack (*Larix laricina* (Du Roi) K. Koch), and balsam fir. Black spruce forms pure stands on ill-drained as well as on upland soils, and it occurs in association with jack pine on excessively drained soils. The predominantly coniferous stands usually have an admixture of broadleaf species, mainly white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.).

The forest regions of Canada have been subdivided by Rennie (*1972a*) into eco-units. Criteria used are forest cover, climate, geology, and soils. Forty-five eco-units have been recognized for eastern Canada. This classification will undoubtedly facilitate description and evaluation of forest-fertilization studies.

FOREST PRODUCTIVITY, ALLOWABLE CUTS, AND WOOD CONSUMPTION

The potential growth of forests varies considerably throughout eastern Canada. Average productivity is highest in the Maritime Region, peak values being reported for Prince Edward Island and New Brunswick (*Manning and Grinnell 1971*). Growth rates are considerably lower in the boreal forest within the Canadian Shield because of short growing seasons and less productive soils. The allowable cut per unit area is lowest for Quebec. The average allowable cut given per unit area for Ontario is notably higher than the cut for Quebec, probably because a large proportion of the forested area in Ontario consists of the more productive Great Lakes-St. Lawrence type forest and because the clay belt with its more productive soils is included in the region of the boreal forest.

The wood resources are used at variable rates in eastern Canada. In all provinces except Prince Edward Island, the allowable cut exceeds consumption by a substantial margin (table 1). Nova Scotia and New Brunswick utilize less than 50 percent of the allowable cut, and in Ontario the consumption is only slightly more than 25 percent of the allowable cut. Quebec seems to use its forest resources to a fuller extent than most other provinces; primary productivity amounts to approximately 70 percent of the allowable cut.

The average volumes harvested per acre and the theoretical cutting cycles would indicate that provinces such as Newfoundland, Quebec, and Ontario have been working, at least up to 1968, with large reserves of mature timber.

Table I.—Allowable cuts and primary forest production in the various provinces of eastern Canada

Province	Allowable cut on forest land allocated to timber production	Primary forest production (average-1964-68)	Average volume harvested per acre	Theoretical cutting cycle
	M cubic feet	*M cubic feet*	*M cubic feet*	*Years*
Newfoundland	145,600	93,158	2,380	140
Nova Scotia	250,000	110,955	1,110	96
New Brunswick	457,000	209,056	1,050	70
Prince Edward Island	3,700	6,199	1,550	131
Quebec	1,346,100	969,584	1,580	251
Ontario	2,271,900	587,174	1,580	283

Source: *Manning and Grinnell 1971*

New Brunswick, with its comparatively high potential productivity, reported the lowest average yield, just exceeding 10 square cunits per acre (1 cunit = 100 cubic feet), and the theoretical cutting cycle is only 70 years. Nova Scotia's yield per unit area and theoretical cutting cycle are only slightly better than those reported for New Brunswick. The low yields in New Brunswick are due to unfavorable age-class distribution. In the case of spruce, the volume in mature and overmature classes was reduced to 21 percent by 1968, probably as a result of continued and full exploitation of all forest areas.

FOREST FERTILIZATION RESEARCH IN EASTERN CANADA

Despire the fact that allowable cuts exceeded current wood consumption, a strong interest in forest fertilization developed in Canada during the 1960's. Possible reasons were the rapid growth of the wood-using industry during this period, diminishing wood supplies near production centres, and unfavorable age-class distribution. A detailed account of fertilization research and fertilizer use in Canadian forestry was given by Rennie (*1972b*) in a report to the 8th World Forestry Congress.

In eastern Canada, some industries and one provincial government proceeded with aerial application of fertilizers on an operational trial basis. In total, probably not more than 5,000 acres have been fertilized. The Pulp and Paper Research Institute of Canada, the universities, and especially the Canadian Forestry Service greatly intensified research in forest fertilization and supporting disciplines during the past decade. Although some projects dealt with young plantations, the main thrust was directed at the mineral nutrition of pole-size and maturing pulpwood stands and their response to fertilizer treatments. These stands were predominantly coniferous, and most of them had regenerated naturally.

Research by the Pulp and Paper Research Institute of Canada

Among the oldest field trials with pulpwood stands are the experiments established by the Pulp and Paper Research Institute in cooperation with industries throughout eastern Canada (*Swan 1969*). These trials usually included application of N, P, and K at various rates. Treatments were based on the results of foliar analysis and bioassays involving greenhouse pot cultures with soil from the area to be treated. To establish a basis for diagnosis of nutrient deficiencies by foliar analysis, extensive sand-culture experiments were carried out with the principal pulpwood species of eastern Canada (*Swan 1970a, 1971*).

Assuming that shortage of N is a principal growth-limiting factor in the northern forest, Weetman and co-workers (*1968, 1971, 1972*) conducted a series of N fertilization experiments in upland black spruce stands in the southern portions of the boreal forest. These studies were aimed to determine growth responses to urea added at different rates, to detect possible interaction between fertilization and thinning, and to evaluate various N carriers for their suitability in forest fertilization. More recently, work was initiated to determine the interrelationship between foliar N levels and current growth of black spruce and jack pine stands. For this purpose, fertilizer N is added as required to maintain pre-determined foliar N levels.

Research by the Canadian Forestry Service

The Canadian Forestry Service is conducting forest-fertilization research in each of its four centres in eastern Canada. Each program includes extensive field experimentation, usually involving application of N, P, and K at various rates and in different combinations. At least in one case, the effect of liming on the growth of coniferous pulpwood stands was tested, and the use of trace elements is contemplated. The field projects are usually complemented by laboratory and greenhouse studies. Newfoundland soils, for instance, are subjected to intensive greenhouse and laboratory testing.

The Newfoundland and Maritime centres have dealt with N volatilization from urea-treated forest soils (*Mahendrappa 1969; Bhure 1970a*). Using a microbiological approach, the Maritime and Laurentian Centres are investigating N and organic matter transformations in the forest floor (*Roberge 1970, 1971; Salonius 1972*). The Maritime and Great Lakes Centres are studying various processes of N cycling in conifer stands (*Mahendrappa and Ogden 1971*). The Laurentian Centre concerns itself with possible effects of fertilizer treatments on insect pests, and the Great Lakes Centre is dealing with mensurational aspects and questions of experimental design in forest fertilization. The comprehensive program of the Great Lakes Centre also includes studies on fertilizer movement, the interrelationship between foliar nutrient levels and tree growth (*Morrison 1972*), and economic aspects of fertilization in pulpwood stands of northern Ontario.

Research by Universities

The Microbiology Department of Macdonald College, McGill University, in cooperation with the Pulp and Paper Research Institute, has studied N relationships in organic surface accumulations of forest soils. Special attention has been given to N transformations in black spruce raw humus (*Chu and Knowles 1966*), hydrolysis of urea (*Roberge and Knowles 1966*), N uptake by black spruce (*Knowles and Lefebvre 1971*), and nonsymbiotic N fixation (*Brouzes et al 1969*).

The Faculty of Forestry of the University of Toronto is experimenting with jack pine in northwestern Ontario. Sandy soil supporting a 49-year-old stand was fertilized by fixed-wing aircraft to determine fertilizer distribution and to evaluate sampling techniques (*Armson 1972*). Additional studies are under way with young plantations to determine interrelationships between fertilizer treatments and spacing of trees and fertilizer herbicide interactions (*Armson and Calvert 1971*).

Research by the Faculty of Forestry and Geodesy of Laval University includes comprehensive field experimentation with balsam fir and jack pine stands, studies of N losses by volatilization (*Bernier et al. 1972*), studies of the mobility of added and indigenous nutrients in fertilized soil, and an evaluation of the ecological impact of forest fertilization. One study involves amino-acid composition of tree foliage from fertilized soil and its effect on the mortality of jack pine sawflies.

The University of New Brunswick studies aim to determine the responses capability of maturing pulpwood stands to nutrient supplements, to relate fertilization responses to soil and stand conditions, and to improve methods of diagnosing nutrient shortages and predicting fertilization responses. Standardized field experiments were established in the 1960's. Field observations are supplemented by laboratory studies of foliar nutrient contents and N and P relationships in forest floor and B-horizon samples.

Research by Provincial Governments

On the initiative of the Pulp and Paper Research Institue, the provinces of Nova Scotia, New Brunswick, Quebec, Ontario, Manitoba, Saskatchewan, and Alberta formed an interprovincial task force on forest fertilization. The provinces agreed to establish and maintain a certain number of field experiments in important cover types. Treatments were standardized and included testing of N at three levels, P at two levels, and K a two levels. Growth measurements are to be made 5 and 10 years after treatments. The results are to be evaluated by the Pulp and Paper Research Institute.

Some provinces have conducted forest-fertilization research independently of and prior to the interprovincial program. Ontario, for instance, has experimented with fertilizers and lime in red pine plantations (*Leech 1965, 1967, 1969*), and New Brunswick established several N, P, and K trials in semimature pulpwood stands.

The Nova Scotia Department of Lands and Forest, in cooperation with the Nova Scotia Research Foundation, has carried out forest-nutrition studies involving aerial and hand applications of fertilizers to red pine plantations and red spruce stands of various age classes, and detailed analyses of tree foliage (*Robertson and MacLean 1968*).

Summary of Preliminary Results

Most of the research described here is in an early stage, and few results have been published. Information available to date has shown low to extremely low N levels in foliage of conifers after stand closure and a positive relationship between foliar N and site productivity (*Gagnon 1964, Lowry and Avard 1967*). Black spruce and jack pine stands were shown to respond strongly to N fertilization (*Weetman 1968, 1971; Hoyt 1972*). Although use of urea may lead to N losses by volatilization (*Mahendrappa 1969, Bhure 1970a, Bernier et al. 1972*), it is believed to be the most suitable N carrier for forest fertilization in eastern Canada, except on sites with dry humus layers (*Weetman 1972*). After rapid hydrolysis (*Roberge and Knowles 1966*), urea N was found to remain largely in inorganic form over extended periods of incubation (*Roberge and Knowles 1965; Bhure 1970b*). Field observations by Roberge and Knowles (*1965*) indicated, however, that substantial quantities of N were immobilized in L, F, and H layers of a black spruce forest floor within 3 years after urea application.

This information is in agreement with foliar N concentrations in black spruce or urea-fertilized soil. N contents of current-year black spruce needles were found to increase strongly during the first growing season after treatment and to decrease rapidly in the following 3 years (*Krause 1971*). Since only a small portion of added N is expected to be taken up by trees (*Knowles and Le-*

febvre 1971), foliar N levels should have remained high for several years after treatment, had the added N remained in a form in which it is readily available to trees.

Although N fertilization has given the largest growth responses, growth improvements in conifer plantations and naturally regenerated pulpwood stands have also been obtained with other elements, applied separately or in combination with N. Recognizing that sites requiring only N for improved growth certainly exist, Swan (*1969*) commented that during his 10 years of field experience no situation was found in which N, applied by itself, gave the best results. A naturally regenerated jack pine stand and a white spruce plantation, both on sandy outwash of Quebec, responded to N and K fertilizer. Potassium responses were also obtained with jack pine on abandoned farmland (*Gagnon 1969*). Black spruce, naturally regenerated, 75 to 85 years old and growing on imperfectly drained soil of northwestern Ontario, responded to addition of P (*Swan 1969*).

The observed response of conifers to K when growing on outwash soils is in agreement with reports from other locations (*Heiberg and White 1951*, *Heinsdorf 1968*), and the positive reaction of black spruce to P on soils with imperfect drainage agrees with observations in New Brunswick (*Krause 1971*).

SOIL, COVER TYPE, AND FERTILIZATION RESPONSE

It was early recognized that N mobility is greatly reduced where forest litter accumulates to form thick surface layers of decay-resistant debris (*Hesselman 1917*). Since then, the problem of raw humus formation has been dealt with by numerous scientists and practicing foresters. Notable are the reports of Rommel (*1935*), Wittich (*1952*), and Handley (*1954*).

Weetman (*1962*) observed that N shortage existed as a result of raw humus formation also in black spruce stands of eastern Canada, and that such stands are likely to respond to N additions. These early observations from Canadian work with closed stands raised a number of questions. How widely distributed are N deficiencies in soils of eastern Canada, and to what extent can growth of pulpwood stands be improved by addition of fertilizer? Are other nutrients also deficient? Does N interact with other nutrients to improve the efficiency of fertilizer treatments?

Some answers to these questions are found in the early results of field experiments established by the University of New Brunswick in cooperation with the Canadian Forestry Service and industries.

In each of these experiments N was applied at the rate of 150 pounds per acre as urea, P at the rate of 100 pounds per acre as triple superphosphate, and K at the same rate as P as sulfate of potash. Applications were made in factorial combination, giving rise to the following treatment combinations: (1) control, (2) K, (3) P, (4) P-K, (5) N, (6) N-K, (7) N-P, and (8) N-P-K.

Fertilizer additions were made to 1/10-acre plots. All treatment combinations were replicated five times in randomized blocks. In each 1/10-acre plot a 1/15-acre plot was concentrically located. Within this smaller plot five trees of the dominant and codominant portion of the stand were selected for installation of aluminum tape dendrometers (*Liming 1957*). The tapes were read at the beginning and/or end of each growing season.

Three of these experiments (Piskehegan, Bathurst, and Canaan) were installed in 55- to 65-year-old black spruce stands of the central and eastern lowland portion of New Brunswick. This area is underlain by red and grey sand and siltstone of Pennsylvanian and Mississippian age. Soils have developed in till, which is derived mainly from the underlying bedrock. These soils are characterized by unusually low Ca saturation of the exchange complex and high acidity. A dominating feature is compaction, which starts in the transitional B horizon and increases with depth. This condition impedes drainage to various degrees and restricts rooting to the very surface layers of the soil.

The three stands responded in a similar way to fertilizer treatments (fig. 1). Trees showed small increases in basal-area growth with addition of K, and somewhat larger increases with addition of P. Of the one-element treatments, addition of N was most efficient. Maximum growth responses were obtained with combined N and P additions. Application of all three elements was less effective than N-P treatment. Response analysis of two-element treatments showed large and statistically highly significant N main effects (table 2). Main effects of P comprised from 30 to 50 percent of the total response to the N-P treatment. Potassium main effects were smallest and non-significant. Nitrogen and K, and P and K, interacted negatively in all cases. A notable positive N-P interaction was observed in the Bathurst experiment.

Two additional experiments were established in the central elevated portion of New Brunswick, (at Nashwaak and Sevogle) where intrusive igneous rocks of variable base content have uplifted paleozoic slate, greywacke, and argillite formations. The soils have developed in a mineralogically richer till than that of the lowland region. Compaction is present in the substratum, but it is less pronounced than in soils of the lowland region; and rooting in the mineral soil is more intensive than in soils of the lowland regions. The forest cover of the experimental sites consisted of mixed stands of red spruce and balsam fir with an average age of approximately 55 years.

Red spruce, the dominant species at the Nashwaak site, also showed maximum response to N-P treatment even though the two elements showed a small negative statistical interaction (fig. 2). N and K did not interact negatively as observed at the black spruce sites. The re-

Figure 1.—Response of maturing black spruce to N, P, and K fertilization at various locations in New Brunswick. Black portions of bars represent growth supported by residual fertility, and light portions represent extra growth due to fertilization.

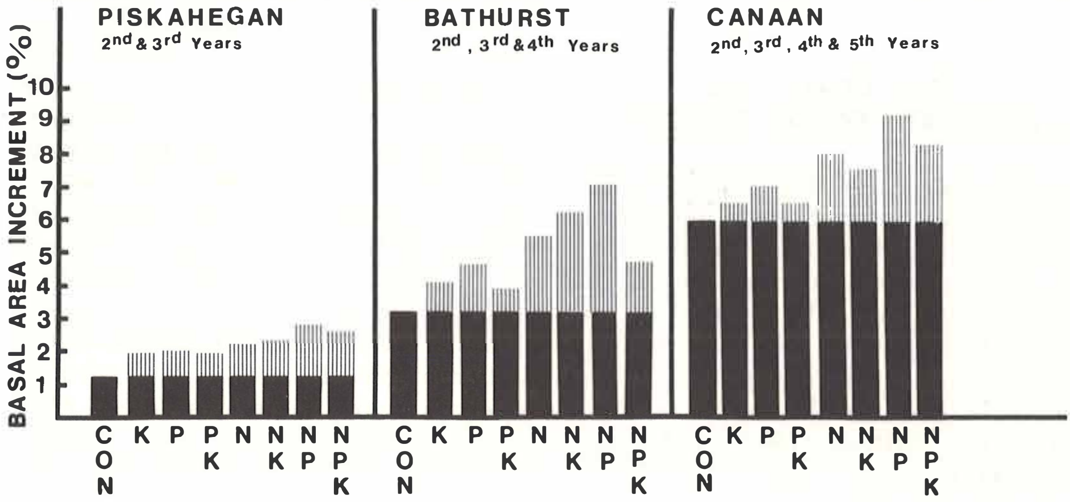


Table 2.—Effect of N, P, and K treatments on growth of maturing conifer stands in New Brunswick

[Growth periods are the same as shown in Figures 1, 2 and 3.]

Treatment	Percent basal-area increment of dendrometer trees						
	Main effects			Interactions			Total response
	N	P	K	NP	NK	PK	
			PISKAHEGAN				
N-P	+0.92	+0.76	—	−0.21	—	—	+1.47
N-K	+0.92	—	+0.69	—	−0.56	—	+1.05
P-K	—	+0.76	+0.69	—	—	−0.75	+0.70
			BATHURST				
N-P	+2.20	+1.21	—	+0.36	—	—	+3.77
N-K	—	+1.21	+0.79	—	−0.10	—	+2.89
P-K	+2.20	—	+0.79	—	—	−1.33	+0.67
			CANAAN				
N-P	+2.02	+1.05	—	+0.05	—	—	+3.12
N-K	+2.02	—	+0.46	—	−1.41	—	+1.07
P-K	—	+1.05	+0.46	—	—	−1.00	+0.51
			NASHWAAK				
N-P	+1.33	+0.96	—	−0.25	—	—	+2.04
N-K	+1.33	—	+0.49	—	+0.05	—	+1.87
P-K	—	+0.96	+0.49	—	—	−1.09	+0.36
			SEVOGLE				
N-P	+1.19	+0.16	—	+0.23	—	—	+1.58
N-K	+1.19	—	−0.06	—	+1.03	—	+2.16
P-K	—	+0.16	−0.06	—	—	+0.48	+0.58
			GREEN RIVER				
N-P	−0.40	−0.14	—	+1.34	—	—	+0.80
N-K	−0.40	—	+0.24	—	+1.78	—	+1.62
P-K	—	−0.14	+0.24	—	—	+0.94	+1.04

sponse to combined N-K treatment was nearly as great as the response to N-P treatment. K applied in addition to N and P did not yield further growth improvement during the first four growing seasons since addition of fertilizer.

Balsam fir in mixture with red spruce at the Sevogle site responded to N, and to K when applied in combination with N (fig. 2). In contrast to previous observation, this experiment showed a large positive N-K interaction and a notable positive P-K interaction.

A sixth experiment was esbablished on the northwestern plateau of New Brunswick. The soil there developed in till derived from slates, argillites, and limestone formations. Although soils are shallow, the bedrock with its vertical cleavages permits deep rooting. The forest cover is nearly pure balsam fir, approximately 50 years old.

The fertilization response pattern of balsam fir in the pure stand at the Green River site was in sharp contrast with the observed responses of the black spruce stands (fig. 3). Growth was slightly depressed on N- and P-treated plots, but somewhat improved on K-treated plots. N and K fertilizer interacted strongly to yield a notable growth response. Positive interactions were also recorded for N and P and for P and K.

Periodic growth as detected by aluminum tape dendrometers, and foliar nutrient levels determined in taped trees, revealed relationships that seem to agree with fertilization-response patterns.

Figure 2.—Response of mixed spruce and balsam fir stands to N, P, and K at different locations in New Brunswick. Black portions of bars represent growth supported by residual fertility, and light portions represent extra growth due to fertilization.

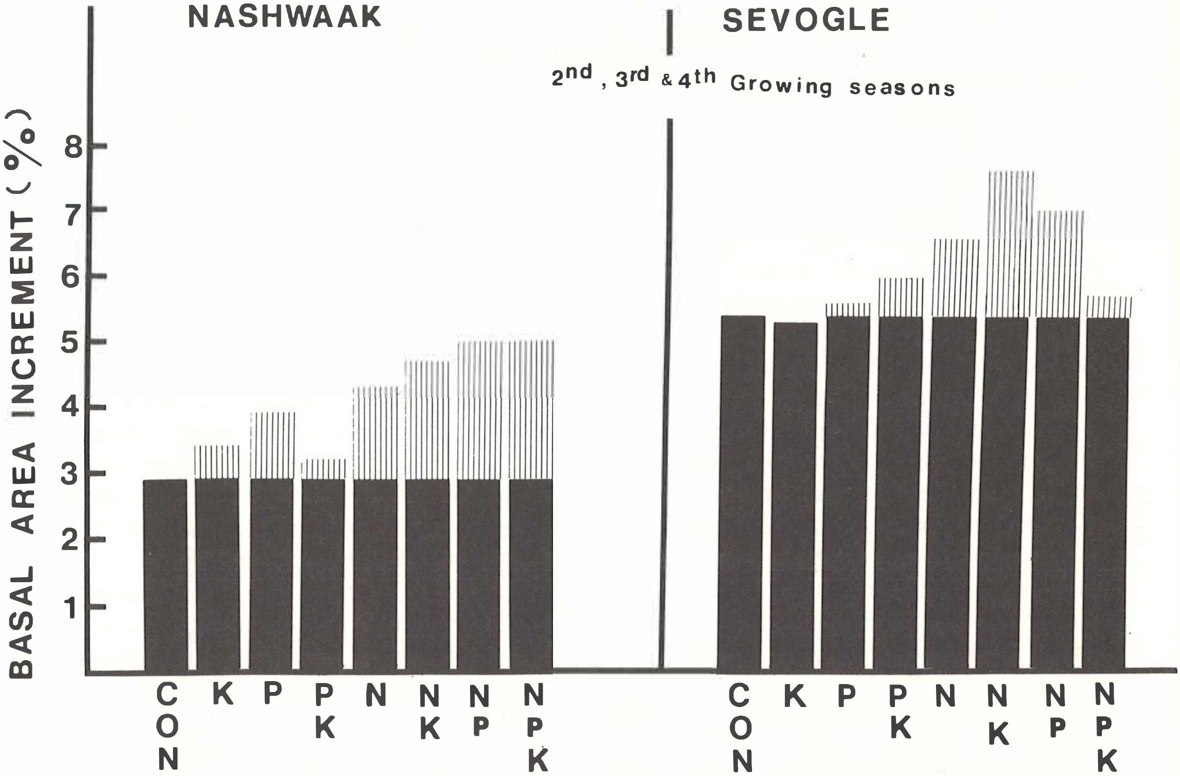
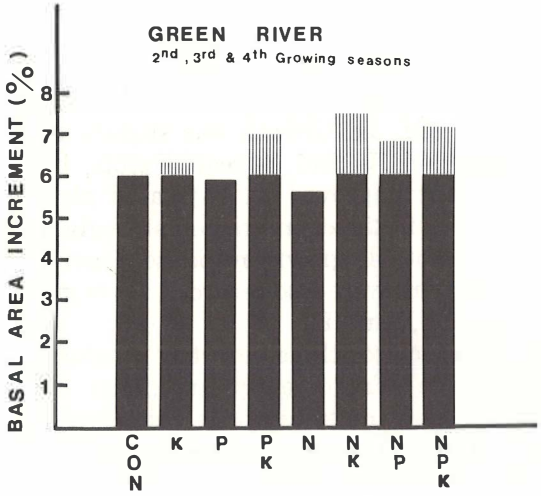


Figure 3.—Response of balsam fir to N, P, and K in the Northwestern Plateau Region of New Brunswick. Black portions of bars represent growth supported by residual fertility, and light portions represent extra growth due to fertilization.



Significant correlation coefficients were obtained for the relationship between foliar N in current-year needles and basal-area growth of all experimental stands except the Green River balsam fir, which did not show a response to N (table 3). No correlation could be shown for foliar P and basal-area growth, probably because of luxurious consumption of P at low N supply.

Foliar K showed negative, non-significant correlation coefficients with growth in black spruce and positive correlation coefficients with growth in balsam fir. Although small, the correlation coefficients for foliar K and growth of balsam fir were significant at the 5-percent level. The ratio of foliar K to foliar N was negatively correlated with growth in the black spruce stands. Correlation coefficients were significant at the 1-percent

Table 3.—Interrelationship between foliar nutrient concentrations determined after completion of the first growing season following fertilizer application and average basal-area increment of dendrometer trees in subsequent years

Experiment	Correlation Coefficients					
	N	P	K	Ca	Mc	K/N
Bathurst	+0.52**	+0.14	—0.19	—0.20	—0.14	—0.48**
Canaan	+0.54**	+0.14	—0.18	+0.49**	+0.21	—0.48**
Piskahegan	+0.40*	—0.04	+0.03	+0.01	+0.19	—0.24
Nashwaak	+0.46**	—0.08	+0.12	n.d.	n.d.	—0.24
Sevogle	+0.53**	+0.14	+0.32*	+0.05	—0.17	+0.02
Green River	+0.22	+0.24	+0.33*	—0.06	—0.40*	+0.14

level. In the Green River experiment, however, the correlation coefficient between the same ratio of foliar nutrient contents and growth was positive.

A fairly close positive relationship was observed for foliar Ca and growth on the Canaan plots and a negative relationship for foliar Mg content and growth on the Green River plots. This observation may be explained by antagonistic relations between K and the divalent ions.

The observed differences in fertilization response patterns may be attributed at least in part to variable fertility of experimental soils.

The native fertility of the soils on the experimental sites has been studied to some extent. The N-releasing properties of forest floor and B-horizon samples were determined in incubation studies (*King 1972*), and contents of mineral N in forest floor and B-horizon samples after 32 days of incubation at 20°C. are reported as mineralization indices (table 4). Mineralization indices were lowest for black spruce sites, which showed high responses to N addition, and highest for the Green River balsam fir site at which the same treatment yielded no response. Mineralization indices of the B-horizon showed a narrow range and were lses consistent with responses than indices of the L-F-H layers.

P was extracted from soil and forest floor by shaking suspensions for 24 hours with anion exchange resin. Far greater quantities of P were extracted from L-F-H layers than from B-horizon samples.

Table 4.—N and P availability in forest floor and B horizon, and response of conifer stands to fertilizer treatment at various locations in New Brunswick

Experiment	Forest Cover	Nitrogen			Phosphorus		
		Mineralization Index[a]		Response	Resin-extract[b]		Response
		LFH	B		LFH	B	
				Percent			Percent
Piskahegan	Black spruce	11	29	+72	40	2.8	+59
Bathurst	Black spruce	19	21	+68	122	4.5	+37
Canaan	Black spruce	22	107	+36	93	1.9	+17
Nashwaak	Red spruce, Balsam fir	158	51	+41	101	2.5	+30
Sevogle	Balsam fir, Red spruce	50	60	+22	296	5.5	+3
Green River	Balsam fir	278	95	—7	245	5.0	—2

[a] Mineralization index is the content of mineral N, in p.p.m. after 32 days of incubation at 20° C.
[b] Resin extractable P is given in p.p.m.

Figure 4.—Relationship between growth of black spruce to age 40 and rooting-space index, which is determined by depth to compacted layer (cm.) plus the reciprocal of the bulk density (g./cm.^{3}) of the compacted layer.

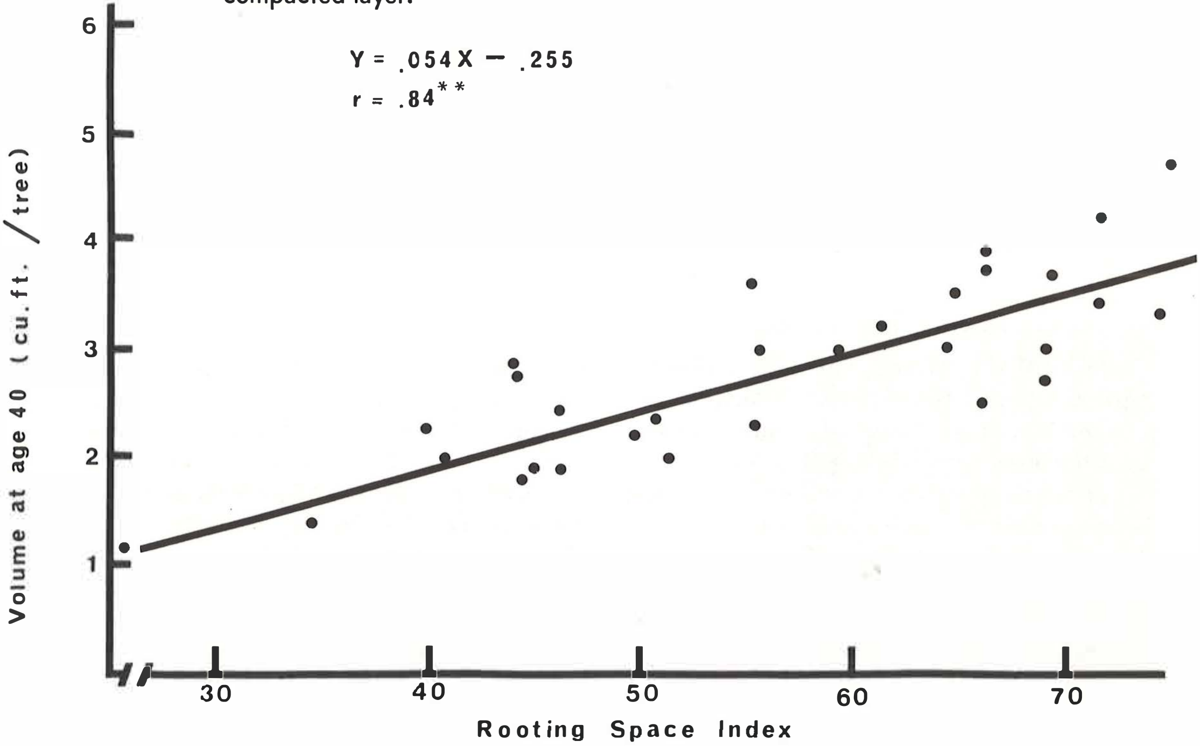
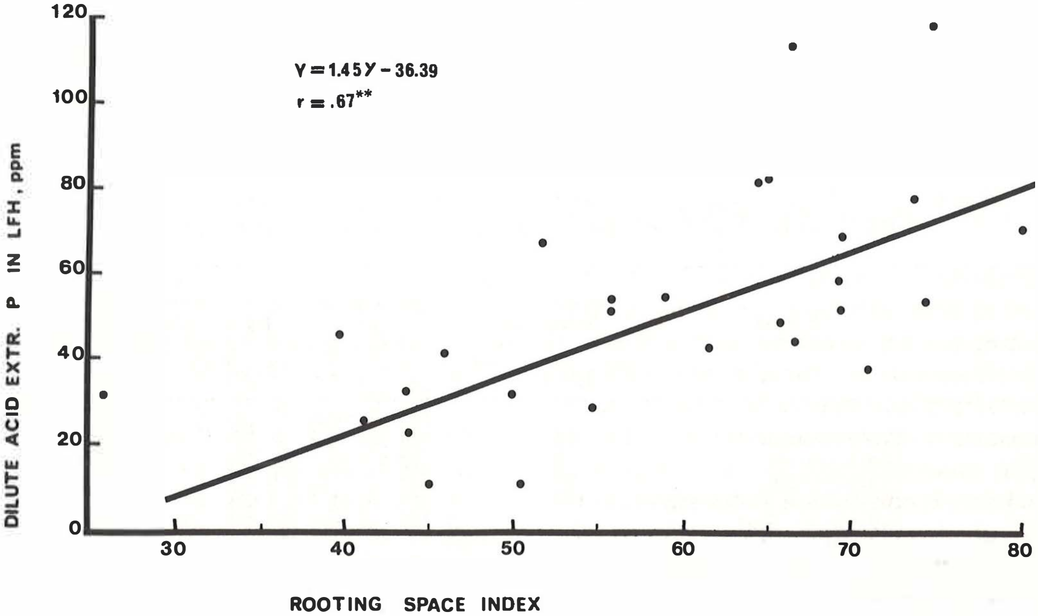


Figure 5.—Relationship between P content in the forest floor extractable with 0.002N H_2SO_4 buffered at pH3 and rooting-space index.



Lowest concentration and highest growth responses to P addition were found at the Piskahegan black spruce site; highest concentrations and very small or no growth responses were found at the two balsam fir sites (table 4).

Additional work with black spruce in the central lowland region of New Brunswick has indicated that an interrelationship may exist between soil physical properties, soil fertility, and tree growth (*MacFarland and Krause 1972*). A very close correlation could be shown between volume growth to age 40 years and a rooting-space index, which is given by the depth in cm. to the compacted layer plus the reciprocal of the bulk density (g.cm.^{3}) of the compacted layer (fig. 4). The rooting-space index, in turn, was well correlated with dilute-acid extractable P in the forest floor (fig. 5).

K relationships of the experimental soil have not been studied in detail, and it is difficult to explain the different behaviour of stands to K addition. Green River balsam fir tended to absorb larger quantities of Ca and Mg than spruce in the lowland regions. It is conceivable that the Green River soil contained higher Ca concentrations than the lowland soils. In agreement with the concept of K intensity in soil (*Beckett 1964*), high contents of divalent ions may lower K uptake even though the concentration of soluble and exchangeable K may remain unchanged.

Fornes *et al.* (*1970*) observed differences in the response of adjacent red pine and Norway spruce plantations to K fertilization of a sandy soil. They attributed this variable behaviour of the two species to differences in their mineral requirements. It is possible that such species differences also explain, in part, the variation in response patterns of our experiments.

Data gained from the six experiments are not sufficient to derive quantitative relationships between soil properties and fertilizer response nor to prepare treatment recommendations that guarantee maximum growth increases in the various regions of the province. However, this information has provided the basis for continued study. Using single-tree plots we are now engaged in determining response surfaces, emphasizing N and P at lowland black spruce sites and N and K at fir and spruce-fir sites in the elevated regions of New Brunswick.

SOME ECONOMIC ASPECTS OF FOREST FERTILIZATION IN EASTERN CANADA

A realistic example showing benefits to be derived from forest fertilization has been given recently by Pritchett and Hanna (*1969*). A slash pine plantation producing 30 cords per acre within a 25-year rotation on poorly drained sandy soil in the southeastern region of the United States may yield an additional 6 cords per acre with 200 pounds of concentrated superphosphate applied per acre after planting. With a stumpage price of $8 per cord and fertilization cost of $10 per acre, the return on the fertilizer investment is 6.5 percent, compounded annually for 25 years.

Although fertilization is being carried out on an operational scale within the latitudes of the northern forest, the economic aspects of such treatments have not been tested extensively. Sufficient information seems to be available for estimating the cost of fertilizer treatment (*Anderson 1969*), but biological information does not appear to be adequate for predicting growth responses reliably. Schweitzer (*1971*) was uncertain whether the available experimental evidence is adequate for justifying the large investments for fertilization in the Pacific Northwest of the United States.

Swan (*1970b*) dealt with the economic aspects of forest fertilization in Canada in a paper presented to the Canadian

Council of Resource Ministers. He pointed out that very few response data from eastern Canadian forest fertilization trials are available; but he indicated that, based chiefly on Swedish experience, the cost of fertilizer-grown wood, on the stump, could range from less than $5 per cunit, in favourable circumstances, to several times this in an unfavourable situation. He stressed that it is the cost of wood delivered to the mill that is of key importance to the wood-using industries, and that the main economic justification for forest fertilization under conditions where the allowable cut exceeds the actual cut is its potential for reducing hauling cost by increasing the productivity of sites relatively close to the mill.

Swan indicated the need for cost-sharing agreements between the landlord (the province) and the tenant (the limit holder) so as to provide an incentive to the latter to undertake forest-fertilization practices; alternatively, the province could waive stumpage charge on fertilizer-grown wood. He added that, with the continually diminishing reserves of readily accessible virgin forest and the steadily increasing demand for wood, there is only one way for the value of wood to go—up. As the value of wood rises, so does the incentive to increase yields, especially in stands close to the industries. He concluded that fertilizers would therefore seem to have an important role to play in the more intensive forestry of tomorrow.

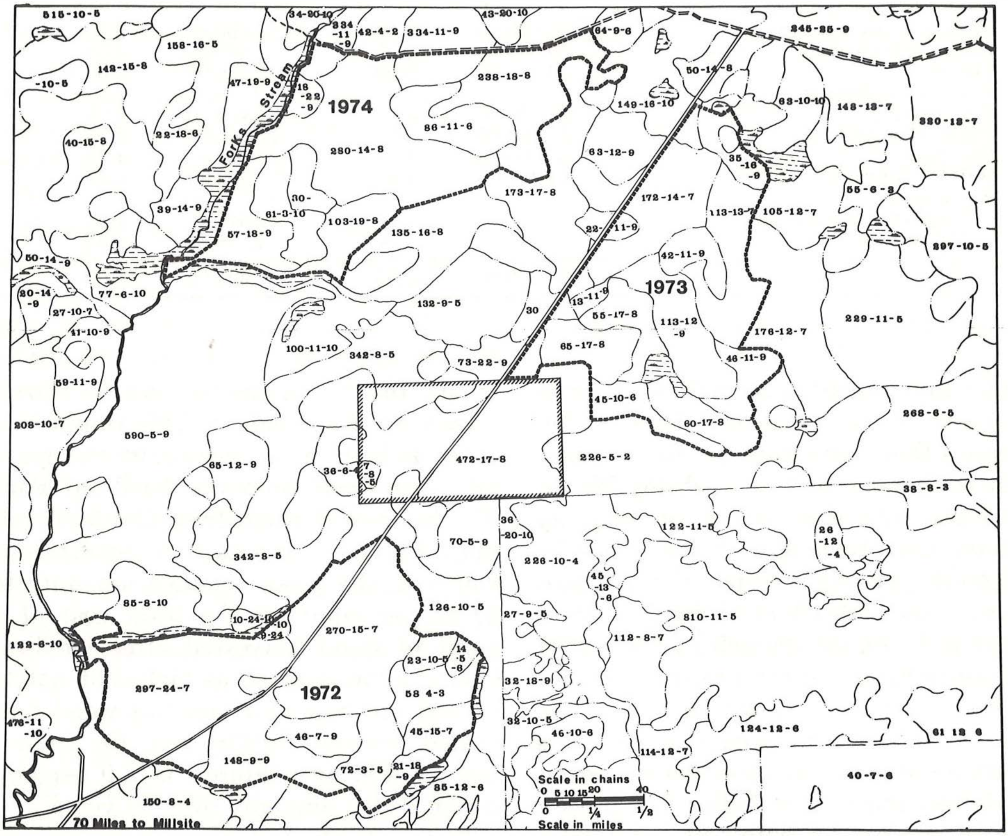
The variability in stocking, yield, and composition of naturally regenerated stands may prove to be a difficulty in forest fertilization on operational scale in eastern Canada. Care must be taken when the results from small experimental plots are used to predict response in large-scale fertilization. Experimental plots are usually chosen in uniformly stocked portions of the stand. Growth rates and fertilization response determined on such plots would tend to be higher than the average growth and response on a large block of forest land that has been fertilized from the air.

Forest conditions in the eastern lowland portion of New Brunswick are exemplified in a type map (fig. 6), prepared by one of the forest industries of the province and slightly modified for the purpose of this discussion. Within the relatively small area marked for cutting in 1972, the variability of stands is such that uniform treatment would not have been justifiable had the company decided to fertilize this area 8 to 10 years before cutting. The large 297-acre block with 24 cunits of harvestable pulpwood is probably over-mature, and present losses through wind breakage may be larger than potential gains from fertilizer treatment. Other smaller blocks support stands with a softwood volume too low to be considered for fertilizer treatment. The only portion that could have been recommended for fertilizer treatment is the irregularly shaped 270-acre block that now supports an average of 15 cunits of merchantable softwood per acre.

Assuming that the company operating in this area wished to improve future stand yield, it could select for fertilization an area such as the rectangular 400-acre block immediately above the 1972 cut. This block comprises a large portion of a 472-acre stand with 80 percent black spruce and balsam fir and a present merchantable volume of 17 cunits per acre. Based on experience gained with similar stands and soil, application of urea at the rate of 400 pounds per acre and of triple superphosphate at the rate of 200 pounds per acre may be recommended.

This treatment, if made in 1973, would be expected to improve the yield by a minimum of 2 cunits per acre over the next 10-year period. Merchantable volume at the time of harvesting would be expected to be 24 cunits per acre or larger instead of 22 cunits per acre. Assuming that experience gained in the northwestern and southeastern regions of

Figure 6.—Type map showing stand distribution and yield in a black spruce area of central New Brunswick. Types are delineated by thin lines and identified by sets of figures giving acreage, yield (cunits/acre) of spruce and balsam fir wood, and proportion (tenths) of total volume consisting of spruce and balsam fir. Areas delineated by heavy broken lines are marked for cutting in year indicated. Map reproduced by courtesy of MacMillan and Rothesay, Ltd., Saint John, N. B.



the United States is applicable to conditions in eastern Canada, the cost of fertilizer treatment is estimated at $26.80 per acre. This includes purchase in bulk of urea at $65 per ton, triple superphosphate at $60 per ton, hauling and fertilizer storage at $6 per ton, and helicopter application at $20 per ton.

Stumpage prices of pulpwood are very low in eastern Canada, and the value of 2 cunits of fertilizer-grown wood would be far too small to pay the cost of fertilization. However, economists, management, and industrial foresters agree that benefits from fertilization are not limited to the value of the additional volume of wood. Savings may be realized in harvesting and transportation costs.

Table 5 shows the estimated cost of wood at mill site from the 400-acre block marked in figure 6. The given example is hypothetical, as none of the amounts listed represents actual costs incurred by any one company. However, the given per-cunit amounts are believed to be representative for New Brunswick conditions (per-

Table 5.—Hypothetical example of cost of wood at mill site from a 400-acre block located 70 miles from the mill and would yield 8,800 cunits without treatment and 9,600 cunits with fertilizer addition 10 years before cutting

Item	Without fertilization		With fertilization	
	Total harvest		Total harvest	
	Dollars	*Cunits*	*Dollars*	*Cunits*
Felling & processing	83,600.00	9.50	83,600.00	8.70
Off-road transport	30,800.00	3.50	33,600.00	3.50
Delivery	79,200.00	9.00	86,400.00	9.00
Stand establishment & protection	26,400.00	3.00	26,400.00	2.75
Support functions	26,400.00	3.00	26,400.00	2.75
Stumpage	39,600.00	4.50	39,600.00	4.13
Service functions	13,200.00	1.50	13,632.00	1.42
Treatment:				
Fertilizer & application	—	—	12,640.00	1.32
Interest (2.9%)	—	—	4,128.00	0.43
Total	299,200.00	34.00	326,400.00	34.00

sonal communication from T. C. Bjerkelund and W. G. Paterson). It is further assumed that harvesting was mechanized, with equipment of the Koehring-Waterous type. With this system, productivity is determined by length of tree bole to be processed per unit volume of wood harvested. Since the effect of fertilization is found in increased diameter growth over the entire length of the tree, and since it does not noticeably affect the height of the tree, the cost of felling and processing of the additional fertilizer-grown wood is negligible. The cost of felling and processing of the total amount of wood from the 400-acre block would then remain unchanged, and the cost per cunit of wood could be noticeably reduced with fertilization.

The amount allotted per cunit for stand establishment and protection is reduced with fertilization because the area involved remains unchanged. Similarly, savings are materialized on a per-cunit basis in support and service functions, which include road construction and maintenance, buildings, transportation of men, goods and materials, accounting, etc. If fertilization is carried out by a company on leased land, it would be reasonable to expect that stumpage payments to the landowner for fertilizer-grown wood are waived. This would lead to a reduction in per-cunit stumpage price for wood from the fertilized area. To the cost of wood from fertilized soil must be added the cost of fertilization, which in the given example amounts to $1.32 per cunit. If the total cost of 1 cunit of wood harvested after fertilization is allowed to be as high, but not to exceed the cost of 1 cunit of wood harvested without fertilization, the investment would bear interest at 2.9 percent, compounded annually over 10 years.

The individual items contributing to the total cost of wood with and without fertilization must be expected to vary widely, depending on woodland conditions and efficiency of company operations. The benefits to be derived from fertilizer treatment must therefore be evaluated carefully in each case. The hypothetical interest rate of 2.9 percent may be substantially higher in some cases and lower in others. Whether or not a company would wish to fertilize under condition of the above example would depend on several factors, foremost wood supply, market stability, and labour relationships.

CONCLUSIONS

Forest growth in eastern Canada is commonly limited by nutrient shortage. Nitrogen deficiencies seem to be most frequent. Probably as a result of low temperatures and reduced biological activity in soil, deficiencies usually develop after stand closure. Stands are characterized by low foliar N contents and very low concentrations of mineral N in the forest floor, a major feeding zone. These stands respond to N additions with increased volume growth.

Urea appears to be a suitable N carrier, although care must be taken in experimental work because control areas may be contaminated by absorption of volatilized NH_3. Response to addition of P may be expected under conditions of impeded drainage and low concentrations of readily available P in the forest floor. Fertilizer P may act independently or may interact positively with N.

On well and excessively drained sites with deep rooting, K deficiency may occur. As in the case of P, fertilizer K may act independently of or interact positively with N to improve growth of closed stands and young plantations.

Fertilizer use on an operational basis would require careful study of soil and stand conditions before treatment. A single application of N may not always produce the desired results. In some instances, such a treatment may remain entirely ineffective. Maximum returns from fertilization can be expected only if such treatments establish and maintain nutritional balance.

Fertilizer use may be attractive to industries whose wood supplies are diminishing and whose operations are mechanized. It may not be profitable for an owner of woodlands to fertilize unless he harvests and delivers wood to the processing centres. Stumpage prices of wood are usually too low in eastern Canada for recovery of investment in fertilization. Major returns are in reduction of harvesting and delivery costs.

REFERENCES

Anderson, H. W.
1969. DOUGLAS-FIR REGION AERIAL FERTILIZATION MAKES STRIDES IN A BRIEF SPAN OF YEARS. Forest Ind. 96(12): 30-32.

Armson, K. A.
1972. FERTILIZER DISTRIBUTION AND SAMPLING TECHNIQUES IN THE AERIAL FERTILIZATION OF FORESTS. Univ. Toronto Fac. Forest. Tech. Rep. 11:28.

Armson, K. A., and R. Calvert.
1971. THE GROWTH RESPONSE OF JACK PINE TO NITROGEN AND PHOSPHORUS. Univ. Toronto Fac. Forest. Glendon Hall Lab. Annu. Rep. 1970-71:4.

Beckett, P. H. T.
1964. STUDIES ON SOIL POTASSIUM. I. CONFIRMATION OF THE RATIO LAW; MEASUREMENT OF THE POTASSIUM POTENTIAL. J. Soil Sci. 15:1-8.

Bernier, B., M. Brazeau, and C. H. Winget.
1972. GASEOUS LOSS OF AMMONIA FOLLOWING UREA APPLICATION IN A BALSAM FIR FOREST. Can. J. Forest. Res. 2:79-82.

Bhure, N. D.
1970a. NITROGEN LOSSES BY VOLATILIZATION FROM UREA APPLIED TO FOREST SOILS. Can. Forest. Serv. Dep. Environ. Bi-Mo. Res. Note 26(3): 30-31.

Bhure, N. D.
1970b. SOME FACTORS AFFECTING RELEASE OF NITROGEN FROM MOR HUMUS UNDER DIFFERENT FOREST STANDS. Can. Dep. Environ. Forest. Serv. Inf. Rep. N-X-40:12.

Brouzes R., J. Lasik, and R. Knowles.
1969. THE EFFECT OF ORGANIC AMENDMENT, WATER CONTENT, AND OXYGEN ON THE INCORPORATION OF N_2 BY SOME AGRICULTURAL AND FOREST SOILS. Can. J. Microbiol. 15:899-905.

Chu, J. P-H, and R. Knowles.
1966. MINERALIZATION AND IMMOBILIZATION OF NITROGEN IN BACTERIAL CELLS AND CERTAIN SOIL ORGANIC FRACTIONS. Soil Sci. Soc. Amer. Proc. 30: 210-213.

Fornes, R. H., J. V. Berglund, and A. L. Leaf.
1970. A COMPARISON OF THE GROWTH AND NUTRITION OF *Picea abies* (L.) KARST. AND *Pinus resinosa* AIT. ON A K-DEFICIENT SITE SUBJECTED TO K FERTILIZATION. Plant & Soil 33:345-360.

Gagnon, J. D.
1964. RELATIONSHIP BETWEEN SITE INDEX AND FOLIAGE NITROGEN AT TWO CROWN LEVELS FOR MATURE BLACK SPRUCE. Forest. Chron. 40(2):169-170.

Gagnon, J. D.
1969. EFFECT OF FERTILIZING AND SCARIFYING ABANDONED FARMLAND. Can. Dep. Environ. Forest. Serv. Bi-Mo. Res. Note 25(1):7.

Handley, W. R. C.
1954. MULL AND MOR FORMATION IN RELATION TO FOREST SOILS. Forest. Comn. Bull. 23. 119 p.

Heiberg, S. O., and D. P. White.
1951. POTASSIUM DEFICIENCY OF REFORESTED PINE AND SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15:369-376.

Heinsdorf, D.
1968. Ernährung and Wachstum Junger Kiefern auf einem an Magnesium und Kalium Armen Talsandboden nach Mehrmaliger Mineralischer Dungung. Arch. Forstw. 17(8): 813-838.

Hesselman, H.
1917. Studier over Salpeterbildningen i Naturliga Jordmaner och dess Betydelse i Vaxtekologiskt Avseende. Statens Skogsforsoksanst. Medd. 13-14:297-528. (German summary).

Hoyt, J. S.
1972. Growth increases after fertilization in a mature jack pine stand. M.Sc.F. thesis, Univ. New Brunswick, Fredericton.

King, H. B.
1972. Nitrogen transformations in forest floor and b horizon samples of podzolic soils in New Brunswick. M.Sc.F. thesis, Univ. New Brunswick, Fredericton.

Knowles, R., and J. Lefebvre.
1971. Field, greenhouse and laboratory studies of the transformation and translocation of ^{15}N-labelled urea in a boreal forest black spruce system. FAO/IAEA Symp. Use Isotopes and Radiation Res. Soil-Plant Relat. Incl. Appl. Forest. IAEA/SM 151/47 Vienna.

Krause, H. H.
1971. Reactions of maturing black spruce stands to n, p and k additions. Agron. Abstr.: 119.

Leech, R. H.
1965. Fertilization of red pine plantations on sandy slopes. Ontario Dep. Lands and Forests Res. Rep. 68:113.

Leech, R. H.
1967. Fertilization of red pine on a sand plain. Ontario Dep. Lands and Forests Res. Rep. 72:53.

Leech, R. H.
1969. Response of a jack pine plantation to urea and potash fertilizers. Ontario Dep. Lands and Forests Res. Rep. 88: 44.

Liming, F. G.
1957. Homemade dendrometers. J. Forest. 55: 575-577.

Lowry, G. L., and P. M. Avard.
1967. Nutrient content of black spruce needles. ii. Variation with crown class and relationships to growth and yield. Pulp Paper Res. Inst. Can. Woodlands Res. Index 188:22.

Mahendrappa, M. K.
1969. Ammonia volatilization from urea-treated soil under a black spruce stand. Agron. Abstr.: 125.

Mahendrappa, M. K., and E. D. Ogden.
1971. Contributions of stemflow, throughfall and rain to the nitrogen cycle in a black spruce stand. Agron. Abstr.: 119.

Manning, G. H., and H. R. Grinnell.
1971. Forest resources and utilization in Canada to the year 2000. Can. Dep. Environ. Forest Serv. Pub. 1304. 88 p.

McFarlane, D. M., and H. H. Krause.
1972. Soil factors limiting black spruce growth in central New Brunswick. Can. Soc. Soil Sci. Annu. Meet. Charlottetown, P.E.I. 15 p.

Morrison, I. K.
1972. Variation with crown position and leaf age in content of seven elements in leaves of Pinus banksiana lamb. Can. J. Forest. Res. 2:89-94.

Pritchett, W. L., and H. Hanna.
1969. Results to date, potential gains in southeast generate cautious optimism. Forest Ind. 96(11):26-28.

Rennie, P. J.
1972a. A tentative fractionation of the principal canadian tree species into broad eco-units to aid in the distribution of forest fertilization trials. Can. Dep. Environ. Forest. Serv. 25 p.

Rennie, P. J.
1972b. Forest fertilization in Canada. Can. Dep. Environ. Forest Serv. Rep. 7 World Forest. Congr. Buenos Aires. 28 p.

Roberge, M. R.
1970. Behaviour of urea added to unsterilized, steam sterilized, and gamma radiation—sterilized black spruce humus. Can. J. Microbiol. 16:865-870.

Roberge, M. R.
1971. Respiration of black spruce humus sterilized by heat or irradiation. Soil Sci. 111:124-128.

Roberge, M. R., and R. Knowles.
1965. Available nitrogen in a black spruce humus fertilized with urea. Pulp Paper Res. Inst. Can. Woodlands Res. Index 172:31.

Roberge, M. R., and R. Knowles.
1966. Ureolysis, immobilization, and nitrification in black spruce (*Picea mariana* mill) humus. Soil Sci. Soc. Amer. Proc. 30:201-204.

Robertson, R. G., and K. S. MacLean.
1968. Preliminary forest fertilization studies in Nova Scotia. Nova Scotia Dep. Lands and Forest. 14 p.

Romell, L. G.
1935. Ecological problems of the humus layer in the forest. Cornell Univ. Agr. Exp. Sta. Mem. 170.

Rowe, J. S.
1959. Forest regions of canada. Can. Dep. N. Affairs and Nat. Resources Forest. Br. Bull. 123.

Salonius, P. O.
1972. Microbiological response to fertilizer treatments in organic forest soils. Soil Sci. 114:12-19.

Schweitzer, D. L.
1971. Forest fertilization in the Pacific Northwest, a case study. Forest Econ. Sub Group Workshop on Uncertainty in Forestry Investment Decisions Regarding Timber Growing, 15th Congr. IUFRO, Gainesville, Fla. 14 p.

Swan, H. S. D.
1969. Eastern Canada probes less costly wood—trees on good sites, near mills, fertilized. Forest Ind. 96(12):32-35.

Swan, H. S. D.
1970a. Relationships between nutrient supply, growth and nutrient concentrations in the foliage of black spruce and

JACK PINE. Pulp Paper Res. Inst. Can. Woodlands Pap. 19, 57 p.

Swan, H. S. D.
1970b. ECONOMIC ASPECTS OF FOREST FERTILIZATION IN CANADA. Can. Counc. Resource Min. Forest. Reader Background Pap. Forest. Seminar 1970:26---5-19. Winnipeg.

Swan, H. S. D.
1971. RELATIONSHIP BETWEEN NUTRIENT SUPPLY, GROWTH AND NUTRIENT CONCENTRATIONS IN THE FOLIAGE OF WHITE AND RED SPRUCE. Pulp Paper Res. Inst. Can. Woodlands Pap. 29, 27 p.

Weetman, G. F.
1962. NITROGEN RELATIONS IN A BLACK SPRUCE (*Picea mariana* MILL) STAND SUBJECT TO VARIOUS FERTILIZER AND SOIL TREATMENTS. Pulp Paper Res. Inst. Can. Woodlands Res. Index 129, 128 p.

Weetman, G. F.
1968. THE NITROGEN FERTILIZATION OF THREE BLACK SPRUCE STANDS. Pulp Paper Res. Inst. Can. Woodlands Pap. 6, 45 p.

Weetman, G. F.
1971. EFFECTS OF THINNING AND FERTILIZATION ON THE NUTRIENT UPTAKE, GROWTH AND WOOD QUALITY OF UPLAND BLACK SPRUCE. Pulp Paper Res. Inst. Can. Woodlands Paper 32, 18 p.

Weetman, G. F., R. Knowles, and S. Hill.
1972. EFFECTS OF DIFFERENT FORMS OF NITROGEN FERTILIZER ON NUTRIENT UPTAKE BY BLACK SPRUCE AND ITS HUMUS AND HUMUS MESOFAUNA. Pulp Paper Res. Inst. Can. Woodlands Rep. 39, 22 p.

Wittich, W.
1952. DER HEUTIGE STAND UNSERES WISSENS VOM HUMUS UND NEUE WEGE FUR DIE LÖSING DES ROHHUMUSPROBLEMS IM WALDE. Univ. Göttingen Schriftenreihe Forstl. Fak. vol. 14. 106 p.

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FOREST FERTILIZATION IN THE EASTERN UNITED STATES: CONIFERS

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ABSTRACT. Past and current forest-fertilization experiments have demonstrated that northeastern conifers respond favorably to nutrient supplements when deficiency conditions exist. No universal combination of nutrients or application rate has given response in all situations. Applications of fertilizer to forests are advocated only as a part of intensive silvicultural practice in situations where silvicultural and management objectives are well defined. Wide-scale extensive fertilizer applications in unmanaged natural forest stands are rejected because of high economic and possible environmental risks.

I APPROACH this discussion from the viewpoint of the forest-land manager looking at fertilization as a potential management tool, rather than as a forest scientist looking for details of research studies. I define forest fertilization as the addition of an inorganic or organic substance to stands of forest trees for the purpose of stimulating tree vigor and growth. With this definition in mind, I address my remarks to the following question:

What is the status of forest fertilization of conifers as a silvicultural tool in the Northeast today?

I will deal in general terms with research results of past studies and briefly outline present forest fertilization research, particularly field studies. And finally, I will give my views of forest fertilization as a forest management tool and try to point out some of the questions that must be answered in the future.

PAST RESEARCH

In searching the literature of field trials of fertilizer with northeastern conifers, I found that the work in New York has been concerned mainly with K deficiency and that studies at The Pennsylvania State University have been concerned mainly with treatment of sewage effluent.

The main conifers studied have been white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Ait.), the spruces (*Picea glauca* (Moench) Voss, *P. rubens* Sarg., *P. mariana* (Mill.) B. S. P., and *P. abies* (L.) Karst.) and balsam fir (*Abies balsa-*

mea (L.) Mill.). Mineral nutrition of other important northern conifers—hemlock *(Tsuga canadensis* (L.) Carr.), tamarack *(Larix larcina* (Du Roi) K. Koch), northern white-cedar (*Thuja occidentalis* L.), eastern redcedar (*Juniperus virginiana* L.), and pitch pine (*Pinus rigida* Mill.)—is known only through a few studies of foliage nutrient content and other basic aspects.

The northeastern region has, in comparison with other regions of this country, eastern Canada, and Europe, a relatively low frequency of published research findings (table 1) on the applied or practical aspects of fertilization of conifers as a silvicultural tool.

As early as 1927, greenhouse research was done on the nutrient requirements of black spruce, an economically important northeastern conifer (*Herbert 1927*). Beneficial effects of organic mulches (*Lunt 1951a, 1951b*) and inorganic salts (*Heiberg and White 1951*) and municipal waste water (*Sagmuller and Sopper 1962*) have all been demonstrated in field applications here in the Northeast. Results of field studies have not always been consistent: identical treatments with the same species in different locations have not always given the same response. This emphasizes the importance of soil type and other site factors in response to fertilizer.

The most clearly defined and best understood nutrient problem in the region is that of K deficiency on coarse-textured outwash soils of the Northeast (*Stone and Leaf 1967*). The work of the late S. O. Heiberg and his associates is an outstanding example of specifically defining a problem and demonstrating a solution. This work showed that a single application of K fertilizer to pine or spruce corrects a limiting growth factor, and a sustained growth response is obtained (*Heiberg and White 1951, Fornes et al. 1970*). This K deficiency is known to be a wide-ranging problem in Quebec (*Lafond 1958, Stone and Leaf 1967*) and Maine (*Stratton et al. 1968*).

A pilot-plant-scale application of K fertilizer from aircraft reported by White (*1956*) demonstrated the feasibility of large-scale practical applications. Summaries of the research and basic recommendations for treatment of K deficiencies and a similar problem with Mg elucidated by Stone *(1953)* were published in a practical version (*Heiberg et al. 1954*).

Yet, to the best of my knowledge, in the almost 20 years since this work was done, forest managers have not made use of these research findings by seeking out and treating the conifer plantations and natural stands that occur on the K-deficient sandy soils of the Northeast.

PRESENT RESEARCH

Basic research on nutrient requirements, uptake, utilization, and other fundamental ecological and physiological aspects of forest-tree nutrition is in progress at many of the major universities,

Table 1.—Numbers of papers about forest fertilization of conifers abstracted in Forestry Abstracts section 237: Silviculture, Amelioration of Forest Sites 1957-1971

Date	Location				
	Europe	Eastern Canada	United States		
			Northwest	Southeast	Northeast
1957-61	102	1	3	11	4
1962-66	81	6	4	9	4
1967-71	163	13	10	25	12
Total	346	20	17	45	20

agricultural experiment stations, and by the USDA Forest Service throughout the northeastern region.

Forest industry is currently sponsoring a fertilizer field trial in the spruce-fir forest type in cooperation with the University of Maine. This study is a factorial design with N, P, and K, and some additional N level treatments. Three study areas are located in eastern, north-central, and western Maine. The design and objectives of this work are similar to the Canadian comprehensive study described by Professor Krause. Results to date indicate a diameter growth response to the complete N-P-K treatment in the eastern Maine location but not in the other two. Lack of rainfall and consequently low soil moisture are suggested as possible reasons for lack of response *(Schomaker 1972)* in these areas.

Maine forest industries are also conducting some fertilizer experiments of their own. Scott Paper Company has fertilized about 300 acres in mature spruce-fir stands and regenerated spruce-fir cutover areas. Ammonium nitrate at rates of 100, 150, or 200 pounds of N per acre was applied from a helicopter. Height growth of young spruce and fir in the regenerating stands increased 10 to 45 percent above that on unfertilized areas. Data from mature stands have not been analyzed.

The Dead River Company has fertilized 325 acres with aerial applications of urea in mature and second-growth stands of primary softwood (spruce-fir-hemlock) species, mixed softwood-hardwood stands, and hardwood (birch-beech-maple) stands. Rates of application varied from 50 to 150 pounds of N per acre. Preliminary growth measurements indicate small but definite trends of increased growth of fertilized plots over controls. The Dead River Company has also started a more closely controlled study involving ground application of N, P, K, and minor elements in various combinations and amounts in a second-growth softwood stand.

Several other companies have less extensive but well-designed ground-applied fertilizer studies in progress. Oxford Paper Co. has applied N, P, K, and lime to various species and age classes. Great Northern Paper Co. has applied N, P, K, and lime to mature and regenerating softwood stands. Donworth Timberlands has tried trenching for drainage, combined with lime and N-P-K fertilizer, for regenerating black spruce stands.

There probably are other fertilizer trials that I do not know about elsewhere in the northeastern region. However, I know that forest managers are serious enough about exploring fertilization as a management tool to invest company funds in research projects. In most cases this work has been initiated on the recommendation of company executives. These people have seen fertilizer work in Europe or other regions of this country—sometimes within their own company—and they want to get information applicable to their northeastern lands.

The most immediate benefit to come from these first studies, particularly the larger scale aerial applications, is information about logistics of fertilization. The projects have been large enough to produce cost figures and data on some of the personnel, equipment, distribution-control, and sampling problems that will pertain to operational fertilization projects. None of the operational aspects were particularly discouraging, including the modest costs of $20 to $30 per acre.

Thus past basic studies and current operational-scale applications have demonstrated that fertilization can be a useful management tool here in the Northeast from both biological and management points of view.

FOREST FERTILIZATION CRITERIA

I do not believe that forest fertilization as a silvicultural practice can be applied on the same extensive basis as "forestry" or "forest management" is applied in the Northeast today. Fertilization is not a magic cure-all that can, all by itself, solve the woodland manager's problems of sustaining or increasing a wood supply from a fixed land base. Fertilization is but one input in intensive silviculture. It has a *place* in forest management along with protection, genetic selection, and the all-important control over species composition and stand density. But extensive and indiscriminate aerial applications of one kind of fertilizer at a fixed rate to vast areas of forest land could be extremely wasteful from an economic point of view and potentially hazardous to the environment.

We cannot simply accept forest fertilization as a good thing and set about fertilizing the forest. We must make certain that the potential productivity of the stand is obtained through the fundamental silvicultural inputs, particularly control of species composition and stocking levels. We must fertilize not the forest, but a crop. Specific selected trees must be supplied with required nutrients in such a manner that a specific growth-limiting factor is eliminated.

This implies an ability to diagnose nutrient deficiency problems in a specific way and to apply treatments that will solve the problem. To do this, we must be in the business of growing a crop. We must know what the crop is, and what our specific management objectives are.

These objectives cannot be as loose and extensively defined as our management of today's natural stands, whether of mature, semi-mature, or regeneration age classes. We need specific answers for our region to the age-old inquiries: Where?, What?, When?, and How? The *where* entails defining the species and soil-site situation that can be improved by additional nutrients. *What* asks for the nutrient element or element combinations and what source compound is required to best supply the deficiency. The *when* concerns stage within the rotation and seasonal timing of applications. The *how* covers methods of application, both mechanical distribution and method of placement.

RESEARCH VERSUS APPLICATION

We cannot afford, nor is it necessary to wait for research to answer each of the above questions with significantly demonstrated statistically proven answers. There is not enough time. I believe we are well enough versed in the art of forest fertilization to begin using it now as a silvicultural tool. The first applications should be well enough defined that anticipated benefits will economically justify the treatments applied. The well-defined potassium problem discussed earlier is an excellent example.

Feedback from success or failure of these practical ventures will gradually build up a technology of treatments that work—and sift out specific applications that do not work. From this basic backlog of experience in *how to* and *how not to* fertilize, research can define and conduct studies to answer some of the *why*'s. Interaction between this applied experience and the research answers will generate a strong foundation for intensive silvicultural practice—including forest fertilization.

REFERENCES

Fornes, F. H., J. V. Berglund, and A. L. Leaf.
1970. A COMPARISON OF THE GROWTH AND NUTRITION OF PICEA ABIES (L.) KARST AND PINUS RESINOSA AIT. ON A K-DEFICIENT SITE SUBJECTED TO K FERTILIZATION. Plant and Soil 33: 345-360.

Heiberg, S. O., and D. P. White.
1951. POTASSIUM DEFICIENCY OF REFORESTED PINE AND SPRUCE STANDS IN NORTHERN NEW YORK. Soil Sci. Soc. Amer. Proc. 15: 369-376.

Heiberg, S. O., E. L. Stone, and D. P. White.
1954. POTASH AND MAGNESIUM FERTILIZATION OF YOUNG PINE AND SPRUCE TREES. State Univ. N. Y. Coll. Forest. 7 p.

Herbert, P. A.
1927. A LABORATORY STUDY OF BLACK SPRUCE. J. Forest. 25: 437-442.

Lafond, A.
1958. LES DEFICIENCES EN POTASSIUM ET MAGNESIUM DE QUELQUES PLANTATIONS. Laval Univ. Forest Res. Found. Bull. 1. 24 p.

Lunt, H. A.
1951a. LIMING AND TWENTY YEARS OF LITTER RAKING AND BURNING UNDER RED PINE. Soil Sci. Soc. Amer. Proc. 15: 381-390.

Lunt, H. A.
1951b. EFFECT OF SLASH MULCH AND SLASH BURN ON PINE AND SPRUCE PLANTINGS. Conn. Agr. Exp. Sta. Bull. 548. 21 p.

Sagmuller, C. I., and W. E. Sopper.
1962. EFFECT OF MUNICIPAL SEWAGE EFFLUENT IRRIGATION ON HEIGHT GROWTH OF WHITE SPRUCE. J. Forest. 65: 822-823.

Schomaker, C. E.
1972. FERTILIZATION OF SPRUCE-FIR SITES IN MAINE. Univ. Maine School Forest. Resources Ann. Rep. 2 Proj. M/S-5008. 8 p.

Stone, E. L.
1953. MAGNESIUM DEFICIENCY IN SOME NORTHEASTERN PINES. Soil Sci. Soc. Amer. Proc. 17: 297-300.

Stone, E. L., and A. L. Leaf.
1967. POTASSIUM DEFICIENCY AND RESPONSE IN YOUNG CONIFER FORESTS IN EASTERN NORTH AMERICA. Colloq. Forest Fert. Proc.: 217-229. Jyjäskylä, Finland.

Stratton, K. G., L. O. Safford, and R. A. Struchtemeyer.
1968. TWO FERTILIZER STUDIES WITH WHITE PINE IN MAINE. Res. Life Sci. Summer 1968: 1-6.

White, D. P.
1956. AERIAL APPLICATION OF POTASH FERTILIZER TO CONIFEROUS PLANTATIONS. J. Forest. 54: 762-768.

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FOREST FERTILIZATION IN THE EASTERN UNITED STATES: HARDWOODS

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ABSTRACT. Attempts to improve growth rates of eastern hardwoods by fertilization date back to the early 1930's. Many reports have shown that many species growing on many different sites are responsive to various fertilizer additives. Unfortunately, however, only a small portion of this information is applicable to eastern hardwood forests. Much more research is needed to determine how widespread nutrient deficiencies may be in the northeast and to answer practical questions of how much, when, and where fertilizer amendments are necessary.

INTEREST in forest fertilization to increase production of wood fiber has escalated in the past decade. And for good reason. Well-designed field tests with a number of species have demonstrated favorable growth response—in some cases dramatic response—to fertilization. These results—and progress in fertilization research in general—have been summarized in a number of excellent reviews (*White and Leaf 1957*, *Duke University 1959*, *Arneman 1960*, *Walker and Beecher 1963*, *Tamm 1964*, *Mustoja and Leaf 1965*, *Armson 1967*, *Bengtson 1968*, *Baule and Fricker 1970*). Unfortunately, relatively little of this past work applies directly to hardwoods in the eastern United States.

In this paper we have attempted to provide an up-to-date progress report on fertilization of eastern hardwoods for increased fiber production.

ACCOMPLISHMENTS

The first experiments involving field fertilization to improve growth rates of eastern hardwoods date back to the early 1930's (table 1). Probably the first work was started by Wyman (*1936*) with young pin oak (*Quercus palustris* Muenchh.) near Ithaca, N.Y., in 1930–31. This test, conducted under lawn conditions, showed that diameter growth was increased for two to three seasons by a single application of N. In 1934, tests were made on mature American elm (*Ulmus americana* L.) and in

Table 1.—Summary of published hardwood field fertilization tests

Major species	Tree size	Nutrients tested	Location	Reference
American elm	Standards	N	New York	Pridham (1939)
Black walnut	Seedlings	N,P,K	Michigan	Schneider et al. (1970)
Cottonwood	Cuttings	N	Tennessee	Curlin (1967)
Dogwood	Understory	N,P,K; lime	Tennessee	Curlin (1962)
Green ash, American elm, red oak, black locust	Seedlings	N,P,K	Iowa	McComb (1949)
Honey locust	Saplings	P,K	Blue Ridge Mts.	Zarger and Lutz (1961)
Hybrid poplar	Cuttings	N,P,K	Quebec	Aird (1956)
Hybrid poplar	Seedlings	N,P,K	Quebec	Aird (1962)
Hybrid poplar	Saplings	N,P,K	Ohio	Aughanbaugh and Mitchell (1963)
Mixed oaks, sugar maple, beech, hickory, black gum, yellow-poplar, basswood, white ash	Standards	N	Southern New York	Mitchell and Chandler (1939)
Mixed oaks, red maple	Standards	N,P	Southern New York	Finn and Tryon (1942)
Mixed oaks	Standards	N,P; lime	Pennsylvania	Ward and Bowersox (1970)
Pin oak	Saplings	N	New York	Wyman (1936)
Pin oak, white ash, honey locust	Saplings	N,P,K; trace elements	Illinois	Himelick et al. (1965)
Red oak	Standards	N	New York	Pridham (1941)
Sugar maple	Standards	N,P,K	Massachusetts	Mader et al. (1969)
Sweetgum, water oak, willow oak	Poles	N,P,K	Louisiana	Broadfoot (1966)
Sweetgum	Poles	N,P,K	Illinois	Gilmore et al. (1971)
Sycamore	Cuttings	N,P,K	Piedmont	Huppuch (1960)
Sycamore	Seedlings	N,P,K	Georgia	Broadfoot and Ike (1968)
Various	Saplings, poles, standards	N,P,K Mg; trace elements	Illinois	Neely et al. (1970)
White ash	Seedlings	N,P,K; lime	Ohio	Cummings (1941)
Yellow-poplar	Seedlings	N,P	Georgia	McAlpine (1959); Ike (1962)
Yellow-poplar	Seedlings	N	Ohio	Chapman (1933)
Yellow-poplar	Poles	N,P,K	Michigan	Finn and White (1966)
Yellow-poplar, mixed oaks, hickory	Various	N,P	Tennessee	Farmer et al. (1970)
Yellow-poplar	Seedlings	N,P	Tennessee	Farmer et al. (1970)
Yellow-poplar	Poles	N,P,K; Ca	Ohio	Vimmerstedt and Osmond (1970)
Yellow-poplar	Seedlings	N,P,K	Mississippi	Blackmon and Broadfoot (1970)

1936–40 on roadside red oak (*Quercus rubra* L.) (*Pridham 1939, 1941*). In these tests, N fertilization produced a marked response in foliage color, but diameter growth was not substantially increased.

Also in the early 1930's, Chapman (*1933*) found that yellow-poplar (*Liriodendron tulipifera* L.) responded to ammonium nitrate applied to silt loam soils of Ohio. On acid soils of low fertility, however, applications of N, P, K and dolomitic limestone to white ash (*Fraxinus americana* L.) and yellow-poplar failed to produce a marked growth response (*Cummings 1941*).

In 1935-37 Mitchell and Chandler (*1939*) established a series of field plots in southern New York to test the effects of N rates on growth of mixed northern hardwoods. From this work, the first extensive experimentation in forest stands and now a classic, they reported response and "optimum" foliar N concentrations for 11 hardwood species. In a subsequent evaluation, Chandler (*1943*) noted that response had persisted for 7 years, and at that time fertilized white ash were still growing at twice the rate of unfertilized control trees.

In 1938, Finn and Tryon (*1942*) began field tests on the Black Rock Forest to compare the effects of leaf mould, N, and P fertilizer additions on growth of mixed oaks and red maple. Best growth was obtained with leaf mould, followed by P, and then N. The increase measured over 3 years amounted to 64, 42, and 23 percent more than growth of controls, respectively.

Beginning in 1939 and continuing through the mid-40's, McComb (*1949*), in Iowa, conducted extensive fertilization tests with red oak, American elm, green ash (*Fraxinus pennsylvanica* Marsh.), and black locust (*Robinia pseudoacacia* L.). Although many of these tests were run in pots, he also made field experiments showing that N and P deficiencies were factors limiting growth of ash and red oak on forest soils; that N was more severely limiting than P; and that once the initial N deficiency was overcome, the addition of P was associated with a further growth increase. Black locust showed response to P only, indicating that this leguminous tree was nodulated and fixing its own N.

In the following decade and early 1960's several hardwood fertilization studies dealing almost entirely with planted seedlings on non-forest sites indicated the responsiveness of yellow-popular, honey locust (*Gleditsia triacanthos L.*), hybrid-poplar (*Populus* cv. Charkowiensis X *P.* cv. Caudina, *P.* cv. Generosa), and sycamore (*Platanus occidentalis* L.) to fertilizer additives (*Aird 1956 and 1962, McAlpine 1959, Huppuch 1960, Zarger and Lutz 1961, Ike 1962, Aughanbaugh and Mitchell 1963*).

And in another study, dogwood (*Cornus florida* L.) showed a marked response to fertilization in tests evaluating N, P, K and dolomitic lime under forest conditions (*Curlin 1962*). Response, attributed exclusively to N, was greatest during the first season, diminished rapidly thereafter, and was not significant during the third and fourth seasons.

More recently, fertilization trials in established stands have provided useful information about the extent of nutrient deficiencies and the duration and degree of response obtainable. In a slow growing yellow-popular stand in Michigan, N-P-K fertilization increased height growth 100 percent, diameter growth 85 percent, and lasted in some degree for 5 years (*Finn and White 1966*). In Massachusetts, a threefold increase in diameter growth of declined sugar maple (*Acer saccharum* Marsh.) occurred after a complete N-P-K treatment (*Mader et al. 1969*).

In mixed upland hardwood stands in the Tennessee Valley, where widespread N and P deficiencies occurred, 5-year basal-area growth was increased approximately 50 percent by N-P fertilization

(*Farmer et al. 1970*). In Pennsylvania, N and lime applications in a mixed upland oak stand produced a 45-percent increase in volume over a 5-year period (*Ward and Bowersox 1970*). In southern Illinois, 5-year basal area and height growth of sweetgum (*Liquidambar styraciflua* L.) were increased 60 and 33 percent, respectively, by N fertilization (*Gilmore et al. 1971*).

In Ohio, the best 2-year volume growth of yellow-poplar was obtained at high rates of N and P in combination with low rates of K (*Vimmerstedt and Osmond 1970*). In Mississippi, annual N and N-P-K applications produced 65- and 44-percent responsees in diameter and height growth, respectively, in sweetgum, water oak (*Quercus nigra* L.), and willow oak (*Quercus phellos* L.) stands (*Broadfoot 1966*). Similar responses for other timber species in various sections of the country have also been observed (*Blackman and Broadfoot 1970, Broadfoot and Ike 1968, Carter and White 1970, Curlin 1967, Farmer et al 1970, Jones and Curlin 1968*). And positive responses of many species of hardwood shade trees to fertilization have been demonstrated in Illinois (*Himelick et al. 1965 and Neely et al. 1970*)

Pot tests with yellow birch seedlings revealed acute P and N deficiencies as well as the need for limestone in acid soils from northern New Hampshire (*Hoyle 1969, 1970*). The limestone, in addition to overcoming deficiencies, served to reduce abnormally high Mn and Al concentrations that were thought to be near toxic levels. Field tests with these amendments are now under way.

In West Virginia, a factorial experiment with potted red oak seedlings grown in a sandy alluvial soil showed that N was the primary limiting nutrient; that P applied simultaneously with N gave additional response once the N deficiency was overcome; and that further response to K was obtainable once N and P were adequately supplied (*Auchmoody 1972a*).

Another pot test with both forest and old-field soils from Iowa and Missouri indicated N and P deficiencies for maximum growth of planted red oak seedlings (*Phares 1971a*). Additional study of growth in relation to light supply and nutrients confirmed that fertilization was necessary to obtain maximum red oak seedling production on these soils, but that fertilization could not overcome adverse effects stemming from low light intensities (*Phares 1971b*).

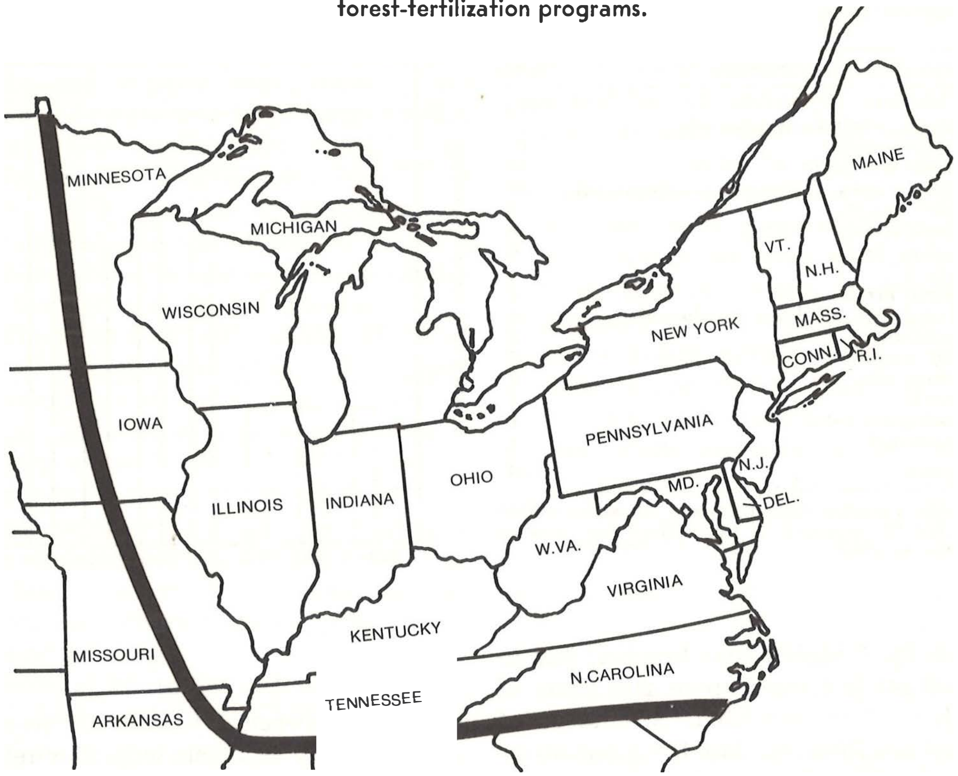
Because ultimate evaluation of forest fertilization practices must include changes in log quality as well as changes in growth rate, the effects that fertilization might have on epicormic-branch formation is an important issue. Kormanik and Brown (*1969*) found that heavy fertilization stimulated suppressed buds to form epicormic branches on sweetgum. A different study with red oak and yellow-poplar showed that moderate rates of N, P, and K did not stimulate epicormic branches to form, but that N had a strong tendency to increase growth of existing epicormics, particularly on the upper bole, where light was not such a limiting factor (*Auchmoody 1972b*).

CURRENT RESEARCH PROGRAMS

To obtain information about current fertilization activities in the Northeast, we made 73 inquiries to industrial, university, and federal installations that we knew or thought might be conducting fertilization research with hardwoods.

The survey area was delineated by North Carolina and Tennessee on the south and by sections of Missouri, Iowa, and Minnesota on the west (fig. 1). We consulted the major pulp and paper companies and allied industries listed in the *Wood and Woodlands Directory* (*1970*). institutions offering professional education in forestry, federal forest experiment stations, the Tennessee Valley Authority,

Figure 1.—The area surveyed for information about current forest-fertilization programs.



and the Oak Ridge National Laboratory.

Each was asked if they had fertilization work in progress and, if so, to supply a brief set of statistics about it. Replies were received from more than 90 percent of those asked. The following information is based on those replies, many of which came from the people or organizations represented here at this meeting today.

In the Northeast at least 95 field fertilization studies are now under way (see appendix). Of these, 47 are being conducted by universities, 41 by federal agencies, and 7 by industry. (Field studies by seven other investigators were not known to the author at the time this report was prepared, and they are not discussed here; this work, mainly with sycamore and sweetgum, is listed in the appendix.)

Eighty-three of the 95 studies—about 87 percent—are oriented toward increasing forest growth rates. The other 12 are concerned with such issues as water quality after fertilization of complete watersheds, fertilizer/genetic interactions, effects on wood properties, and influence on seed and sap production.

Of the 83 growth studies, 29 apparently are also oriented toward identifying specific limiting nutrients while the other 54 are oriented mainly toward the degree of response that might be obtainable. It is noteworthy that optimum rates of fertilization are being studied in 29 experiments.

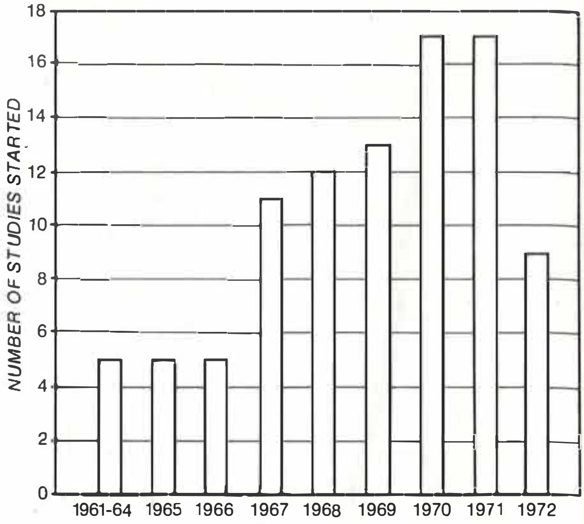
Seventy of the tests—about 75 percent—are concerned with established stands; and 25 deal, for the most part, with planted seedlings. The majority of tests in established stands are with trees fall-

Table 2.—Number of active hardwood field-fertilization tests, by species.

Species	Tests
	No.
1. Mixed northern hardwoods	17
2. Yellow-poplar	17
3. Black walnut	16
4. Upland oaks (primarily northern red)	16
5. Hard maple	15
6. Black cherry	8
7. Yellow birch	6
8. Aspen	4
9. Paper birch	4
10. Mixed Appalachian hardwoods	4
11. Sycamore	3
12. Red maple	3
13. White ash	2
14. Beech	1
15. Sweetgum	1
16. Basswood	1
Total[a]	118

[a] Total exceeds the number of active field tests due to inclusion of more than one species in some studies.

Figure 2.—Age and number of hardwood fertilization tests in the northeastern United States.



ing in the 30-to-70-year bracket, but in several studies trees up to 200 years of age have been fertilized. A number of species are involved, but the greatest interest is with mixed northern hardwoods, yellow-poplar, black walnut, sugar maple, and the upland oaks (table 2).

It is significant that 72 percent of the work under way is less than 5 years old, and 45 percent of the tests are only in their third growing season or less right now (fig. 2). Moreover, except for one small study, none is older than 10 years.

Nineteen of the tests are located in unthinned stands and 45 are in thinned stands; 13 tests in thinned stands include thinning without fertilization as a separate treatment. Thirty-one studies are with younger stock—both planted and natural—located on cutover forest land or on nonforest sites.

N is being tested either singly or in combination with other nutrients in all but five studies. The most commonly used N source was ammonium nitrate, which was used in four times as many tests as urea. Application rates for N ranged from a low of 33 pounds/acre to a high of 900 pounds/acre, but the majority were between 150 and 300 pounds/acre. In only two tests were slow-release N fertilizers being evaluated.

P, applied either singly or in combination with other nutrients, was included in 66 tests—about 70 percent of the total. The use of triple superphosphate outnumbered the use of normal superphosphate by approximately 3 to 1. Application rates varied from a low of 13 to a high of 262 pounds/acre P(30–600 pounds/acre P_2O_5), but most applications were between 44 and 87 pounds /acre P(100–200 pounds/acre P_2O_5).

K was being used in 52 tests; usually, although not always, in combination with N and P. The most common source of supply was muriate of potash. Application rates varied from 33 to 332 pounds/acre (40–400 pounds/acre K_2O).

Magnesium, apart from that supplied by lime, was being tested in only six studies. Lime was included in 19 tests and "complete" fertilizers were being used in 20 tests. Lime has been applied at rates up to 10 tons/acre.

The experimental plots being used were generally small. Plot size varied from 0.01 acre to 10 acres, but 0.10-acre plots and smaller were common and those 0.50 acre and larger were uncommon. Most studies had multiple tree plots, but 16 studies were based only upon single trees. The most common experimental unit was individual trees (56 studies), but changes in stand productivity were being evaluated in 34 cases.

The most frequently measured indicator of response was d.b.h. (83 studies), followed by nutrient uptake (51 studies), height (48 studies), diameter growth at heights above breast height (9 studies), and foliar weight (9 studies). Other variables mentioned included water quality, epicormic branching, survival, seed production, frost resistance, root development, sap characteristics, and aboveground biomass.

Sixty-eight studies included soil analysis, plant analysis, or both. Forty-one studies involved both; 13 other studies involved soil analyses and 14 involved tissue analyses only.

Of the 83 studies oriented toward increasing growth rates, 36 reported positive response to fertilization, 10 indicated no response, and 37 were uncertain—mainly because studies were new or because measurements had not yet been taken.

STATE OF THE ART

Published results, together with interim results from studies in progress, show that we have learned many details, since 1930, about the response of hardwoods to fertilization. A status report such as this seems an appropriate place to ask: What do these details add up to? Where do we stand? What general conclusions can we draw from our past efforts?

We do not pretend that our list is complete, but we believe that the following major conclusions provide a strong foundation for future research:

- There is unquestionable evidence that a number of hardwood species have the potential ability for responding in growth rate to fertilization. Response has occurred on a variety of sites and with a range of age classes from young seedlings to middle-aged trees. Because certain hardwoods are generally recognized as being more nutrient-demanding than conifers, there is speculation that they might respond more vigorously to fertilization. While this may be correct, it is also generally true that natural stands of these species normally occupy the most fertile sites available.
- Response to fertilization depends on the supply of essential soil nutrients relative to the nutrient requirements of the species, genetic limitations on growth, and to growth-limiting site parameters such as moisture regime, soil volume, and climate. Fertilization will not increase productivity when there are no nutrient deficiencies or when growth is limited by other factors.
- N is by far the primary growth-limiting nutrient in hardwood forests, but response from P may frequently be forthcoming after the N deficiency is overcome. Although instances exist where response has been greatest with "complete" fertilization as compared to N only, rarely has response to these other nutrients occurred when they have been applied singly without N. Liming may be necessary in highly podzolized soils because of Al and Mn toxicity. In both pot and field tests, liming has effectively reduced Mn concentrations in yellow birch and sugar maple foliage.
- Response to N fertilization, where it occurs, is rapid and detectable the first year, but often is greatest in the second

season. N increases leaf size, mass, and number; produces dark green foliage; retards leaf abscission; and may increase photosynthetic efficiency.

- The duration of response from a single fertilizer application in hardwood forests has not been clearly established. But, unlike the situation in agriculture, effects upon growth persist for several seasons. The length of time that fertilizer nutrients remain available for growth depends a great deal on the material used, the particular nutrients of concern, soil conditions, and topographic configuration of the site. Response duration from a single application of N is apparently quite variable, lasting for time spans as short as 2 years and in excess of 18 years (personal communication from R. H. Finn, based on stem analysis of trees fertilized in the 1930s on Black Rock Forest plots). Variation in loss from NH_3 volatilization and leaching of mobile NO_3 ions, particularly during the dormant season and on steep topography, is suggested as the possible cause. With P, rapid conversion of available into unavailable forms particularly in acid soils well supplied with iron and aluminum, may seriously limit the time that this element remains available for absorption.

- The amount of response obtainable from fertilization is also variable, but apparently depends on pretreatment growth rates (a function of site quality), species, and rate of fertilization. Stand density is also an important factor ,and it is well known that yields may be affected as much by spacing as by any nutrient treatment. Despite the variation in response to fertilization, the data available for stands not showing obvious nutrient disorders or abnormally slow pretreatment growth rates indicate that growth may be increased on the average by as much as 80 percent.

- Field fertilization trials are now the only reliable method of identifying nutrient deficiencies. Neither soil nor foliar tests have yet been field-calibrated and perfected for diagnosis of critical nutrient regimes in hardwood forests. Although data on soil and foliar nutrient composition as they relate to response are accumulating, they are too fragmentary for reliable response predictions to be developed.

- Thus the major conclusion to be drawn from work to date must be that we have only scratched the surface of what needs to be learned about fertilization of eastern hardwood forests.

RESEARCH NEEDS

After summarizing what is now known about fertilization of eastern hardwood forests, we can now list problems that we think should be placed high on the list of research priorities. We have grouped these into five categories, focusing primarily upon practical physical aspects associated with the use of fertilizers for increasing production of wood fiber. However, it is not our intention to slight economic studies, and especially the many required fundamental studies that necessarily are associated with these leading issues. We stress the importance of investigating basic problems to the depth necessary for complete understanding.

I. Establish Additional Field-Fertilization Tests

Despite 40 years of research, we still have little definite information about how widespread and how serious nutrient deficiencies may be in the Northeast and how they can be recognized. Field-fertilization trials are now the most dependable method for identifying such deficiencies, and the only dependable method for quantifying response. And we have only begun to tackle the practical application problems of what nutrients to apply, in what form, how much, where, and when.

Although significant increases in the number of field trials have occurred in recent years, current studies are hopelessly inadequate for providing the information needed, even for the most important species. Moreover, current tests are so diverse in nature that meaningful comparisons and syntheses of results will be most difficult.

If we are to accomplish or even make significant progress in the job of installing, maintaining, and analyzing the additional field trials needed, we must pool resources, focus our objectives, and initiate a comprehensive program of field testing. Because no single agency has the resources necessary to do this, we emphasize that a cooperative effort is paramount.

The cooperative research programs in forest fertilization at the University of Washington, North Carolina State University, and the University of Florida are outstanding examples of what may be accomplished by regional group research efforts. We do not imply that such a formalized approach to forest-fertilization problems in the Northeast is necessary or even desirable, because of great regional diversity. On the other hand, some degree of uniformity in field-plot technique and laboratory methods would be most desirable. There is also need to establish a mechanism by which collaboration between investigators could be improved.

II. Develop Diagnostic Criteria

One of the key factors of a successful fertilization program lies in knowing which nutrient or nutrient combinations are deficient and where these deficiencies occur. Probably nothing else will hasten the use of fertilizers as a means of increasing fiber production more than the development of reliable diagnostic criteria from which response can be predicted.

This is an area where pursuit of many fundamental issues is first necessary before soil test values, tissue test values, or visual criteria can be used with any degree of accuracy or predictive reliability. Such basic questions as what type of material to sample, where should it come from, when should it be sampled, and how many samples are necessary are among the unknowns for most hardwoods. For tissue analyses, should we sample buds, bark, leaves, petioles, or sap? Which of these are most sensitive to changes in external nutrient supply and which correlate best with growth response? How about the many problems associated with sampling large trees? From what soil horizons should samples be taken to best correlate with response? What extracting solution should be used in determining available nutrients? Can useful criteria be developed on visual appearance alone and eliminate the need for soil and tissue testing? Can response be related to permanent features of the landscape? The list goes on and on.

III. Determine Effects on Environmental Quality

This is an area about which we know very little, but it is fast becoming a matter of concern because of recent broad ecological implications. What happens to fertilizer nutrients that are introduced into hardwood forest ecosystems? Do they run off and contaminate our streams? Do they find their way into deep aquifers? What portion of them may be lost to the atmosphere by volatilization? A few answers are slowly beginning to accumulate; but these questions need much greater attention, especially if fertilization of large forest areas becomes a reality.

IV. Evaluate Fertilizer/Genetic Interactions

Perhaps one of the most promising areas for fertilization studies is closely related to genetics and plant breeding. The possibility of developing superior tree strains that possess the ability for outstanding response to intensive fertilization regimes is intriguing. There are good indications that this may be possible through a program of field selection and breeding of individuals showing exceptional response in field-fertilization tests.

V. New Approaches

The standard approach in almost every forest fertilization test has been to broadcast plant nutrients upon the soil, usually in a single application. This has been done continually, yet we know that N retention is difficult and that P can be quickly converted to chemical forms that are not available for tree growth. Furthermore, we know that certain N fertilizers, particularly urea, are prone to large losses from volatilization of ammonia.

Is direct application of nutrients to the soil really the best way to fertilize? Do we have to tolerate the risk of nutrient loss by leaching and volatilization, chemical tie-up, or use by undesirable vegetation? What about foliar application of nutrients or direct injection of nutrients into the tree whereby these risks could be completely eliminated? Could fertilizers with slow-release characteristics such as the metal ammonium phosphates, urea - formaldehyde, sulfur - coated urea, and resin-coated urea be substituted for the water-soluble formulations now in general use?

These possibilities, although known for some time, are largely unexplored. But their importance cannot be overstressed because widespread economic acceptance of forest fertilization may depend heavily upon development and use of materials that release nutrients slowly and will maintain response over long-term intervals without jeopardizing our water supplies or environment.

REFERENCES

Anonymous.
1970. 1970 wood and woodlands directory. Pulpwood Production and Sawmill Logging 18(1): 22-58.

Aird, P. L.
1956. Fertilizers in forestry and their use in hardwood plantation establishment. Pulp and Pap. Mag. Can. 57: 376, 379-381, 384.

Aird, P. L.
1962. Fertilization, weed control and the growth of poplar. Forest Sci. 8: 413-428.

Armson, K. A.
1967. Review of forest fertilization in Canada. Can. Forest. Branch Dep. Pub. 1186. 175 p.

Arneman, H. F.
1960. Fertilization of forest trees. Advance. Agron. 12: 171-191.

Auchmoody, L. R.
1972a. Effects of fertilizer-nutrient interactions on red oak seedling growth. USDA Forest Serv. Res. Pap. NE-239. 5 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Auchmoody, L. R.
1972b. Epicormic branching: seasonal change, influence of fertilization, and frequency of occurrence in uncut stands. USDA Forest Service Res. Pap. NE-228. 8 p. NE. Forest Exp. Sta., Upper Darby, Pa.

Aughanbaugh, J., and W. Mitchell.
1963. Results show poplar fertilization improves growth. Ohio Farm and Home Res. 48: 53, 55.

Baule, H., and C. Fricker.
1970. The fertilizer treatment of forest trees. BLV, Munich. 259 p.

Bengtson, G. W.
1968. Progress and needs in forest fertilization research in the South. *In* Forest fertilization . . . theory, and practice: 234-241. TVA, Muscle Shoals, Ala.

Blackmon, B. G., and W. M. Broadfoot.
1970. Fertilizer improves poplar growth. Miss. Farm Res. 33:7.

Broadfoot, W. M.
1966. Five years of nitrogen fertilization in a sweetgum-oak stand. USDA Forest Serv. S. Forest Exp. Sta. Res. Note 50-34. 3 p. New Orleans, La.

Broadfoot, W. M., and A. F. Ike, Jr.
1968. Research progress in fertilizing southern hardwoods. *In* Forest fertilization . . . theory and practice: 180-184. TVA, Muscle Shoals, Ala.

Carter, M. C., and E. H. White.
1970. The necessity for intensive cultural treatment in cottonwood plantations. *In* Silviculture and management of southern hardwoods: 28-38. La. State Univ. Press.

Chandler, R. F. Jr.
1943. The influence of nitrogeneous fertilizers on growth and seed production of deciduous trees. Nat. Fert. Assoc. Joint Comm. Nitrogen Util. Annu. Meet. Proc. 2: 40-46.

Chapman, A. G.
1933. Some effects of varying amounts

OF NITROGEN ON THE GROWTH OF TULIP-POPLAR SEEDLINGS. Ohio J. Sci. 33: 164-181.

Cummings, W. H.
1941. FERTILIZER TRIALS FOR IMPROVED ESTABLISHMENT OF SHORTLEAF PINE, WHITE ASH AND YELLOW POPLAR PLANTINGS ON ADVERSE SITES. J. Forest. 39: 942-946.

Curlin, J. W.
1962. DOGWOOD RESPONDS TO NITROGEN FERTILIZATION. J. Forest. 60: 718-719.

Curlin, J. W.
1967. COLONAL DIFFERENCES IN YIELD RESPONSE OF *Populus deltoides* TO NITROGEN FERTILIZATION. Soil Sci. Soc. Amer. Proc. 31: 276-280.

Duke University.
1959. MINERAL NUTRITION OF TREES. Duke Univ. School Forest. Bull. 15. 184 p.

Farmer, R. E., Jr., G. W. Bengtson, and J. W. Curlin.
1970. RESPONSE OF PINE AND MIXED HARDWOOD STANDS IN THE TENNESSEE VALLEY TO NITROGEN AND PHOSPHORUS FERTILIZATION. Forest Sci. 16: 130-136.

Farmer, R. E., Jr., E. A. Snow, and J. W. Curlin.
1970. EFFECTS OF NITROGEN AND PHOSPHORUS FERTILIZATION ON JUVENILE GROWTH OF PLANTED YELLOW-POPLAR ON AN ERODED OLD FIELD. Soil Sci. Soc. Amer. Proc. 34: 312-313.

Finn, R. F., and H. H. Tryon.
1942. THE COMPARATIVE INFLUENCE OF LEAF MOULD AND INORGANIC FERTILIZERS ON THE GROWTH OF RED OAK. Black Rock Forest Pap. 17: 108-109.

Finn, R. F., and D. P. White.
1966. COMMERCIAL FERTILIZERS INCREASE GROWTH IN A YELLOW-POPLAR PLANTATION. J. Forest. 64: 809-810.

Gilmore, A. R., R. A. Young, and L. E. Arnold.
1971. RESPONSE OF SWEETGUM TO FERTILIZATION IN SOUTHERN ILLINOIS. Univ. Ill. Agr. Exp. Sta. Forest. Res. Rep. 71-2. 2 p.

Himelick, E. B., D. Neely, and W. R. Crowley, Jr.
1965. EXPERIMENTAL FIELD STUDIES ON SHADE TREE FERTILIZATION. Ill. Nat. Hist. Surv: Biol. Note 53. 12 p.

Hoyle, M. C.
1969. RESPONSE OF YELLOW BIRCH IN ACID SUBSOIL TO MACRONUTRIENT ADDITIONS. Soil Sci. 108: 354-358.

Hoyle, M. C.
1970. GROWTH AND NUTRITION OF YELLOW BIRCH AS AFFECTED BY THE NUTRIENT STATUS OF A PODZOL SOIL. *In* TREE GROWTH AND FOREST SOILS: 221-233. Oreg. State Univ. Press, Corvallis.

Huppuch, G. D.
1960. THE EFFECT OF SITE PREPARATION ON SURVIVAL AND GROWTH OF SYCAMORE CUTTINGS. USDA Forest Serv. SE. Forest Exp. Sta. Res. Note 140, 2 p. Asheville, N.C.

Ike, A. F., Jr.
1962. FERTILIZED YELLOW-POPLAR SEEDLINGS MAINTAIN GROWTH ADVANTAGE AFTER FOUR YEARS. USDA Forest Serv. SE. Forest Exp. Sta. Res. Note 175, 2 p. Asheville, N.C.

Jones, H. C., III, and J. W. Curlin.
1968. THE ROLE OF FERTILIZERS IN IMPROVING THE HARDWOODS OF THE TENNESSEE VALLEY. *In* FOREST FERTILIZATION . . . THEORY AND PRACTICE: 185-190. TVA, Muscle Shoals, Ala.

Kormanik, P. P., and C. L. Brown.
1969. ORIGIN AND DEVELOPMENT OF EPICORMIC BRANCHES IN SWEETGUM. USDA Forest Serv. Res. Pap. SE-54, 17 p. SE. Forest Exp. Sta., Asheville, N. C.

Mader, D. L., B. W. Thompson, and J. P. Wells.
1969. INFLUENCE OF NITROGEN ON SUGAR MAPLE DECLINE. Mass. Agr. Exp. Sta. Bull. 582. 19 pp.

McAlpine, R. G.
1959. RESPONSE OF PLANTED YELLOW-POPLAR TO DIAMMONIUM PHOSPHATE FERTILIZER. USDA Forest Serv. SE. Forest Exp. Sta. Res. Note 132. 2 p. Asheville, N.C.

McComb, A. L.
1949. SOME FERTILIZER EXPERIMENTS WITH DECIDUOUS FOREST TREE SEEDLINGS ON SEVERAL IOWA SOILS. Iowa State Coll. Agr. & Mech. Arts Res. Bull. 369: 406-448.

Mitchell, H. L., and R. F. Chandler, Jr.
1939. THE NITROGEN NUTRITION AND GROWTH OF CERTAIN DECIDUOUS TREES OF NORTHEASTERN UNITED STATES. Black Rock Forest Bull. 11. 94 pp.

Mustanoja, K. J., and A. L. Leaf.
1965. FOREST FERTILIZATION RESEARCH, 1957-1964. Bot. Rev. 3 (2): 151-246.

Neely, D., E. B. Himelick, and W. R. Crowley, Jr.
1970. FERTILIZATION OF ESTABLISHED TREES: A REPORT OF FIELD STUDIES. Ill. Nat. Hist. Surv. Bull. 30 (4): 235-266.

Phares, R. E.
1971a. FERTILIZATION TESTS WITH POTTED RED OAK SEEDLINGS. USDA Forest Serv. Res. Note NC-114. 4 pp. North Cent. Forest Exp. Sta., St. Paul, Minn.

Phares, R. E.
1971b. GROWTH OF RED OAK (*Quercus rubra* L.) SEEDLINGS IN RELATION TO LIGHT AND NUTRIENTS. Ecology 52: 669-672.

Pridham, A. M. S.
1937. GROWTH OF PIN OAK (*Quercus palustris*)—REPORT OF SEVEN YEARS' OBSERVATION. Amer. Soc. Hort. Sci. Proc. 35: 739-741.

Pridham, A. M. S.
1939. RESPONSE OF MATURE AMERICAN ELM TO AMMONIUM SULFATE AS A FERTILIZER. Amer. Soc. Hort. Sci. Proc. 37: 1075-1076.

Pridham, A. M. S.
1941. RESPONSE OF RED OAK TO FERTILIZATION WITH AMMONIUM SULFATE. Amer. Soc. Hort. Sci. Proc. 39: 439.

Schneider, G., G. Khattak, and J. N. Bright.
1970. MODIFYING SITES FOR THE ESTABLISHMENT OF BLACK WALNUT. *In* TREE GROWTH AND FOREST SOILS: 155-169. Oreg. State Univ. Press, Corvallis.

Tamm, C. O.
1964. DETERMINATION OF NUTRIENT REQUIREMENTS OF FOREST STANDS. Int. Rev. Forest. Res. Vol. I: 115-170. Academic Press, New York.

Vimmerstedt, J. P., and C. A. Osmond.
1970. RESPONSE OF YELLOW-POPLAR TO FERTILIZATION. *In* TREE GROWTH AND FOREST SOILS: 127-154. Oreg. State Univ. Press, Corvallis.

Walker, L. C., and R. L. Beecher.
1963. Fertilizer response with forest trees in North America. Nat. Plant Food List, 24 p. Washington, D.C.

Ward, W. W., and T. W. Bowersox.
1970. Upland oak response to fertilization with nitrogen, phosphorus and calcium. Forest Sci. 16: 113-120.

White, D. P., and A. L. Leaf.
1957. Forest fertilization: a bibliography, with abstracts, on the use of fertilizers and soil amendments in forestry. N. Y. State Univ. Coll. Forest. Tech. Pub. 81. 305 p.

Wyman, D.
1936. Growth experiments with pin oaks which are growing under lawn conditions. Cornell Univ. Agri. Exp. Sta. Bull. 646. 23 p.

Zarger, T. G., and J. A. Lutz.
1961. Effect of improved thornless honeylocust shade trees on pasture development. TVA Tech. Note 34. 12 p.

APPENDIX

Directory of Current Forest-Fertilization Research with Hardwoods

Species	Investigators[1]
1. Aspen	15, 39
2. Basswood	1, 2, 37
3. Black cherry	2, 3, 4, 5, 7, 23, 24, 25, 31, 37
4. Black walnut	8, 10, 30, 46, 47
5. Mixed northern hardwoods	17, 19, 28, 29, 37
6. Red maple	2, 4, 11, 23
7. Sugar maple	4, 5, 7, 11, 17, 21, 23, 24, 28, 31, 33, 36, 37, 42, 46, 49
8. Sweetgum	8, 9, 13, 18, 20, 22, 40, 41
9. Sycamore	8, 13, 14, 18, 20, 22, 40, 41, 47, 48
10. Upland oaks	1, 2, 6, 9, 16, 25, 26, 27, 32, 35, 37, 38, 43, 44, 45, 46, 47, 50
11. White ash	25, 31, 37
12. Yellow-poplar	1, 2, 9, 12, 16, 25, 31, 34, 46, 47, 51

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LANDSCAPE GEOCHEMISTRY AND FOREST FERTILIZATION

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ABSTRACT. An introduction to the subject of landscape geochemistry, focusing attention on relationships between landscape geochemistry and forest fertilization. An orientation landscape geochemistry project is described, with special reference to a method for determining the element status of forest trees and stands, which is believed to be independent of within-season or season-to-season variation in chemical composition.

GEOCHEMISTRY is essentially the study of the role of all elements in the Periodic Table in the synthesis and decomposition of natural materials of all kinds. The broad scope of geochemistry was stressed by the pioneer workers in the field, including V. I. Vernadski in Russia, F. W. Clarke in America, and V. M. Goldschmidt in Norway, who laid the foundation of the subject during the early years of this century. Further information about the history of geochemistry may be found in the classic textbook by Rankama and Sahama (*1950*).

LANDSCAPE GEOCHEMISTRY

Landscape geochemistry is concerned with the circulation of chemical elements at or near the surface of the earth where the lithosphere, hydrosphere, atmosphere, and biosphere interact. Landscape geochemistry does not stand alone, but draws heavily on information obtained from other disciplines, including chemistry, physics, geology, geophysics, geochemistry, geomorphology, biology, and ecology.

The concept of holism is at the heart of landscape geochemistry, because it is believed that a systematic study of the circulation of chemical elements in many components of landscapes will frequently provide a kind of information different from that obtained from detailed studies of particular landscape components. For this reason the study of landscape geochemistry is often more concerned with *volume* units of landscape than with areas. Such volumes may vary in scale from less than a cubic metre to the whole surface of the globe.

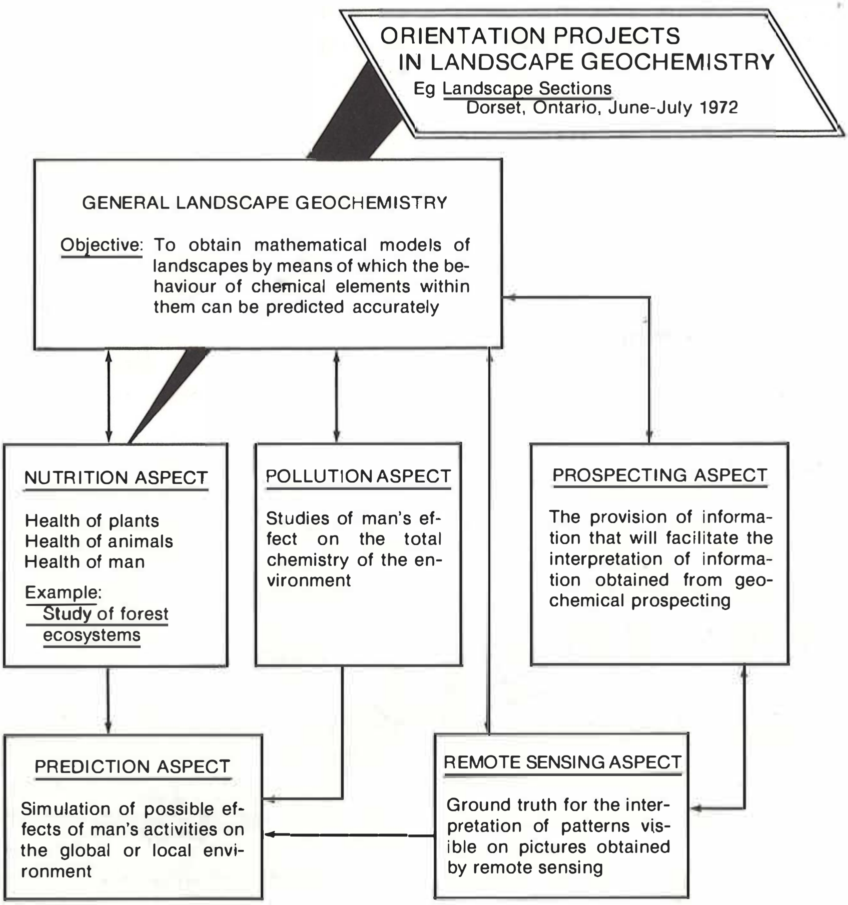
Systematic landscape geochemistry

study has been greatly stimulated by scientific advances during the 1960's. For example, it is now possible to determine the content of over 60 chemical elements in the same sample at the same time, some at concentrations far below 1 p.p.m. (*Morrison 1972*); and the use of the electronic computer combined with modern methods of systems analysis (*Reichle 1970*) indicates that reliable mathematical models for simulation of the circulation of chemical elements in landscapes may be prepared during the near future.

Modern landscape geochemistry has gradually evolved from foundations laid by Polynov (*1937*), Perel'man (*1961*), Glazovskaya (*1963*), and other workers. Landscape geochemistry is closely related to other holistic approaches to the description of landscapes, including that by Sukachev and Dylis (*1964*) in Russia and those by Hills (*1953*) and Krajina (*1965*) in Canada. Several practical applications of the landscape-geochemistry approach are being actively researched (fig. 1).

One serious problem that faces research workers in landscape geochemistry is the establishment of conceptual models of nature that can facilitate the interchange of chemical and descriptive information between the different aspects of the subject. Much progress in this field may be expected in the near future.

Figure 1.—The scope of landscape geochemistry.



A SIMPLE EXAMPLE

At the present state in the evolution of landscape geochemistry, it is desirable to carry out research on relatively simple conceptual models of nature to establish patterns of behavior of elements under ideal conditions. Many attempts to study the details of the circulation of chemical elements (for example around mineral deposits) in landscapes have provided inconclusive results because the landscapes studied were too complicated to provide simple statements of the behavior of chemical elements concerned. Experience with systems analysis suggests that although complexity can be added to simple landscape models, it is not always possible to subtract the effects of complexity from an already relatively complex situation.

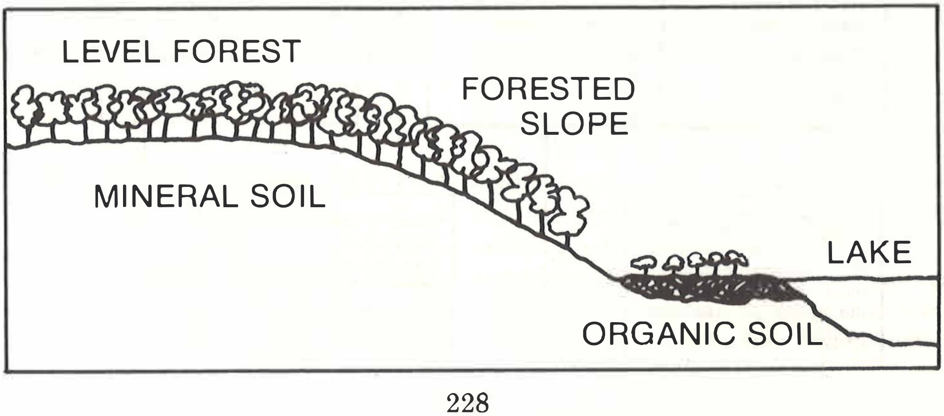
A relatively simple conceptual model of a landscape was drawn in March 1972 as a preliminary to finding a field area for a summer field project (fig. 2). This conceptual model includes a part of the Earth's surface where the lithosphere, biosphere, and atmosphere interact (the forested hillslope); where the biosphere and hydrosphere interact with the atmosphere (the forested bog); and where the hydrosphere interacts with the biosphere and atmosphere (the lake).

In addition a moisture gradient is to be expected between the hilltop and the hillbottom, which will result in variations in the morphology of the soil cover types and variations in the distribution of the tree species comprising the forest cover. It should be noted that the hillslope models (fig. 2) is essentially a landscape section with no thickness. In practice it was decided to study a 20-m. wide strip of country as though it were a section rather than a volume unit of country. When the experiment was devised, it was decided to restrict preliminary investigations to samples from soil profiles and tree crown branches.

In planning landscape geochemical projects, three hierarchies involved in the classification of matter should be considered in relation to each other. In the proposed study the hierarchy of space (or more correctly scale) was considered to be such that the traverse would be 500 m. long. If it were shorter than this it would be likely to be too complex to study, and if it were more extensive it would be impractical to study on the required scale in the time available.

The second hierarchy studied is that of time. The aim here was to sample the soils and trees within a single instant of time (some 3 weeks in duration) during June and July 1972. This would provide an overview of the distribution patterns for elements in soils and plants at this

Figure 2.—A conceptual model of a landscape section.



time. A second purpose of the investigation would be to use 10 years of branch growth as a history book for the growth and element status of the trees growing in the stand. Details of this approach to the estimation of the element status of forest trees have been described previously (*Fortescue and Hughes 1971*).

The third hierarchy to be considered was the complexity of the materials selected for chemical analysis. In the case of the mineral soils, the chemical data would be expressed as parts per million of an element in the cold hydrochloric acid soluble part of the oven-dry -80 mesh fraction of the soil. In the case of the bog soils, the basis for the chemical analysis would be the aqua regia soluble portion of the dry ashed material expressed on an oven-dry basis. The content of the chemical elements in the tree branch material would be expressed as parts per million oven-dry weight. All chemical determinations were to be carried out using a Perkin Elmer 403 Atomic Absorption apparatus with automatic sample changer and Teletype printout attachment.

The elements to be included in the study would represent nutrients, micronutrients, and nonessential elements (*Fortescue and Marten 1970*). In practice, data were obtained for Mg, Mn, Fe, Cu, Zn, Pb, and Al. Only data for the micronutrient manganese and the nonnutrient element lead is discussed here in relation to the soils and plants, although estimates will be included for all seven elements in the tree branch material because this data is of particular interest to scientists involved in forest fertilization.

THE SECTION AT DORSET, ONTARIO

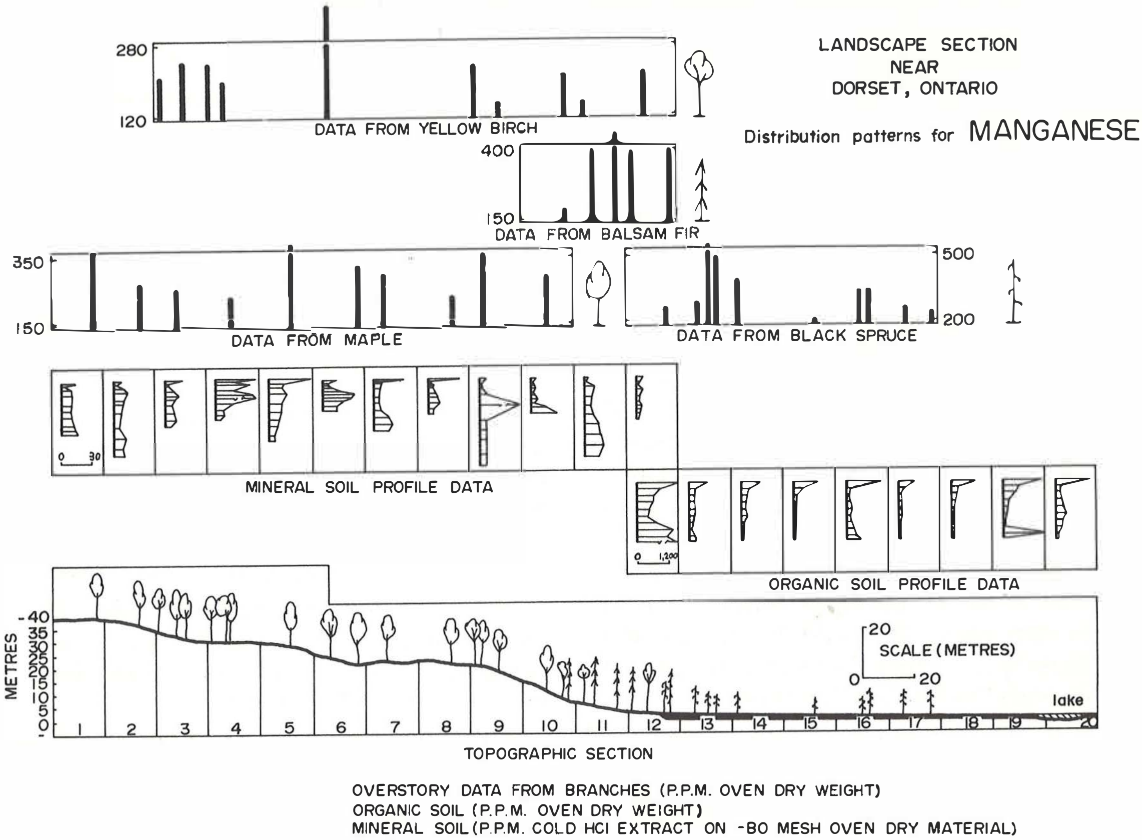
The air photographs of an area of some 200 square miles situated in the vicinity of the town of Dorset, Ontario (some 120 miles north of Toronto), were studied to discover a landscape section of the type described above and illustrated on figure 2. After 12 possible sites had been selected, 11 were rejected on the basis of laboratory, airborne, or ground investigation.

The section finally chosen closely approximates to the conceptual model (fig. 3), and is located some 8 miles north and east of the town of Dorset. The section is 400 m. long, extending from a hilltop to a small lake. Twelve soil pits were dug at regular intervals down the slope and nine bog cores were obtained from the organic terrain. Individuals of four species of tree maple, black spruce, balsam fir, and yellow birch (fig. 3)—were chosen for study. Ten soil samples were taken from profiles exposed in each pit and ten samples of bog material from each borehole. It should be noted that the maple trees were taken from the hillslope, the black spruce trees from the organic terrain, the balsam fir trees from the transition between the mineral and the organic terrain, and the yellow birch from different locations on the slope.

Data for the content of Mn and Pb in the soils, and average 1965-66 branch-growth samples for the trees, are plotted on figures 3 and 4. These plots are on a logrithmic scale to match those plotted on figure 5. It is evident that the vertical distribution patterns for Mn in the mineral soil differ from those for the organic soils. Enrichment of Mn at the surface is evident in all the organic soils and in the soils from plots 3, 4, 5, 6, 7, and 8. The distribution of Mn in the subsoil appears to vary in relation to the depth of the soil profiles.

The Mn content of the black spruce branches reaches a maximum some 30 m. from the edge of the bog. This suggests, but does not prove, that there is an edge effect along the margin of the bog, which affects the uptake of Mn by the spruce. It would be interesting to know if this is related to the higher amount of Ca available to plants growing on the bog margin. The data for Mn in the branches of maple and yellow birch does not appear

Figure 3.—Distribution patterns for manganese in a landscape section.

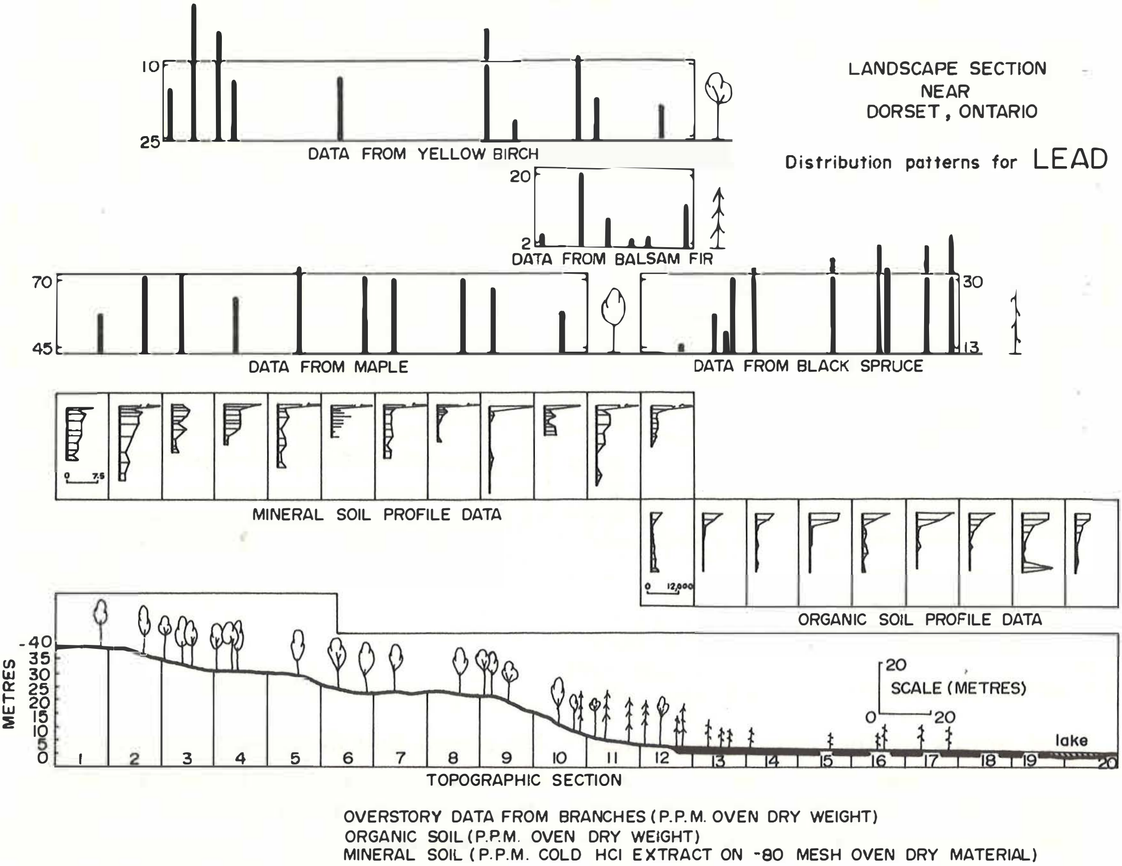


to have consistent trends within it. In the case of balsam fir the uptake of the element appears relatively low on the well-drained mineral soil.

The distribution patterns for Pb (fig. 4) are different from those for Mn in the mineral or the organic soil. The enrichment of Pb in the organic layers of both types of soil may be natural or may result from atmospheric fallout. Two observations can be made regarding the distribution of Pb in the trees: First the content of Pb increases in the black spruce branches towards the lake; and second, the Pb content of yellow birch is highest at the hilltop.

It should be stressed that these observations for Mn and Pb are included here as examples of the kind of distribution patterns that are involved in a holistic approach to the geochemistry of a landscape section. Other patterns, some of them more marked than those described here, were found in the data sets for the other five elements included in the study. Although the techniques of sample collection and chemical analysis used here may be relatively crude, the important conclusion from this orientation study is that, with modern equipment, it is possible to carry out experiments of this type relatively rapidly and cheaply. The whole Dorset project was carried out by four people in less than 2 months. This includes sample collection, sample preparation, and chemical analysis of

Figure 4.—Distribution patterns for lead in a landscape section.



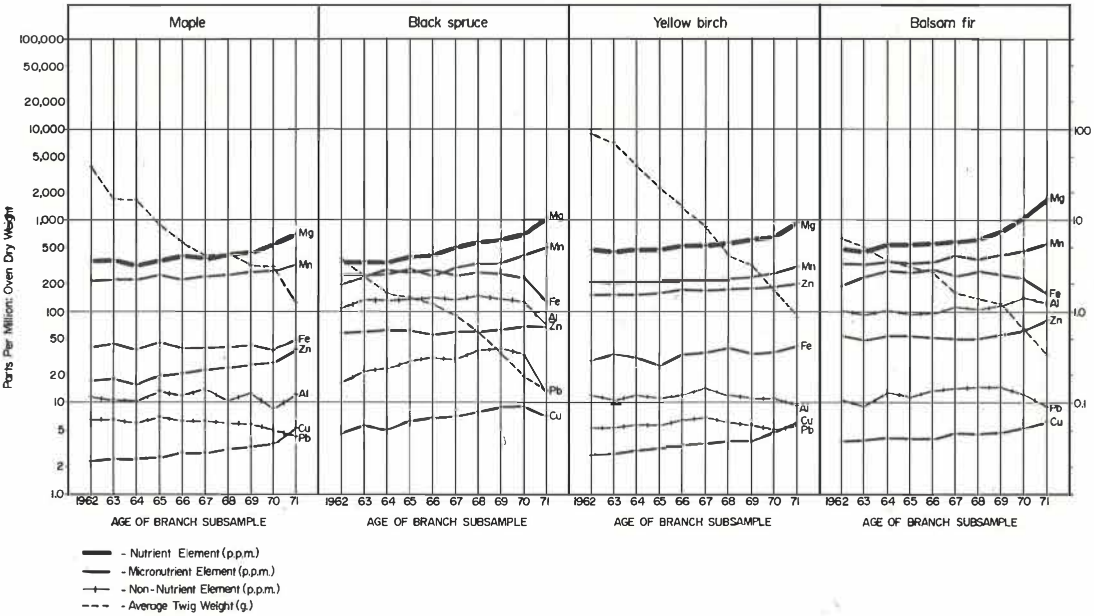
over 600 samples for seven elements each, and the preparation of a draft report.

ELEMENT STATUS OF FOUR TREE SPECIES

Of particular interest to scientists involved with forest fertilization research are the estimates of element status for the four tree species growing at the Dorset site (fig. 5). The technique used to obtain these data (fig. 5) has been described in detail (*Fortescue and Hughes 1971*). Briefly, each tree of a given species selected for sampling is felled, and branch-growth sections from the upper crown representing each year's shoot elongation over a 10-year period are separated and analysed separately. Thus 10 chemical analyses for each element are obtained from each tree. Data for branch subsamples of the same age for the different individuals of the same species are averaged to provide points on concentration lines for each element (fig. 5). After subsampling, the branch subsamples are oven-dried, weighed, and counted, and the average twig weight of each subsample is obtained. These data are also averaged for all trees and plotted on figure 5 as an indication of the tree growth rate during the 10-year period.

With this technique it is believed, but not yet proven, that estimates of the ele-

Figure 5.—Estimates for the element status of branches from four species growing on the Dorset landscape section.



ment status of the trees are obtained that are free from within-season and season-to-season variations in chemical composition. It is currently believed that the most reliable estimates are those from branch subsamples that are too old to be seriously affected by the processes associated with the growing shoot and small enough so that a reliable estimate of the average twig weight may be obtained. This is the reason for using the arithmetic averages of element content for the 1965 and 1966 growth, which are plotted on figure 3 and figure 4.

It is evident (fig. 5) that the growth rates for branches of the two deciduous species were similar and that the coniferous species grew slower than deciduous trees. The curves for Mn were—as expected—highest of all elements in the branches. The content of Mn in the branches tends to increase towards the growing shoot, which is best illustrated by balsam fir. In general, the curves obtained for the four micronutrient elements were similar to those obtained for Mn except that in the case of Fe (and in black spruce, Cu as well), there was a decrease in concentration in the younger branch samples.

The significance of this observation is not yet clear. As expected, the concentration levels for the micronutrients are different in the deciduous and the coniferous trees. Birch is known to be an accumulator of Zn, and this effect is seen clearly in figure 5. The behavior of the two nonnutrient elements—Pb and Al—is of particular interest because in all cases the content of these elements was found to decrease towards the growing point of the branch. This effect is most marked in black spruce trees.

It seems clear that the branch method of element status determination provides information that may be of particular interest in forest fertilization research. For example, if an application of N fertilizer had been applied to the forest in 1966, the effect on the branch subsample growth would be seen in data for subsequent years on the diagram, together with the effect on the relative proportions of the other nutrient and nonnutrient elements in the branches.

But one must not be prematurely optimistic about this approach because it is known that some elements are translocated within branches. This may complicate to an unknown extent the interpretation of data obtained from the proposed technique when it is applied to forest trees, or stands, after fertilization. Consequently more research is required to solve these problems. However, from the viewpoint of landscape geochemistry, the branch method may be suitable for the preparation of general estimates of the element status and growth of trees, which can be directly compared with others obtained from the same tree species growing in different areas.

DISCUSSION

It should be stressed the approach adopted in the Dorset project is in the nature of an orientation survey designed to obtain experience with the approach in forested landscapes. It is hoped that this experience will stimulate further thought and research along these lines in the near future.

Forest-fertilization research is a special case of a more general subject involving the geochemistry of landscapes. A simple conceptual model of a forest hillside has been used to illustrate some principles of landscape geochemistry that may be applicable to forest-fertilization research. More research along these lines is required before the importance of the approach described here can be fully evaluated.

REFERENCES

Fortescue, J. A. C., and Jane Hughes.
1971. A PRELIMINARY STUDY OF THE USE OF BRANCH MATERIAL FOR THE ESTIMATION OF THE TRACE ELEMENT STATUS OF A FOREST STAND. Brock Univ. Dep. Geol. Sci. Res. Rep. Ser. 1, 38 p.

Fortescue, J. A. C., and Marten G. G.
1970. MICRONUTRIENTS: FOREST ECOLOGY AND SYSTEMS ANALYSIS. *In* ANALYSIS OF TEMPERATE FORESTS ECOSYSTEMS ECOLOGICAL STUDIES, ANALYSIS AND SYNTHESIS, vol. 1: 173-198. Springer Verlag, Berlin.

Glazovskaya, M. A.
1963. ON GEOCHEMICAL PRINCIPLES OF THE CLASSIFICATION OF NATURAL LANDSCAPES. Int. Geol. Rev. 5(11): 1403-1431.

Hills, G. A.
1953. THE USE OF SITE IN FOREST MANAGEMENT. Forest. Chron. 29(2):128-136.

Krajina, V. J.
1965. BIOGEOCLIMATIC ZONES AND BIOGEOCENOSES OF BRITISH COLUMBIA. *In* ECOLOGY OF WESTERN NORTH AMERICA vol. 1, Univ. Brit. Columbia Dep. Bot.

Morrison, G. H.
1972. SPARK SOURCE MASS SPECTROMETRY FOR THE STUDY OF THE GEOCHEMICAL ENVIRONMENT. N. Y. Acad. Sci. Ann. 199:162-173.

Perel'man, A. I.
1961. LANDSCAPE GEOCHEMISTRY. xx p. Geografgiz, Moscow.

Polynov, B. B.
1937. CYCLE OF WEATHERING. (Trans. by A. Muir.) xx p. Murphy and Co., London.

Rankama, K., and T. G. Sahama.
1950. GEOCHEMISTRY. Univ. Chicago Press, 911 p.

Reichle, D. E.
1970. ANALYSIS OF TEMPERATE FOREST ECOSYSTEMS. Springer Verlag, Berlin, 304 p.

Sukachev V., and Dylis N.
1964. FUNDAMENTALS OF FOREST BIOGEOCOENOLOGY. (Trans. by J. M. Maclennan.) Oliver and Boyd, Edinburgh, 672 p.

ACKNOWLEDGMENTS

The writers thank Brian Grant and Edwin Gawron, who collected the samples from the Dorset landscape section; and Mr. and Mrs. Curtis, who carried out the chemical analysis of the Dorset material in the geochemical laboratory at the Department of Geological Sciences, Brock University. This research was supported in part by N. R. C. Grant No. 34-52-01 and by the N. R. C. Grant to the President of Brock University.

CRITIQUE:
FOREST FERTILIZATION—RETROSPECT AND PROSPECT

by PETER J. RENNIE, *Program Coordinator, Soils; Program Coordination Branch, Canadian Forestry Service, Department of the Environment, Ottawa.*

ABSTRACT. Twenty-two formal contributions at the Symposium included original research and reviews of overall regional objectives, economic and human relationships, fiber production, special crops and situations, practical and theoretical methodologies, and effects of fertilization on water quality, streamflow, wildlife, and insect and disease organisms.

IT IS BECOMING the fashion for critique discussants gravely to survey their rapidly evaporating audience, to commiserate on the difficulties of summarizing even further the many already highly condensed papers, then to embark bravely on one of two courses: either to abandon the papers and foist an essentially subjective viewpoint on the audience, or to adhere slavishly to the papers and regurgitate once again their summaries.

I propose to avoid these pitfalls, possibly by falling between two stools and making a pitfall of my own! When I reflect on past fertilization meetings, on the structure and content of this particular one, and on the invigorating discussions and atmosphere that have permeated our proceedings over the past few days, I see nothing to commiserate about. I can only feel a sense of euphoria by having participated in what can fairly be described as a milestone event in the development and progress of forest fertilization.

At first sight many, along with Professor Stone, must have questioned the basis of our regional framework. When I got out map and compass to see what a circle with a radius of 465 miles centered on Warrensburg might embrace, so blue and endless was the ocean that it seemed that a sextant was required more than a compass! And when I doubled the radius to allow for the sports-car enthusiast and the Canadian programs of western Ontario and the more northerly parts of the Appalachian system, the region then appeared to embrace an impossible diversity, ranging from the tundra of Hudson Bay to the tropics of Florida—not excluding, of course, Bermuda!

In reality, no one is suggesting the inflexibility of a particular geometrical shape to define our region. Indeed, however wide or near particular fertilization programs might be in the Northeast, they are in fact characterized by three important features. First, they are situated in the most densely populated area of North America. Second, they are located in forests or situations where through demand or activity there is either a stress condition or an early likelihood of one. Third, they are where they have a potential for impinging upon very large numbers of the public, either obviously or less obviously.

Other characteristics of the Northeast may be invoked and debated, such as a greater or lesser degree of continentality in climate, a very considerable influence of quaternary glaciation, and so forth; but the features that serve to unify and provide pertinency to our Symposium's dual theme are those just described, which stem from the intensive utilization and management of resources in an increasingly populated land. What is relevant to our region may not be relevant to other regions today, but could well be tomorrow, when their levels of utilization and population attain those of the Northeast. Therefore, just as the pioneering work on potassium nutrition conducted here in the Pack Forest two decades ago sparked interest, endeavor, and progress far beyond its original context, so there are good reasons to suppose that this novel Symposium and its new way of looking at fertilization will be the forerunner of many others.

Insofar as it is possible to split a symposium comprising several interrelated parts, the more environmental aspects will be discussed by Kenneth Reinhart, whereas the more traditional aspects of nutrition are to fall to me. For convenience, I propose to adhere to the historical pattern of development of our discipline and discuss nutritional aspects first.

SUBJECT MATTER

In concept, our Symposium is regional in scope and embodies a dual theme, stemming from a consideration of forest fertilization in an environmental context.

The 22 formal contributions may be grouped in a number of ways: the one that follows is merely a particular one and should not be taken to initiate any futile demarcation dispute. Five main groups of papers can be identified.

The first two papers (by Stone and by Hughes & Post) provide the framework of our endeavor by discussing overall objectives, economics, and human relationships.

The second main group comprises seven papers. Four of these (Safford, Krause, Auchmoody & Filip, and von Althen & Ellis) reveal the many regional programs concerned with fiber production in coniferous and hardwood crops. The other three papers (Yawney & Walters, Czapowskyj, and Richards & Leonard) deal with special forest crops and situations—Christmas trees, spoil banks, urban forestry—that have strong environmental links and might well be classified in this way.

The third group is methodological in nature. Two papers (Gagnon, Beaton) are oriented practically, to describe the significance and potential of new fertilizer materials and their application. Strong environmental links are evident here too. Two other papers (Mader, Armson) are oriented more theoretically, dealing with procedures for diagnosing nutrient requirement and growth response. The fifth paper in this group (Gladstone & Gray) warrants separate identity by its representation of the important but neglected aspect of wood quality.

The fourth group comprises two important papers (Brett, Weetman & Hill) that bridge the traditional and newer aspects of fertilization. One shows how a number of different disciplines are being built into a more synoptic and ecological understanding of the growth response to fertilization: the other reminds us of the complex system of producers, consumers, and decomposers that can be disturbed in various ways when the forest ecosystem is manipulated through fertilization.

Finally, there is a fifth group of five papers (Werner, Hornbeck & Pierce, Aubertin *et al.*, Behrend, Shigo), all intimately concerned with the environmental effects of fertilization—be they water quality, streamflow, wildlife, or insect and disease organisms.

One is obliged to ask in general terms: How well or inadequately do the five sections or 22 papers cover the waterfront? Bearing in mind the wealth and diversity of the many facets that go to make up forest fertilization, and remembering the makeup of the Gainesville and Finnish symposia sponsored by the Tennessee Valley Authority and International Potash Institute, we may readily see that our Symposium is roughly half their size. With this obvious constraint, the coverage is remarkably good. There is little if any repetition: most conventional topics are included; and the Symposium is novel and outstanding by bringing together for the first time solid contributions on numerous nutritional and environmental aspects.

One notable omission is nursery production. Although it is fair to say that progress on this front has been so outstanding that no unsurmountable problems remain, it is salutary to recall that much of this success has been achieved by diagnostic and other procedures whose adoption for other stages of forest growth is still in course of investigation. Nursery research still warrants close inspection. These are, moreover, days of change: container-grown stock with special nutrient regimes is increasingly supplementing or supplanting traditionally raised bare-root stock. Such developments are worth studying.

Perhaps not so much an omission rather than an elusiveness is the reporting of exactly how much commercial fertilization is going on. There seems to be a need for a better specification of what is research and what is regular practice. I realize, of course, that sometimes a sharp separation between the two cannot be made, for company fertilizer trials are often semi-operational, and most programs are as yet research; but the researcher can very easily remain in a fool's paradise if he loses sight of the relevance of the technique he is researching and is not made aware of problems as seen and experienced by the forest manager. Therefore, I believe our Symposium, along with others, could have been strengthened by a more obvious representation of commercial practice and the forest manager's viewpoint.

Although there are outstanding exceptions, there did seem to be more opportunity to specify the particular ecological conditions within which studies were conducted. We all know the cost of research and will certainly not easily forget Dr. Stone's figure of $100 per corn plot. There is an increasing need to know and cite the ecological parameters of a study, so that its results may be extrapolated successfully for the maximum possible benefit. Perhaps a final absence to be noted are those highly specialized physiological, soil, or other studies that can sometimes open up vistas of new approaches and practices.

More than counterbalancing these minor lacunae, however, is a solid middle-of-the-road coverage that incorporates many valuable recent results and reviews in the traditional areas of our subject, together with many thought-provoking and stimulating ideas in the newer environmental aspects.

HIGHLIGHTS OF NUTRITIONAL ASPECTS

We might usefully enunciate a general framework objective for all forest-fertilization research. Quite simply, we seek a reliable, economic, and environmentally safe technology. For the Northeast, with its twin pressures of utilization and population, a number of regional objectives have been identified, all of which fall within this framework objective. These regional objectives are real. They are precursors of situations that can be visualized as becoming more widespread elsewhere when population and utilization pressures build up.

The specification of regional objectives is both an assurance and a warning. Their detail should alleviate any fears environmentalists might entertain that fertilization signifies some wholesale attack upon the landscape. Specific situations have been identified. These should serve to remind nutritional researchers of the socio-economic forces that make certain situations relevant and others not so. A focusing of research effort is facilitated. This is nowhere more important than in costly and ambitious programs of cooperative field-trials: only the relevant should be embraced, not an entire ecological spectrum. The objectives remind us of the sometimes forgotten situations—nurseries, Christmas trees, sugarbush, spoil banks, etc.—where more has been done from the research stage to a successfully applied commercial practice than with adult forests. Aside from their intrinsic merits, such studies have valuable pointers to impart for those concerned with fertilization at establishment and semimaturity.

The plea for more regional cooperation warrants special support. Scarcity of expertise to round out the many specialties implicit in forest fertilization is one reason. Another is the way programs frequently develop in isolation. New programs are continually being started without the results of past efforts being sufficiently analyzed, publicized, and heeded. The variety of approaches and methodologies often renders comparison impossible. The viewpoints of company forester, fieldman, and boffin can remain compartmentalized. The solution of these problems is not simple, and I am not sure that at this stage in the state of our art we should seek to impose excessive standardization and inflexibility. What seems optimal today could be obsolescent tomorrow. Nevertheless a more intimate way of working could do much to eliminate the less promising and to promulgate the best from other disciplines.

We are fortunate to have available a lucid contribution on the key role of economics (Hughes & Post). Not only do we see the value of the field experiment underlined, but we are presented with a very balanced argument for implementing field experiments whose designs permit economic analysis. There is little doubt that appreciable past field experimentation has been suboptimal in design and that we are moving into a period when field designs will receive far more scrutiny. Usually a chronological series of field experiments are required to specify an optimum combination of nutrients and dosages: it is reassuring to know that, provided experiments within the series are well designed, economic analysis need not be delayed, although it is obviously desirable if a multivariable design able to elicit the optimum treatment can be implemented at the start. As a particular type of multivariable design—the rotatable factorial—has attracted appreciable attention, it is worth stressing that this is not necessarily the most appropriate of the multivariable designs available to provide a response-surface. Of particular value is the discussion on raising the allowable cut, for much fertilization centers on the semimature rather than the preharvest growth-stage, on the assumption that increased growth at semimaturity is just as economic.

Programs concerned with adult conifers in the Northeast display similarities and differences. Several species under investigation are the same in both the United States and Canada. Commercial practice is as yet very limited, in spite of encouraging experimental results. One wonders why. Does experimentation stop short of being taken to the pilot-scale and full-scale demonstration? Does the inadequate publication of field experimentation restrict awareness? Is industry insufficiently motivated? Are some of the field trials untrustworthy? Is there inadequate contact among different agencies?

These and other questions need to be answered to remedy an unsatisfactory situation, for it is clear that research is generating the most encouraging growth-responses to fertilization. Of particular interest is the similarity in response reported for black spruce over wide geographical areas (Krause) in respect of N and N+P treatments. This gives strong support to Safford's plea to initiate combined research and application now, for the more promising recipes are already at hand. Differences between our two countries seem to be a greater interest in K in the United States compared with N-P-K combinations in Canada, a greater use of NH_4NO_3 rather than urea in the United States, and the rather understandable greater interest in conifers in Canada.

For hardwoods, on the other hand, there is greater activity in the United States: Auchmoody & Filip's paper is a masterly summary and reference document. Once again, however, we see the relatively small interest by industry and wonder how much commercial practice is actually going on. The results of these authors' questionnaire-enquiry are most encouraging. It is now possible to predict with fair precision the blend of nutrient-elements and dosages likely to give positive growth-responses.

One wonders, again, if lack of publicity has militated against commercial application. Perhaps such questionnaires, painstaking analyses, and the distillation of highlights from a mass of unpublicized experimentation is a labor-of-love task we have insufficiently provided for. The Canadian contribution in this area (Ellis & von Althen) underlines the point made earlier on how specific rather than general are interests in fertilization. In the challenging problem of fertilizing at establishment, it is commendable to see both a positive and a negative result critically discussed. Too often a negative result has been miscalled a negative experiment and buried. We need, I think, a comprehensive yet simple system of recording all field experiments started, with sufficient detail of their ecological and environmental parameters to permit analysis at any time for a variety of purposes and hypotheses.

In the case of the special crops—sugarbush and Christmas trees (Yawney & Walters)—we are shown how important it is to optimize fertilizer treatments in respect of certain highly specific attributes of the final crop rather than for some general growth characteristic. It is interesting to see that for sugarbush a ratio of post- to pre-treatment sap yields, analogous to the growth-ratios for fiber crops, is a means of successfully overcoming tree-to-tree variability. In view of the methodological difficulties associated with the use of large trees, one is tempted to ask if a greenhouse approach with juvenile seedlings has possibilities. In such an approach, some more readily measurable tissue characteristic might be used as an indicator of subsequent sap yield and sugar content to elicit promising fertilizer schedules more speedily.

The review papers concerned with the rehabilitation of spoil banks (Czapowskyj) and urban and recreational sites (Richards & Leonard) elegantly demonstrate how valuable an aid fertilization can be for the enhancement of the environment. Each area is a complex field in itself, with individual situations within each calling, in turn, for individual consideration. Greenhouse pot-trials are clearly of considerable value for the spoil-bank situation, and in addition there is scope for much field experimentation with combinations of fertilizer, tree seedlings, and N-fixing lesser vegetation. The importance of rehabilitation measures in urban recreational areas is emphasized by the observation that in heavily pressured parks a rotational cycle of use and rehabilitation has to be operated. Of particular interest are the pollution/nutritional relationships discussed, for they illustrate how carefully nutritional regimes may have to be tailored to prevent certain flora from being eliminated.

Of similar significance to the environment is Gagnon's review of the scale of sewage and town-waste production and the scope fertilizers derived from such potential pollutants have. In our increasingly industrialized society it is evident that greater amounts of such waste products will make their début as possible fertilizer materials. A valuable service will be rendered to society, no less to forestry, if we are able to indicate which of such materials can be used successfully in forestry.

Diagnostic procedures to assess fertilizer requirement can be regarded as the slowly developing theoretical basis for all fertilizer practice. Mader's comprehensive treatment constitutes a veritable vade-mecum on the topic. The emphasis given to correctly assessing inherent site potential cannot be exaggerated, for many fertilizer trials have been incorrectly located through ignoring this aspect. I believe that more data about critical foliar levels for conifers in the Northeast are available than is suggested. For example, I know that soil-nutrient levels correlate well with peatland productivities in Newfoundland. But aside from minor qualifications, it is salutary to note that after a most critical analysis of foliar and soil diagnostic aids, the reliable and recommended procedure is still the well-designed field trial.

The proposal for a cooperative network of logically sited and well-designed trials deserves careful study. Yet many of the agencies that would be expected to participate have initiated a substantial number of trials. In eastern Canada, for example, there are well over 160 major field installations concerned with adult forest to be maintained during the next 5 to 10 years. The difficulty of finding areas of homogeneous forest large enough for new trials is turning researchers' attention to the possibilities of smaller single-tree plot designs.

In the discussion concerned with the evaluation of growth responses, one wonders whether the situations in the Northeast where fertilization is being tested to secure dominance and diameter-growth in overdense stands call for special assessment techniques. In the more detailed treatment of foliar and soil diagnostic procedures (Armson), one is compelled to question the progress and utility of the multiple-regression approach compared with critical foliar-levels. The papers cited are from the mid-1950s and, although relationships were statistically significant, their predictive value for another area of the same soil type was not corroborated.

Although the difficulties and limitations of the diagnostic procedures were discussed critically, I do not believe that all soil procedures "must be arbitrary". To employ N KCl or 0.01 M $CaC1_2 \cdot 6H_2O$ to measure pH, for example, is obviously an attempt to replace arbitrariness by a more theoretically based approach—a process that achieves greater or less success in all scientific method.

Many of us have wondered how we might refine our tree growth-response criteria. The lucid contribution on wood-quality attributes of significance in pulping (Gladstone & Gray) should do much to permit the nutritionist to advance beyond a simple density determination.

Finally, two papers (Brett, Weetman & Hill) show how the traditional nutritional approach is broadening out to embrace environmental considerations.

In the first, we saw an attempt to avoid some of the inconsistencies of past field experimentation when inexplicable or contradictory responses were sometimes obtained. The program is clearly ambitious and calls for more resources than many agencies could allocate to one study. But the approach has merit and aspires to give a synoptic meaning to each discipline participating. One might take a pessimistic view and ask whether the modelling might prove as restricted in utility as the multiple-regression formulas in foliar analysis. Or one might speculate about how unconvincing a note many new ventures start on and about the undoubted successes that growth-simulation modelling is already having.

Although the second paper is restricted to adult forest, it too demonstrates the importance of focus. Almost no specialty could be excluded if one thinks of the effects that fertilization might have upon forest ecosystems. One supposes that rather than trying to measure everything, everywhere, and at once, a strict attention to priorities would identify, first, the forests of interest, then the components of the particular forest of major importance that require study through appropriate disciplines.

The same critical perspective is necessary in the energy discussion. Environmentalists will be heartened to know that even if 2 million acres of forest were fertilized annually in North America, this would add only 1 percent to the tonnage of N already being used. In fact, only about 20,000 acres of forest are now fertilized annually in Canada, accounting for a mere 0.01 percent of the overall tonnage of N used. The fuel required to generate this would amount to no more than one or two freight-train loads of coal! This more comprehensive way of viewing relative demands on resources and the economics of production has been neglected.

The restricted uptake of applied N by trees must make many of us wonder, along with Auchmoody & Filip, whether some alternative method of application should be investigated. An important question that arises from the discussion of leaching losses from different N-sources is that, although urea may show least N losses, it is far more likely to disperse organic matter into the lower parts of the soil profile and eventually into the drainage waters. Is it possible that on balance the optimal N source might not yet be known? Except on outwash sands, N is identified as the most important single nutrient element, but not the nutrient most likely to give the maximum growth response: this is usually a N+P combination. Both papers ably reveal the types of studies in progress to ensure that fertilization does not harm the environment.

THE TASKS AHEAD

The rationale for the Symposium and for bringing nutritionists and environmentalists of the Northeast together stems from the more intensive use of the forest resource and environment in an increasingly populated and accessible land. It is important that the two groups continue to work together and become progressively more interrelated.

Nutritionists in all facets of forest fertilization in the Northeast are united by a common objective. They seek a reliable, economic, and environmentally safe technology.

For a variety of reasons—scarcity of expertise, cost of research, past suboptimal field experimentation, numbers and types of agencies involved, and the unpublished nature of field trials—a more collaborative and mutually informative system of working warrants development. It is possible that a representative working group could study how this might be achieved and put forward proposals.

Our Symposium has brought to light much research and many field trials showing very encouraging growth responses to fertilization. Unfortunately, the extent of commercial fertilization has not been sharply quantified, but seems small. The reason for this imbalance needs investigating and, if possible, remedying.

The general smallness of commercial fertilization and the quite specific and different forest conditions where fertilization is currently of interest suggest that there is unlikely to be an early wholesale fertilization of vast forest areas. For the nutritionist, this calls for a sharp focusing-in on those specific forest conditions where socio-economic forces generate an interest in fertilization, rather than an approach that endeavors to embrace the entire ecological spectrum.

Forest situations that will receive increasing attention in the coming years are nurseries, sugarbush, Christmas trees, spoil banks, urban and recreational areas, and juvenile growth at establishment, as well as semimature and pre-harvest coniferous and hardwood forests.

Because of the large number of field trials already in existence that remain unreported in the scientific literature, there seems to be a special need not only to implement some type of simple information data-sheet that could describe the essentials of a trial and its ecological setting, but also to make more provision for critically analyzing and reviewing the distribution and results of such trials.

In spite of the obvious progress being made in the challenging task of developing reliable foliar and soil diagnostic techniques, it is clear from several authorative contributions that the well-designed field trial will remain the only reliable means of testing for nutrient requirement for quite a number of years.

If the results from field trials are to be analyzed economically, their designs must be appropriate. For both nutritional and economic reasons, experimental approaches should generate the optimum blend of nutrients and dosages in the eliminative manner successfully developed and applied in agriculture.

Scope is seen for pot trials, and it is expected that critical foliar-levels now being published will generate appreciable interest and testing towards refinement.

Following this Symposium, more interest can be expected in the effects of fertilization on wood quality, an important area that nutritionists have hitherto been unable to exploit adequately.

Numerous studies complementary to the field trial are necessary to ensure that fertilizer recipes are environmentally safe. Two important papers reveal the way fertilizers can react with nontarget components of the forest ecosystem and indicate the approaches and types of studies that could be conducted to develop an environmentally safe technology.

In view of the very positive growth responses to N and N+P combinations, it is expected that considerable activity will focus on fertilizer sources containing these nutrient elements, on the reactions such materials might undergo in the soil, and on the pathways and processes by which such applied elements are transported or immobilized within the ecosystem.

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CRITIQUE: FOREST FERTILIZATION IMPACTS ON WATER AND THE ENVIRONMENT

by KENNETH G. REINHART, *Forest Hydrologist, USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pa.*

ABSTRACT. Forest fertilization can contribute in many ways to an improved environment. It can help restore denuded or overused areas, improve wildlife habitat, release forest land for nonproduct uses, and help to recycle waste products. Yet forest fertilization could have a negative impact on the environment. The problem most likely to be encountered is an increase in the N level in streams and lakes, possibly leading to eutrophication. An important safety factor here is the likelihood that only limited areas will be treated, and these infrequently.

IN HIS CRITIQUE of this Symposium, Dr. Rennie has covered general and nutritional aspects. I will present a few comments on the effects of forest fertilization on the environment.

In our region, fertilizers have not yet been applied as a regular forest-management practice. Thus we are in the unusual and fortunate position of considering environmental impacts at an appropriate early stage (Hornbeck & Pierce). We must not only give due weight to these impacts; we must also convince the public that we are doing so.

Fertilizer applications that might be made can be classified in two general ways: (1) applications for increasing timber production; and (2) applications for other purposes.

OTHER THAN TIMBER PRODUCTION

Where the objective is not timber production, it may be the revegetation of disturbed areas (Czapowskyj), improvement of wildlife habitat (Behrend), or protection or rehabilitation of recreation areas (Richards & Leonard). Revegetation of bare areas improves aesthetics, controls erosion, and protects streams from sediment. Fertilizers have already been used rather extensively for revegetating logging roads and strip-mined areas.

Enhanced awareness of environmental concerns will lead to increased use of fertilizer for these purposes in the future. Improvements in wildlife habitat and recreation areas are other possible benefits. These non-timber applications may have some adverse off-site effects, but considering particularly the limited areal extent of these practices, any detrimental effects should be minor.

FOR TIMBER PRODUCTION

In the near future, most fertilizer applications will probably be made to enhance timber growth. Of the 95 studies on fertilizing hardwoods reported to Auchmoody and Filip, 83 were oriented toward increasing forest growth rates. For environmental purposes we must consider side effects, both damaging and beneficial.

In assessing the potential problem, we should first consider the expected extent of fertilizer application. Several speakers (Safford, Hughes & Post, Ellis, Auchmoody & Filip) said that forest fertilization should not and will not be used indiscriminately on all timber-producing lands. Biological and economic considerations will limit the areal extent, intensity, and frequency of application. Thus, as compared to agricultural practice, use of fertilizer in the forest should have much less impact on the environment.

On the other hand, water in forest streams and lakes is now of relatively high quality, and even a relatively small input of nutrients may be damaging. As Werner suggests, though we can draw upon experience in agriculture, forest fertilization may be unique enough to require a separate analysis.

In any operation, there are side effects on nontarget species and on other aspects of the ecosystem. Side effects must be studied for two reasons: (1) to promote the understanding necessary to achieve the objective of improved tree growth; and (2) to avoid serious detrimental impacts on the environment.

Thus the man who wants to grow more and better trees for profit—as well as the environmentalist—is concerned with determining and assessing side effects (Brett). The presentations in this Symposium are encouraging; I see no likelihood of operators throwing on the fertilizer to see what happens next.

Negative Side Effects

Some side effects of fertilizer use may have a negative impact on environment. These include: (1) increased nutrients in streams and lakes (Hornbeck & Pierce, Werner, Aubertin et al., Richards & Leonard); (2) increased organic inputs to streams (Werner); (3) decreased water yield (Hornbeck & Pierce, Aubertin et al.); (4) damage to nontarget species (Aubertin et al., Shigo, Weetman & Hill); and (5) air pollution (mentioned indirectly).

The increase ot nutrient inputs to streams and lakes is likely to be the most controversial aspect of forest fertilization.

N promises to be the element of major concern, for two reasons: indications are that more N will be applied than any other nutrient; and the N compounds are more subject to leaching than the other candidates for use (Pierce & Hornbeck, Werner). The general absence of overland flow in the forest prevents nutrient loss into the stream through erosion.

The major problem is the increase of N, especially as nitrates, in streams. The question arises: will this reduec water quality to the point where it will no longer meet drinking-water standards? The studies cited in papers presented (Hornbeck & Pierce, Werner, Aubertin et al.) indicate fairly low levels of N in soil leachates and in streamflow, though comparison is difficult because of different modes of expression. The *maximum* stream values for N after fertilization of the Fernow watershed (Aubertin et al.) did exceed drinking-water standards. But this followed complete fertilization of the whole small drainage all at one time. Dilution in time and space will serve to reduce this concentration. From the data available, I believe that forest fertilization can be planned and conducted without raising levels of nitrate N above the current drinking-water standard (10 p.p.m.). If this allowable level is lowered —and such action is under discussion— further consideration might have to be given to this subject.

N inputs to groundwater would be much like those to streamflow and would not be likely to create a serious problem.

But what of stream and lake eutrophication? Will N inputs be large enough to cause trouble? Here we have a much more complicated problem than the one presented by drinking-water standards. And we have more unanswered questions. We have some data (Aubertin et al.), and we will be getting more about how fertilizing watersheds affects N levels. But to what extent is N limiting in dependent aquatic ecosystems, and how much eutrophication, if any, will result from a given increased input? I haven't seen answers to these questions. We may need case-by-case studies because the answers will vary with the chemical makeup and other characteristics of individual streams and lakes and their patterns of use.

In the Fernow experiment (Aubertin et al.), an amount equal to 18 percent (45 pounds per acre) of the N applied was lost to the stream in the first year. This is high, especially since the urea they used has been considered less subject to leaching than many other formulations. For both economic efficiency and environmental protection, there seems to be a real need for a form less soluble than the urea used there and for different methods or timing of application to reduce this discharge into the stream.

That fertilizer application can trigger the release of nutrients other than those applied cannot be neglected, though the problem does not appear to be a major one. In the Fernow experiment (Aubertin et al.), only N was applied; but some increase in Ca discharge into the stream was also measured.

Successful forest fertilization will augment organic-matter production and might increase the organic input to the stream (Werner). I don't think a moderate increase in growth will have any serious effect here, but we need to learn more about it.

Forest fertilization will decrease water yield (Hornbeck & Pierce), at least slightly. No measurable change was found in the Fernow experiment (Aubertin et al.). From this result and other experience, I expect that the effect of fertilization on water yield will be small, generally not noticeable, and not measurable. Where forest cover is being established on open land, fertilizers may speed the time when the forest's higher rate of water use is achieved. The same might be true after fertilizing a forest cover that initially was too sparse to occupy the site fully.

Forest fertilization may affect many nontarget species; it may kill understory vegetation in local areas (Aubertin et al.), depress mycorrhizae (Shigo), and change the absolute or relative numbers of various consumers and decomposers (Weetman & Hill). Generally these effects will be important only as they affect long-range fertility, water, aesthetics, or some such resource value. These side effects must be studied lest prescribed fertilizer practices fail in one respect or another and the reasons remain undiscovered until it is too late.

Air pollution was not specifically discussed, but the loss of applied N through ammonia volatilization was mentioned (Aubertin et al.). And there must certainly be some loss of material to the atmosphere during aerial application. There doesn't seem to be any serious problem here, but possible impacts should be considered when planning and conducting fertilization practices.

Positive Side Effects

There are some side effects of fertilizer application for wood production that have positive environmental impacts. These include: (1) reducing land area needed for timber production (Aubertin et al.); (2) increased productivity of aquatic flora and fauna (Werner); (3) improved wildlife habitat (Behrend); and (4) recycling of problem materials (Gagnon).

In the long run, perhaps the most important of the desirable side effects of forest fertilization, along with other intensive practices, will be the production of needed wood supplies on a smaller land area (Aubertin et al.). This should release some lands for other purposes, or decrease the impact that withdrawals for other purposes would have on these supplies. This may be considered a continuation of the agricultural trend of the last century or more; more forest land is now available for a variety of uses because of high crop production on prime acres.

We have already labeled eutrophication a negative side effect. In some circumstances, increased nutrient levels in stream or lake water will have a beneficial effect by increasing aquatic productivity, including fish (Werner). Which happens when and where may require case-by-case studies and much more basic knowledge than we now have.

We have also mentioned the possibility of obtaining wildlife benefits by using fertilizers. But wildlife habitat—particularly the nutritional value of browse and herbage—may be improved by fertilization for timber production (Behrend). The extent of such improvement will probably be slight unless wildlife objectives are built into the design of the practice.

Waste products of our society—compost from garbage, sewage sludge, and sewage effluent—may be applied to forest land (Gagnon). In setting objectives for these actions, the relative weight given to the need for disposal of wastes and the desirability of increased tree growth will vary, but generally both objectives can be achieved in some measure. Properly conducted disposal of waste in this manner can help keep our environment clean, but care must be taken to avoid adverse effects. I'm sure all aspects of this combination of opportunity and problem are being discussed thoroughly at the Symposium on Recycling of Wastewater and Sludge being held at the Pennsylvania State University concurrently with our Symposium.

Weetman and Hill discussed energy use in fertilizer production. When materials like sewage effluent are used instead of commercial fertilizers, this problem disappears.

Other Side Effects

Fertilization may affect insect and disease control (Shigo). I was unable to list this as either positive or negative, because apparently the effect can be either. I can only repeat Shigo's admonition that we cannot afford to treat the subject lightly.

I am sure there are other effects of forest fertilization on water and the environment, but I hope that you will agree that this covers most of the important ones.

PLANNING AHEAD

We may someday expect a wide variety of practices applied in many different situations. The environmental responses will also vary widely. We need to learn a great deal more about these. Fertilization practices must be planned carefully in light of the specific conditions in and adjacent to the area to be treated. And the environmental effects of fertilizer applications should be monitored carefully, at least until we are in a better position to predict impacts.

This Symposium has been a good start, but much remains to be done. Stone, Mader, and others emphasized the need for regional collaboration and teamwork to improve our knowledge about forest fertilization. These recommendations should be heeded when considering environmental impacts as well as wood production.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1973-710-598/581

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