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Evaluating Forest Sites for Potential Growth Response of Trees to Fertilizer¹

Introduction

Greatly intensified forestry practices will be necessary to meet the wood fiber needs of the future. The demand for timber products is projected to increase about 80 percent in less than 30 years (U.S. Forest Service, 1965). A rapid rise in the demand for forest products and a substantial, steady decline in the number of acres of forest land available for commercial timber production have created strong pressures for greatly intensifying forest management practices (U.S. Forest Service, 1969).

A potentially powerful silvicultural tool, forest fertilization, is currently the subject of much interest in connection with meeting needs for substantially increasing growth rate of trees. Evidence is accumulating that fertilizing forest stands has often led to substantially improved tree growth. Fertilizing does not guarantee improvement in tree growth, however. Added nutrients may be fixed in the soil in an unavailable form, volatilized, or lost by leaching. In addition, forest productivity is often more limited by unfavorable moisture and temperature conditions than by nutritional deficiencies.

Costs of applying fertilizer to forest stands in the Douglas-fir region currently average about \$23 per acre. These costs must be regarded as investments in growing stock, and the increased growth must be sufficient to pay back the investment plus interest.

Ecological considerations also are important in making decisions on the use of forest fertilizer. Public awareness and concern over quality of the environment indicate that forest managers will be under constraint to avoid any unnecessary alteration of natural balances. For these reasons, we believe that nutrients should be added only to those ecosystems in which we can be assured of an increase in tree productivity.

We do not now possess the information we need to determine where fertilizer will provide an economic response of tree growth (Strand and Miller, 1969). In this paper, we suggest that any satisfactory model for understanding the environmental interactions that control productivity must include considerations of (1) adequacy of the nutrient supply in soil; (2) adequacy of tree nutrition; and (3) constraints on productivity other than nutrients (such as moisture supply, temperature, and genetic factors). Results of our analyses agree with findings by Gessel, Stoate, and Turnbull (1965) that nitrogen is at present the principal limiting nutrient element

¹Paper 790, School of Forestry, Oregon State University, Corvallis, Oregon 97331.

for growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Therefore, in the following discussion, most of our remarks and illustrations concerning tree nutrition will be limited to nitrogen.

Soil Fertility

Soil fertility is the ability of a soil to supply nutrients to growing plants. A soil is a dynamic reservoir of plant nutrients, the supply of which is regulated by the return of nutrients through litter decomposition, rainfall, biological activity in the soil, and the capacity of the soil to hold nutrients in an available form.

We have long relied largely upon chemical analyses of soil profiles for information on soil fertility although our methods of chemical extraction may be unrepresentative of forest plants (Ralston, 1964; Viro, 1961). Empirical relations have been useful when determined within well-defined soil-classification units. The diversity of soils and climates in the West, however, encourages an approach more closely related to the processes of nutrient uptake and utilization. Even the best methods with radioisotopes (Bowen, 1971) prevent our assessing the total nutrient reserve in heterogeneous soil profiles. The nutrient supplying power of agricultural soils is often measured by bioassay (Jenny *et al.*, 1950). If forest soils are to be studied, however, agricultural bioassay must be altered in two ways. First, forest plants, rather than agricultural crop species, must be used, because requirements for the two kinds of plants are substantially different (Vlamiš *et al.*, 1959; Waring and Major, 1964). Second, the entire soil profile, or at least the major portion infiltrated with fine roots, must be represented so that concentrations of nutrients, rocks, organic matter, or other parts of the soil system are not modified by mixing.

On the basis of the foregoing requirements for adequately assessing soil fertility, we determined the nutrient supplying power of several soil profiles by growing seedlings of Douglas-fir and Shasta red fir (*Abies magnifica* var. *shastensis* Lemm.) in reconstructed profiles of a number of relatively young, undeveloped forest soils. These growth studies were carried out under a standardized regime which included favorable moisture, temperature, and light.

Soil was collected in the fall for the reconstructed profiles in three- to six-inch layers from the bottom of a two-ft profile upward in a steplike progression. Near the surface, soil material was removed in one- to three-inch layers. After collection, these soil layers were carefully placed into plastic lined, aluminum containers, five inches in diameter and 24 in deep. In initial survey work, four such samples were collected from an area 100 ft square.

After collection, the soil material was allowed to remain in a cool, shaded environment at field capacity for four months. Four pregerminated seeds of Douglas-fir and Shasta red fir were then planted in each soil container. The bioassay was conducted in a growth room with a 21°C, 15-h day; 10°C, 9-h night; and 14-17°C soil temperatures. Light was provided at 1000 ft-c from fluorescent and supplemental incandescent sources. Each soil container was rotated systematically every three days. At weekly intervals, sufficient water was added to bring all soils to their equilibrium weight at field capacity. One hundred samples were thus evaluated at one time. All seedlings were harvested after five months of growth. Plant dry weight produced above the seedling cotyledon was used as an index of soil fertility.

Plant Demand for Nutrients

The nutritional status of a plant reflects the degree to which the soil nutrient supply meets plant requirements under a particular environment. A rapidly growing plant may be under nutritional stress while, on the same soil, another plant with different nutrient requirements or of slower growth habit may be adequately supplied.

A minimum nutrient level is necessary for the formation and development of new foliage and other organs. This nutrient requirement is always met in the case of natural vegetation because, where soil fertility is low, selection has long favored those species with lower requirements. Selected genetic strains show markedly higher requirements for nutrients and the introduction of such genetic stock will increase the need for fertilization (Fritchett and Goddard, 1967; Walker and Hatcher, 1965). Each plant has a level of nutrition that is sufficient to assure optimum growth. Levels above those essential for optimum growth can be attained but do not contribute further to plant growth.

The nutritional level just adequate to maintain optimum plant growth is referred to as the "critical level" (Ulrich, 1952). It is usually assessed by chemical analysis of various parts of a plant particularly sensitive to nutritional stress.

The least nitrogen reported in expanded foliage of Douglas-fir is about 0.6 percent dry weight (Gessel *et al.*, 1960), a value that agrees with those we measured in the foliage of Douglas-fir plants growing under maximum demand in the growth room. Thus, we can assume that living needles with total nitrogen contents of about 0.6 percent have no mobile nitrogen that can be translocated to other tissue.

A critical value for foliar nitrogen has not been firmly established for Douglas-fir, although values as high as 1.7 percent nitrogen may be required (van den Driessche, 1969). Gessel *et al.* (1960) state that all visible symptoms of nitrogen deficiency disappear if foliar nitrogen remains above 1.1 percent during the autumn season.

Unfortunately, the critical level determined in laboratory experiments may be unrealistically high for field conditions. Laboratory experiments are generally conducted with small seedlings grown in water or sand cultures, often under an abnormally demanding environment without the benefit of the normal root-mycorrhizal association. Recent studies in fertilized plantations suggest that less nitrogen may be required under environments representing less than the optimum potential for growth (Tamm, 1968; Sandvik, 1968).

One of the most disturbing practices in assessing foliar nutrition is the usual preference of investigators for sampling during the dormant season (Gessel, 1962; Leyton, 1958; Tamm, 1964). This practice may result in low sampling error, but, by following it, much biological information is sacrificed. Many researchers have found that nitrogen content in foliage varies seasonally (Youngberg, cited by Lavender, 1970; Tamm, 1955; Smith *et al.*, 1970). But only the last authors cited have recommended that the "best time to characterize the differences in nitrogen is during periods of rapid growth after reserves are depleted and demands for nitrogen are large." The period of maximum demand for nutrients varies from place to place and year to year. It can best be characterized by reference to a particular stage in the morphological development of a plant. Thus, the plant's phenology, not a calendar date, determines the time of sampling.

Although it is well documented that new foliage is a sink for nutrients, the source of mobile nutrients in the older foliage has usually been ignored. We submit that this is a basic error. Figure 1 shows the seasonal change in foliar nitrogen of the previous year's foliage in three Douglas-fir trees growing on relatively fertile, clay soil to which sufficient water was provided to secure some second flushing of foliage. The assumed critical level of 1.2 percent foliar nitrogen agrees with that found in similar foliage of plants growing under the most productive environments in the region where our assessment of soil fertility, plant nutrition, and other environmental variables was made (Waring, 1969).

As new foliage expanded, the nitrogen level began to drop and reached a minimum during late summer (Fig. 1). Some recovery took place during the winter although it was not sufficient to restore the nitrogen to its original status. These findings suggest that the most appropriate time to sample tree foliage during the growing season would be after new foliage has fully expanded. We find, however, that maximum nitrogen translocation has already taken place on some sites when the new foliage is only at the "brush stage."

Because the dry weight of needles can vary by more than 20 percent during the growing season, comparisons of nutrient status in plants are difficult unless sampling is confined only to one period. For this reason, expressing concentrations as mg cm⁻³ or some similar units (Tamm, 1955; Tamm, 1964; Cassidy, 1970) would be an additional improvement in assessing seasonal changes in nutrition. We do not favor the practice of reporting results on a per needle or shoot basis; such expressions mainly reflect differences in growth, not nutrition (Tamm, 1964).

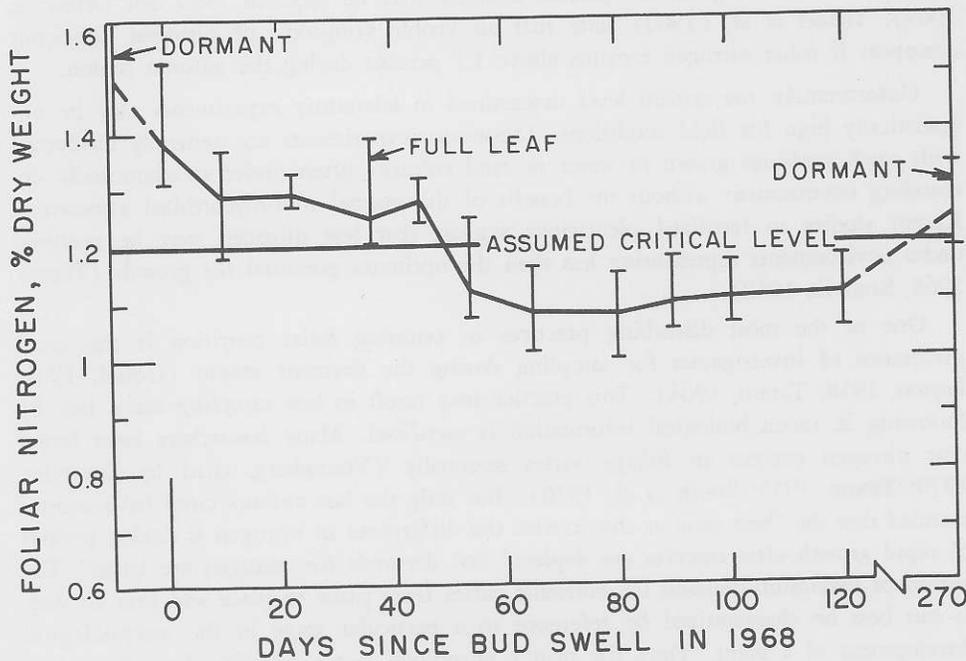


Figure 1. Seasonal variation in nitrogen content of mature Douglas-fir needles (1967 foliage).

Forest Productivity

Plant productivity is a function not only of soil fertility and plant nutrition but also of the genetic potential of a plant and the limitations upon that potential from the entire environment. Drought alone may increase foliar nitrogen to values above 3 percent as Heiner (1968) found in his study of different Douglas-fir populations and Zinke (1962) reported with ponderosa pine growing on poor sites in California. In such instances, adequate fertility and adequate nutrition have little influence upon productivity. This is not an isolated example. Both the vegetative composition and productivity of native forests are more generally limited by moisture and temperature than by inadequate supply of available nutrients (Waring, 1969). Strong winds, snow, and ice may also strictly limit tree growth in many parts of the world by damaging the crown or uprooting exposed trees.

Ecologists have developed various approaches for classifying forest environments. Some of those recently devised are based upon measured environmental gradients (Waring and Major, 1964; Griffin, 1967; Waring, 1971). In the last reference, the productivity and distribution of Douglas-fir and Shasta red fir are depicted as functions of both moisture (Waring and Cleary, 1967) and temperature gradients (Cleary and Waring, 1969). Six of the sampled environments labeled for reference in Figure 2 represent a range of stands dominated by Douglas-fir and Shasta red fir. We can see that Shasta red fir is generally restricted to the cooler environments, usually where moisture stress is not severe. Douglas-fir occupies warmer sites across a complete range of moisture stress conditions. Stand productivity, as indexed by maximum height, decreases with decreasing temperatures and available water.

Interrelations among Soil Fertility, Plant Nutrition, and Productivity

We have distinguished among (1) the nutrient supply in the soil, (2) demand for nutrients by plants, and (3) other constraints on productivity. Now we will focus upon important interrelations to see whether our conceptual model can provide interpretation for a range of real situations.

To do this, we will select some extreme environmental combinations referenced by number in Figure 2. In Table 1, the six ecosystems are referenced again by number, and indices to their soil fertility, foliar nitrogen, and productivity are given. The nutritional data are an average from three trees, 1-2 m tall. Variation among the three trees was rarely more than 0.1 percent nitrogen and less than 0.05 percent in most instances.

Assuming that at least 1.2 percent nitrogen during the active period is necessary to sustain maximum growth for both Shasta red fir and Douglas-fir, then Stand 17 appears nearest to optimum. At that site, soil fertility is high, nutrition is adequate, and productivity is the highest among the listed Shasta red fir stands. Stand 7, on the other hand, appears to have adequate foliar nitrogen only during the dormant season. During the growing season, a decrease to 0.94 percent suggests the limiting ability to supply nitrogen of the soil derived from weathered quartz diorite. Stand 18, also developed on soils derived from quartz diorite, has a limited supply of nutrients in the soil, but more than adequate foliar nutrition during the dormant season. This response could reflect the reduced demand of plants growing near timberline where a lack of soil moisture and the mechanical effect of snow and wind combine to limit productivity. Yet, nutritional stress appears to develop during the growing season.

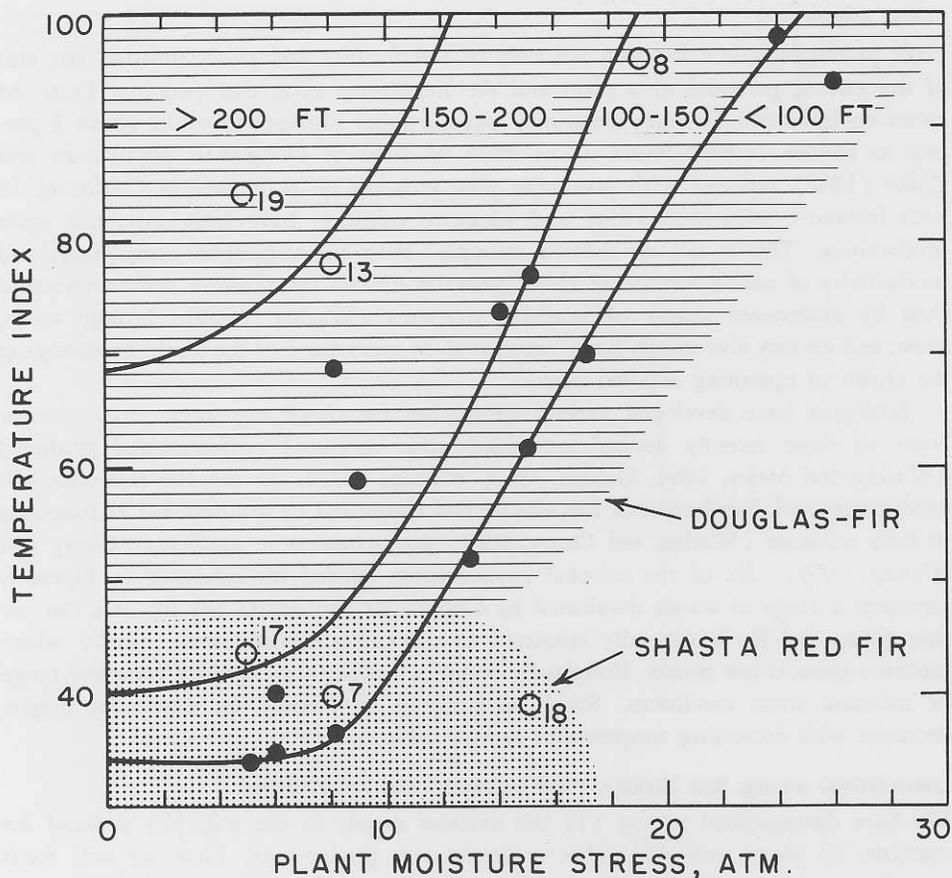


Figure 2. Forest productivity (maximum height) in relation to moisture and temperature. Numbered circles are referred to in text. Moisture stress gradient is based upon the maximum recorded, before dawn, during the growing season in conifers, three to six ft tall. The temperature index represents the potential growth of Douglas-fir, derived by summation of the growth possible each day during the growing season (Waring, 1969).

Ecosystems dominated by Douglas-fir, on soils weathered from quartz diorite, may have temperatures that encourage growth but an inadequate supply of nitrogen even during the dormant season (Stand 8). Moisture stress is a problem in Stand 8, a type dominated by ponderosa pine (Waring, 1969). Here, additions of fertilizer might well increase the nutritional level of the plants without substantially increasing productivity. Stand 13 is located on relatively infertile soils developed from hard green schists. The moisture regime is favorable, and, under such circumstances, the nitrogen level becomes critical during the growing season, but not to the extent that primordial development and foliar expansion are prevented. Increasing the nutritional level through fertilization should increase productivity substantially. The highest recorded productivity in our study of the Eastern Siskiyou Mountains of southwestern Oregon and northwestern California was that of Stand 19. Not only does it have a high index of soil fertility and an excellent moisture and temperature regime, but an adequate nutritional status is maintained throughout the growing season. Because nutritional demands appear

TABLE 1. Soil fertility, nitrogen status, and productivity of Shasta red fir and Douglas-fir in the Siskiyou Mountains of southwestern Oregon.

Stand	Soil fertility		Productivity ³			
	Bioassay, % of max. ¹	Coef. of variation	Foliar nitrogen ²		Site index, ft	Maximum height, ft
			Dormant, %	Active, %		
Shasta red fir						
17	79	0.42	1.23	1.17	---	158
7	27	.51	1.22	0.94	---	145
18	23	.25	1.46	0.96	---	55
Douglas-fir						
8	28	.13	1.01	0.87	120	---
13	30	.21	1.26	0.82	150	---
19	75	.54	1.34	1.20	190	---

¹ Determined by growing Shasta red fir or Douglas-fir seedlings on reconstructed soil profiled for five months under a standardized environment.

² Determined by micro-Kjeldahl analysis on whole first-year needles sampled from three trees, one to two m tall, in October, 1967, and on the same foliage at the time of "brush stage" the following year.

³ Measured directly on an average of five dominant or codominant trees.

to be met, fertilization is a poor investment. Productivity can probably not be substantially increased, at least through additions of nitrogen alone.

If these interpretations are correct, then forest fertilizer trials should include foliar analyses during both the active and the dormant seasons. Such information compared with *field-defined critical levels* for all of the essential plant nutrients could determine: (1) whether plants really are deficient in something; (2) whether fertilizer is effective in improving the nutritional status, and (3), together with knowledge on moisture stress patterns, whether temperature and other major environmental factors provide a satisfactory model for understanding the environmental interactions that control productivity.

Direct measurement of even the major environmental factors is often impossible, but through a survey of soil and vegetation and with the knowledge of experienced personnel, the major constraints upon productivity can often be estimated adequately. Any attempt to improve productivity through the application of fertilizers should, however, include an assessment of foliar nutrition during both the active and dormant part of the growing season. Increases in the level of nutrition can thus be verified and interpreted in comparison with field-defined critical levels.

Summary

Decreasing forest land area and increasing demands for wood fiber require more intensive forestry. One potential means of increasing production is applying fertilizer. But the questions arise: "Where will fertilizing improve the nutrient status of trees and will such improvement lead to increased growth?" To answer these questions, we must assess how nutrients in soil become available to plants and thus increase their growth. To do this, we must distinguish among (1) the nutrient supply in the soil, (2) demand for nutrients by plants, and (3) other constraints on productivity.

In evaluating the nutrient supply in soil, we reconstructed soil profiles and grew

tree seedlings in them under a demanding, standardized environment. We determined plant demand for soil nutrients in the field, assessing the level of foliar nitrogen in the previous year's needles during the period of peak demand when new foliage was expanding and during the previous dormant season.

From an environmental classification, we were able to recognize when other constraints such as moisture and temperature would make forest fertilization an unlikely economic venture and possibly an ecological mistake. The treatment of these problems was not definitive, but with some modifications, the approaches suggested should have wide application.

Acknowledgments

Many valuable ideas come through informal exchanges. Waring, during his recent sabbatical, had an opportunity to discuss many of the points raised in this paper with European scientists. Where a particular idea originated is often difficult to establish, but many of the points raised in this paper were discussed at length with Werner Koch, University of Munich, L. Leyton, Oxford University, and C. O. Tamm, University of Stockholm, and to these men formal acknowledgment is given. In addition, we are particularly indebted to Robert Tarrant, of the U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, for critically reviewing the manuscript. This work was supported through a McIntire-Stennis Federal Grant.

Literature Cited

- Bowen, G. D. 1971. Early Detection of Phosphate Deficiency in Plants. *Commun. in Soil Sci. and Plant Anal.* In press.
- Cassidy, N. G. 1970. The distribution of potassium in plants. *Plant and Soil* 32: 263-267.
- Cleary, B. D., and R. H. Waring. 1969. Temperature: collection of data and its analysis for the interpretation of plant growth and distribution. *Can. J. Bot.* 47: 167-173.
- Gessel, S. P. 1962. Progress and problems in mineral nutrition of forest trees. *In* *Tree Growth*. Edited by T. T. Kozlowski. Ronald Press Co., New York. Pp. 221-235.
- _____, T. N. Stoate, and K. J. Turnbull. 1965. The Growth Behavior of Douglas-fir with Nitrogenous Fertilizer in Western Washington. College of Forestry, Univ. Washington, Seattle. *Res. Bull.* 1.
- Heiner, T. C. 1968. Physiological and Anatomical Studies of Several Groups of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) Seedlings which Demonstrated Differential Survival Potential under Drought Stress. M.S. Thesis, Oregon State Univ., Corvallis, Ore.
- Jenny, H., J. Vlamis, and W. E. Martin. 1950. Greenhouse assay of fertility of California soils. *Hilgardia* 20: 1-8.
- Lavender, D. P. 1970. Foliar Analysis and How It Is Used. *For. Res. Lab., Oregon State University, Corvallis, Ore. Res. Note* 52.
- Leyton, L. 1958. The relationship between growth and mineral nutrition of conifers. *In* *The Physiology of Forest Trees*. Edited by K. V. Thimann. Academic Press, New York. Pp. 323-345.
- Pritchett, W. L., and R. E. Goddard. 1967. Differential responses of slash pine progeny lines to some cultural practices. *Soil Sci. Soc. Amer. Proc.* 31: 280-284.
- Ralston, C. W. 1964. Evaluation of forest site productivity. *In* *International Review of Forestry Research 1*. Edited by J. A. Romberger and P. Mikola. Academic Press, New York. Pp. 171-201.
- Sandvik, M. 1968. Mineralernaering og gjødsling. *Norsk. Skogbruk* 24: 1-27.
- Smith, W. H., G. L. Switzer, and L. E. Nelson. 1970. Development of the shoot system of young loblolly pine: 1. Apical growth and nitrogen concentration. *Forest Sci.* 16: 483-490.
- Strand, R. F., and R. E. Miller. 1969. Douglas-fir growth can be increased, report from Pacific Northwest shows. *Forest Industries* 96: 29-31.
- Tamm, C. O. 1955. Studies on forest nutrition. I. Seasonal variation in the nutrient content of conifer needles. *Medd. Staten Skogsforskningsinst* 45: 1-25.
- _____. 1964. Determination of nutrient requirement of forest stands. *In* *International Review of Forestry Research 1*. Edited by J. A. Romberger and P. Mikola. Academic Press, New York. Pp. 115-170.

- _____. 1968. An attempt to assess the optimum nitrogen level in Norway spruce under field conditions. *Studia Forestalia Suecica* 61.
- Ulrich, A. 1952. Physiological bases for assessing the nutritional requirements of plants. *Ann. Rev. Plant Physiol.* 3: 207-227.
- United States Forest Service. 1965. *Timber Trends in the United States*. U.S. Dep. Agr., Forest Resources Rep. 17.
- _____. 1969. Douglas-fir Supply Study. U.S. Dep. Agr., Portland, Oregon.
- Van Den Driessche, R. 1969. Tissue Nutrient Concentrations of Douglas Fir and Sitka Spruce. *Brit. Col. For. Serv. Res. Note* 47.
- Vlamis, J., A. M. Schultz, and H. H. Biswell. 1959. Nutrient response of ponderosa pine and brush seedlings on forest and brush soils of California. *Hilgardia* 28: 239-254.
- Virc, P. J. 1961. Evaluation of site fertility. *Unasyva* 15: 2-7.
- Walker, L. C., and R. D. Hatcher. 1965. Variation in the ability of slash pine progeny groups to absorb nutrients. *Soil Sci. Soc. Amer. Proc.* 29: 616-621.
- Waring, R. H. 1969. Forest plants of the Eastern Siskiyou: their environmental and vegetational distribution. *Northwest Sci.* 43: 1-17.
- _____. 1971. Matching species to site. *In* *Regeneration of Ponderosa Pine*. Edited by R. H. Hermann. School of Forestry, Oregon State Univ., Corvallis, Ore. Pp. 54-61.
- _____, and B. D. Cleary. 1967. Plant moisture stress: evaluation by pressure bomb. *Science* 155: 1248-1254.
- _____, and J. Major. 1964. Some vegetation of the California coastal redwood region in relation to gradients of moisture, nutrients, light, and temperature. *Ecol. Monogr.* 34: 167-215.
- Zinke, P. J. 1962. A fertility survey of California forest. Paper presented to North Coast Forest Soil Fertility Conf., Eureka, Calif.

Received August 23, 1971.

Accepted for publication November 15, 1971.

Association News

The 45th annual meeting of the Northwest Scientific Association will be held on the campus of Western Washington State College, Bellingham, Washington on March 23-25 (from noon Thursday to noon Saturday).

In addition to the Association's regular technical sessions, the meeting will feature a timely symposium on "Research on Coniferous Forest Ecosystems: First-Year Progress in the Coniferous Forest Biome, US/IBP." The symposium organizers (Jerry Franklin of the U.S. Forest Service, Dale Cole of the University of Washington, and Richard Waring of Oregon State University) have prepared an outstanding program that will have interest and value for *all persons concerned with ecosystem analysis*. About thirty invited papers will be given during the 1½-day period of presentations.

Also worthy of note, the traditional formal banquet has been replaced with an *informal* Friday evening spaghetti dinner, including appropriate beverages. Plan now to come—and bring your families.

Information about on-campus housing and local hotels and motels will be mailed with the program for the meeting early in March. For further information or any help you may need, write or call one of the co-chairmen for program and arrangements—Willard A. Brown or W. Louis Barrett, Physics Dept., WWSC, telephone 206-676-3819.

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Copies of "The Biology of Alder," proceedings of a symposium at the 1967 annual meeting, are still available in quantity or singly; free on request to the Director, Pacific Northwest Forest & Range Experiment Station, Box 3141, Portland, Oregon 97208.