THE BLACK ROCK FOREST

BULLETIN No. 5

HENRY H. TRYON, *Director*

POT CULTURE TESTS OF FOREST SOIL FERTILITY

With Observations on the Effect of Varied Solar Radiation and Nutrient Supply on the Growth and Nitrogen Content of Scots and White Pine Seedlings

By
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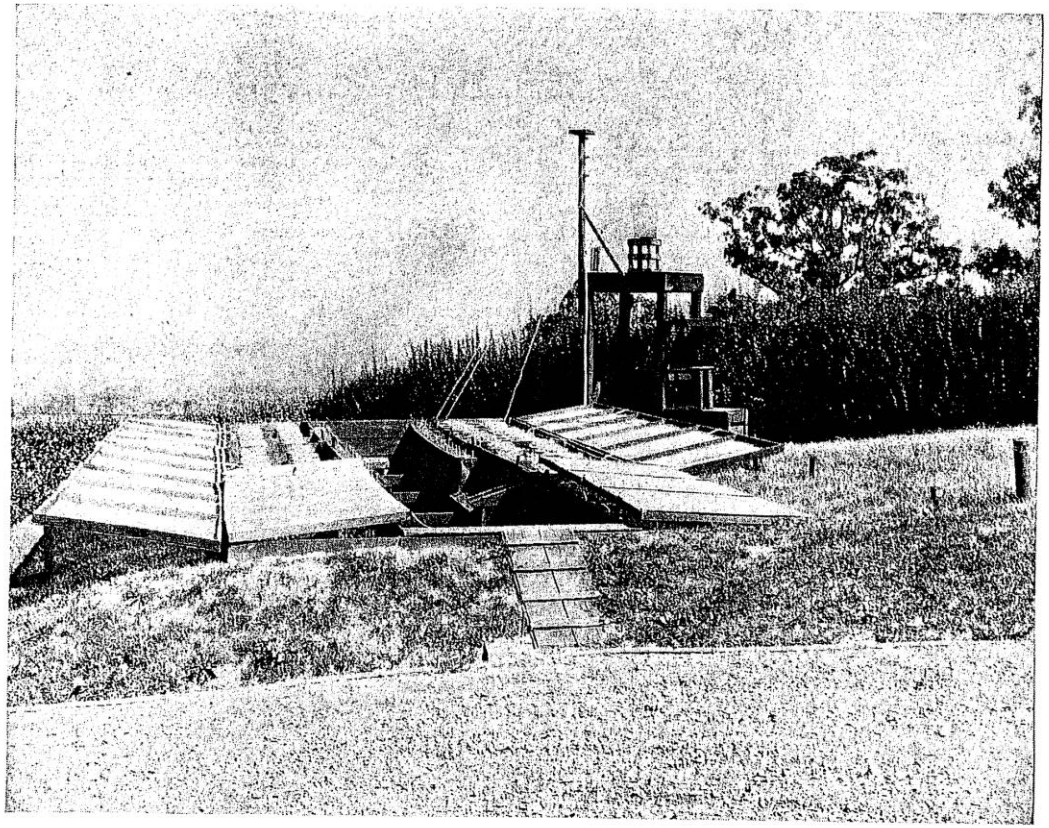

GENERAL VIEW OF EXPERIMENTAL ARRANGEMENT.

Distilled water is piped to all parts of pit from supply bottles on raised platform in background. One Cello Glass screen (right) is closed; at the left is a lath screen to reduce light intensity.

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THIS study was initiated under the general direction of the late Professor Richard Thornton Fisher, Director of the Harvard Forest. It was his hope that studies of this character would advance the science of silvics and the art of silviculture. His wise and friendly counsel was a never-failing source of stimulation and knowledge.

The writer is especially indebted to Professor P. R. Gast, of the Harvard Forest, for generously permitting various unpublished data to be included in this report, for guidance in planning this and subsequent studies, for the many helpful suggestions regarding chemical methods and statistical treatment, and for valuable aid and advice in preparing the manuscript. Much credit is also due to Mr. H. H. Tryon, Director of the Black Rock Forest, for guidance and criticism in the silvical aspects of these studies. The writer is further indebted to Mr. A. B. Hatch, in the Department of Botany, Harvard University, who helped to plan and observe these experiments and who did much of the photographic work; to Professor T. J. B. Stier, of the Laboratory of General Physiology, Harvard University, for constructive criticism of the manuscript; and to Messrs. Elmer Snow, Clayton Knowlton, R. Love, A. Nelson and Raymond Finn, laboratory assistants, who aided with the observations, chemical analysis and computations.

ABSTRACT

IN TWO series of pot-culture experiments the effects of simultaneously varied nutrition and radiation on the physiology of white pine (*Pinus strobus*) and Scots pine (*P. sylvestris*) were studied. Details of equipment for watering, character of sand, nutrient concentrations, measurement of radiation, protection, effect of variation in seed-size, harvesting and nitrogen analysis are given. The yellow-green of nitrogen poverty, the purple of phosphorus deficiency and the chlorosis with K and Ca lacking were observed. Increase in radiation intensity from 50% to full "light" increased dry weights of Scots seedlings only at higher nitrogen supplies. Summated radiation over a growth period determines dry weight at end. Root-shoot ratios were calculated. Size and development of root systems varied inversely as nitrogen supply. The nitrogen supply was varied over a range sufficient to demonstrate beneficial and injurious effects. The optimal supply of 300 p.p.m. resulted in 3.2% N on dry weight. The dry weight of seedlings under varied nitrogen conditions can be predicted within ± 2% by the Mitscherlich formula. The nitrogen content as total and as percent of dry weight are predictable from the nitrogen supply. Total content is apparently independent of other conditions.

These techniques and information provided the method for determining deficiencies in P, N, K, Ca in the four main types of soil on the Black Rock Forest. It was concluded that N is increasingly available in the ratios: Ridge 4.1, Mid-slope (good) 5.6, Mid-slope (poor) 6.2, and Cove 10. The K and Ca are relatively abundant except in the Ridge soil. All soils were found deficient in P.

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INTRODUCTION

A pot culture technique for detecting soil nutrient deficiencies and estimating the nutrients in forest soils available to tree species is the subject of this report. It is based upon the principle of nutrient extraction by plants and utilizes silvical information gained from a series of experiments studying the gross relations of various nutrient elements to the growth and chemical composition of coniferous seedlings. The method is intended to forward ecological investigations concerned with the identification and measurement of soil nutrient changes that invariably accompany natural forest succession or conversion by artificial means. Consequently it forms a sound basis for determining the success of cultural treatments designed to improve the soil, and therefore the ultimate health, of degenerate forest stands such as comprise a large portion of the Black Rock Forest.

The Black Rock Forest is representative of the sprout hardwood type that covers thousands of acres in the Hudson Highlands of New York and Northern Jersey. From pre-Revolutionary times the forests of this region have been cut repeatedly for cordwood, poles, posts and fenders. The usual procedure seems to have been to clear cut about every thirty years. Probably the length of the cycle was dependent chiefly upon the size of the timber and the demand for fuel by brick yards and for charcoal pits. These two uses formerly absorbed the greater part of the forest production. Besides this injurious cutting, fires did further damage by burning large areas at frequent intervals. Fire not only damages standing timber and destroys the younger reproduction, but often burns the organic layers of the forest soil. The results of the misuse to which the forest has been subjected are evidenced by relatively thin soils, an increase in the number of weed species, partial or total elimination of the more desirable species from certain areas, and a present crop of trees—mostly from large or diseased stools—that lack in vigor and reproductive capacity.

In the autumn of 1927 the Black Rock Forest was established and placed under management as a field laboratory where the silvicultural methods best suited to the forests of the region might be determined and applied (Tryon, 1930). Careful application of methods proved satisfactory by experiment will, it is hoped, restore the stands of the forest to a healthy condition.

Various types of experimental cuttings have been made. Some have been thinnings of varying severity to decrease the density of over-stocked stands; others, more cultural in nature, included the removal of "wolf" trees, undesirable or unimportant species, dead (mostly chestnut), dying and poorly shaped individuals. Some crop cuttings of the selection type have been made in the more mature stands to provide openings in which to establish seedling reproduction. Quite often the cutting was a combination of several cultural methods. But always the better formed individuals of the more desirable species have been selected as the first crop; to be harvested as soon as the advance growth is well established.

Some areas have been clear cut in strips. Here more than in any other cutting intensive weeding will be necessary if the new crop is to be composed chiefly of seedlings and of shoots from the smaller stumps, for sprouts from the larger stumps are as prolific as they are undesirable. If new and vigorous stock is to be introduced the sprouts of the old diseased stumps must be suppressed.

A study of the physical properties of the Cove soils of the Black Rock Forest was made by Scholz (1931). He drew the conclusion that the abuse to which the forest had been subjected was more strongly evidenced by the degeneration of the growing stock than by the physical condition of the soil. Although not as deep as desirable, most of the coves and slopes are covered with a favorable brown earth type of soil, loose and with a granular structure. Gast, in his comment (Scholz, *loc. cit.*), points out that improvement due to careful management will no doubt in time bring about a gradual transition to the more desirable crumb structure. But immediate improvement is desired in the increase of available nutrients, especially in the upper soil horizons where most of the feeding roots are located.

The silvicultural methods that have been applied to the stands of the Black Rock Forest undoubtedly affect the soil. It is well known that openings in the canopy are accompanied by, and are indirectly responsible for, soil changes. The local climate—radiation, temperature, moisture conditions and humidity—of the forest floor varies with the density of the canopy. The activity of the microflora and microfauna in the soil, the weathering of the mineral soil, the occurrence and prevalence of various types of ground cover, all of which have a direct effect on the chemical and physical composition of the soil vary with the local climate. Thus the activity of the agencies directly responsible for soil changes varies with local climate; and silvicultural operations (cuttings) change local climate by disturbing the canopy. Therefore it would be helpful to identify in the early stages the more subtle soil changes following cutting. Immediate recognition of silvicultural treatments beneficial to the soil may hasten the rejection of unsuitable methods and the early adoption of advantageous procedures.

The physical properties of soils are relatively easy to determine. The literature is replete with various satisfactory methods. Furthermore the study of Scholz (1931) has shown the soils of the Black Rock Forest to be in a relatively good physical state. A study of the chemical fertility is therefore the immediate need.

AVAILABLE METHODS FOR DETERMINING SOIL FERTILITY

THERE are two general ways in which a measure of soil fertility may be obtained: (1) by direct analysis, chemical or electro-chemical, of the soil or soil extract, or (2) the indirect (biological) method—growing plants in samples of a soil and using either their weights or the quantities of nutrients absorbed by them as an index to the fertility of the soil.

CHEMICAL METHODS

The first method is apparently the simpler of the two. But the early assumption of Liebig (1863) that soil fertility could be determined by direct chemical analysis has not proved practicable. Chemical treatment during the analysis usually causes some of the nutrient substances not available to plants, to be included in the determination. To avoid this difficulty various attempts have been made to find a solvent which will imitate the extractive and absorptive powers of plants growing in a natural environment. Although they vary somewhat in detail, and in the concentrations and kinds of solvents used, many methods of this general type have been proposed: Dyer (1894), Fraps (1909), Tamm (1922), Atkins (1924), Hissink (1925), Wrangell (1927), Dirks and Scheffer (1928), Bray (1929), Spurway (1929 and 1933), Truog (1930), Das (1930), Dahlberg and Brown (1932), Hibbard (1932), Mitchell (1932), and Morgan (1932).

The electrodialysis technique (Mattson, 1926; Bradfield, 1928; Odén and Wykstrom, 1931; Salgado and Chapman, 1931; Wilson, 1931; McGeorge, 1932; Scarseth, 1932; Harper, 1933; Dean, 1934) also gives promise of developing into a simple and adequate method for the determination of the available nutrients in natural soils. But some doubt exists regarding the actual availability to plants of the ''available nutrients'' as determined quantitatively by these methods. This question is further elaborated in the discussion on page 90.

BIOLOGICAL METHODS

The trend in recent years has been toward the second alternative, the biological procedures. The Neubauer method (Neubauer, 1925, '26 and '29), the Hoffer stalk test (Hoffer, 1930), the sap analysis tests of Gilbert and Harden (1927), McCool and Weldon (1928), and Pettinger (1931), the Mitscherlich method (Mitscherlich, 1928; Willcox, 1930), the soil-plaque method (Winogradsky, 1926; Winogradsky and Ziemiecka, 1927 and 1928; Guittonneau, 1929; Sackett and Stewart, 1931; Dahlberg and Brown, 1932; Greene, 1932; Jones, 1932; Pittman and Burnham, 1932; Stewart *et al.*, 1932; Ziemiecka, 1932; Hokensmith *et al.*, 1933), and the *Aspergillus niger* method of Niklas (1930) are all of this general type.

The Neubauer Method

The method proposed by Neubauer and Schneider (1923, see also Neubauer *loc. cit.*) is one of the earliest, and probably the most widely used, of the biological procedures. It consists, briefly, of growing rye seedlings for 14 days in samples of the soil under examination. At the end of this period the plants are analyzed, and amounts of nitrogen, phosphorus, and potassium absorbed by them are taken as a measure of the available quantities of these elements in the soil. Although subsequent European investigators too numerous to mention have made extensive use of this method, its application in this country has been limited. Among American investigators who have followed exactly the Neubauer technique the experiments of Thornton (1931 and 1932) and Stewart *et al.* (1932) may be cited.

Thornton (1931) used the 0.2 N nitric acid extraction method, Neubauer method, Illinois phosphate test, Hoffer stalk test, pot tests and field yields to determine the available phosphorus and potassium in six soil series. The results obtained by the various methods were compared. The comparison showed that: *"With certain soils, especially where single severe deficiencies exist, all methods give correct indications as to the available nutrient supply of the soil; but in numerous instances the correlation between the different methods is very poor."*

In general the results of the Neubauer method were found to agree better with the results of pot and field tests than the other procedures used. He suggests tentative limit values for deficiencies in potassium and phosphorus—determined by Neubauer method—as applied to average field crops under Indiana farming conditions. In a later experiment, Thornton (1932) used the Neubauer method to study the factors affecting the availability of phosphate fertilizers.

Stewart *et al.* (1932) compared the soil-plaque, Neubauer, and Hoffer corn stalk methods. The first two were found to be equally reliable for determining mineral nutrient deficiencies. They also report close correlations between the three methods where comparisons were possible. Although the Hoffer corn stalk test proved satisfactory in the case of marked deficiencies or abundant supplies (potash and nitrogen), some doubt was expressed regarding its dependability in border line cases.

Modifications of the Neubauer Method

Numerous modifications of the Neubauer Method have been proposed. But all are based upon the principle of proportional absorption fundamental to the Neubauer technique.

Gilbert and Harden (1927) proposed testing plant sap. Their data showed a fair relation between the concentration of several nutrient elements in the sap of various field and garden crops, and the fertilizer treatments used. According to McCool and Weldon (1928), fertilizer treatments have a decided effect upon the chemical composition of the sap of various plants. Similarly, Pettinger (1931) found a good correlation between the concentration of potassium and phosphorus in the expressed sap of corn plants grown in a series of variously fertilized soils, and the amounts of these elements supplied the soil. Nitrate nitrogen showed only a fair correlation.

Hoffer (1930) suggests testing the inner stalk tissue of corn plants. Evidence is given to show that potassium and nitrate deficiencies may be detected in this way. A somewhat similar test has been developed by Thornton (1932) for diagnosing phosphorus deficiencies in various crops. Preliminary results were found to be in good agreement with field tests.

The growth of seedlings in pot tests was found by Egnér (1925) to be a good index to the growth of the same crop plants grown on a series of representative soils under field conditions; and chemical analysis of the seedlings yielded quantities of nutrients proportional to those supplied to the soils.

Other Biological Methods

Dry weights of mature plants were used by Mitscherlich (1928) to indicate soil fertility. The method, briefly, is as follows. Crop plants are grown to maturity in samples of the soil under examination. This may be accomplished in the field or in pot cultures. In either event the soil is supplied with varying amounts of a nutrient element. Thus the average quantitative relation between the nutrient and crop yield may be calculated. The Mitscherlich yield formula (p. 39) was evolved to express this relation. Besides predicting yield, this formula may be used to calculate the quantities of the nutrient element (varied) contained in the soil, seed or both. It may also be applied, for the same purpose, to the yields of the same crop plant grown on other soils; or to other crops and nutrients, the standard relations of which have been determined. This method has been extensively used both in Europe and America. For a more complete discussion the reader is referred to Willcox (1930).

A bacteriological method—the soil-plaque test—has been proposed by Sackett and Stewart (1931) to determine mineral soil deficiencies. It is based on a principle originated by Winogradsky (1926 and 1928) who observed that the bacterial genus Azotobacter were sensitive to limiting mineral factors. Sackett and Stewart summarize (*loc. cit.*, p. 9) the principle of the soil-plaque method as follows: *"The mineral food requirements of Azotobacter and farm crops being so similar, we can use the development of Azotobacter colonies as an indication of what might reasonably be expected to take place if the particular soil were planted to sugar beets, corn or some other crop. By adding different mineral fertilizers to the plaques (soil), either singly or in combination, and by observing, 72 hours later, both the number and luxuriance of the Azotobacter colonies, which appear either spontaneously or as the result of inoculation in comparison with those which are present on the untreated plaque, we can gain a fairly accurate idea of both what and how much the soil lacks."*

This method has been used quite extensively by Stewart *et al.* (1932), and others referred to earlier in this discussion. Another somewhat similar method was suggested by Niklas (1930). In this case the determinations are based on the development of the fungus, *Aspergillus niger.*

The biological methods mentioned, since plants are utilized to measure nutrient availability, are apparently superior to direct chemical or electro-chemical analysis of the soil or soil extract. They have proved capable, under most conditions, of detecting soil nutrient deficiencies and of rating soils in the proper order of fertility according to available nutrients. A method is here suggested which by use of a reference scale, obtained from sand nutrient cultures, makes possible exact quantitative comparisons of the available nutrients in natural soils.

METHOD EMPLOYED IN PRESENT STUDY

THE biological method here proposed had its origin in silvical experiments, various phases of which have been in progress at the Harvard Forest for a number of years. The direct precursors were studies made during the summer of 1931 and the writer while a student at the Harvard Forest aided in the execution of the experiment and the preparation of the data. This work has not been published, and since the method used in the 1932 white pine experiment, reported here, is largely based upon the results of the earlier investigation, the more pertinent parts will be included in this report.

The proposed method in common with numerous other biological procedures utilizes the principle of proportional absorption. The chief difference is the addition of a standard of comparison. Evidence has been given to show that both the yield and the quantity of a nutrient element in a plant are proportional—other factors being constant and not limiting—to the quantity of that element in the soil. Interpretation would be simplified if they were directly proportional. Then one might conclude for instance, that a soil was twice as rich in available nitrogen if plants from it contained double the quantity of nitrogen as those from another soil; the same would be true of yield. But, as will be shown, they are not directly proportional. By the use of standards the proposed method attempts to establish a reference scale: to ascertain from sand cultures—nutrients may be varied as pure chemicals known to be available to plants—exactly how yield and the chemical composition of the reference species used vary with the concentration of a given element in the nutrient solution. The results of parallel experiments—the same species growing in samples of natural soils for the same length of time and under similar conditions—can be interpreted quantitatively by comparison with the standard, and the fertility of soil evaluated according to the degree of the determined relations.

Nitrogen was chosen as the first nutrient element to be studied since it is one of the more important and is often a limiting factor in growth. In the voluminous literature dealing with nutrient solution studies few investigators have been found who worked with forest tree species. For this reason and because we are dealing with forest soils, tree seedlings—Scots pine (*Pinus sylvestris* L.)—were used as indicators or reference plants in the 1931 experiment. It is a commercially important species, seed is readily obtained, easily germinated, and growth is sufficient in one season to bring out differences due to nutrient treatment. The seedlings were grown for three months in sand culture receiving a basic nutrient solution with only nitrogen varied. In a parallel experiment seedlings were grown for the same length of time in samples of raw humus admixed with sand.

White Pine (*Pinus strobus* L.) seedlings were used in the 1932 experiment. Nitrogen was again varied in the sand culture nutrient solution and the standard relations determined. Seedlings were also grown in samples of soils from four representative types of the forest. All soils received a basic nutrient supplement, but with various omissions of either P, Ca, N or K, so that soil deficiencies in these elements could be detected by comparison. The available nitrogen of the four soils was evaluated through interpolation based on the standard of comparison.

DETAILS OF EXPERIMENTAL METHOD

Watering Technique, Pots and Sand

In previous soil and sand culture experiments several pot arrangements have been used. The pot used by Neubauer (1925) is of enameled sheet iron, about 10 inches in diameter and 14 inches deep. A slot in the bottom permits excess solution to drain into a pan, from which it may later be returned to the soil. Aldrich-Blake (1930) used a cream glazed pot, 13 inches in diameter and 18 inches deep, having a capacity of 8 gallons. The deep pot was necessary because Corsican pine (*Pinus laricio*) develops a root 17 to 18 inches in length in one growing season. Into an opening at the bottom of the pot was fitted a T-tube, the upper vertical arm of which served as a water level gauge and the lower arm was used to drain off the solution poured over the top every second day. The water level was kept 5 inches from the bottom of the pot by the addition of well water. Sieved Bedfordshire sand having a pore volume of ⅓ the total volume was used, but no data on the distribution of the size classes were reported.

Hesselman (1927) uses a standard 8 inch pot which he imbeds in sand and waters from above with a water gun delivering a very fine spray. Any excess water drains out the bottom of the pot into the sand, possibly carrying with it dissolved nutrients if too much water is added. A sand soil mixture ⅔ by volume of 10 to 28 mesh sand and ⅓ by volume of soil material is used in the pots.

In the 1931 Scots pine experiment, 8-quart galvanized zinc pails 9.5 inches in diameter at the top, 7.5 inches at the bottom and 8 inches deep were used. Each was coated inside with asphalt paint to avoid any action between the metal of the pail and the nutrient solution. The arrangement shown in Plate I (left) was designed for watering. The glass jug serves as a reservoir for the nutrient solution and by applying pressure with a hand pump, the solution may be forced up into the pail through a T-tube inserted in the metal bung in the bottom of the pail. The upper vertical arm of the T-tube serves as a water level gauge for the water in the pail, and the level can be controlled by adjusting the air pressure in the jug. A total volume of 2.25 liters was maintained by the addition of distilled water to take care of loss due to evaporation. Each day the pails were flushed to the top and then the solution allowed to drain down to within 1½ inches of the bottom. This water level in the pail was always maintained. White Ottawa sand, 99.89% pure silica and nearly spherical, was used. The size class distribution was as follows: through a 10 and on a 20 mesh screen, 0.3%; through a 20 and on a 28, 16.2%; through a 28 and on a 35, 74.0%; and through a 35 and on a 40, 9.5%. The pore volume was 39% of the total volume.

The arrangement just described is an adaptation of the methods used by Aldrich-Blake (1930) and by Eaton (1931). Its chief advantages are: (1) there is no chance for loss of nutrients as in the Hesselman method, (2) even distribution of the solution is assured, (3) the volume of the solution, and hence the concentration of the various nutrient elements in solution is easily controlled, and (4) a large quantity of solution may be used. The latter is an advantage that will be more fully discussed later. The method proved fairly satisfactory when only sand was used, but in preliminary tests with humus mixed with sand the results were not satisfactory. Keen (1930, p. 350) cites evidence showing that there may be a deficiency of aeration in pot experiments. This was the case with the pails containing the sand-humus mixture. Anaerobic decomposition was evidenced by the formation of marsh gas in the bottoms of the pails. The lack of aeration was due to waterlogging caused by a combination of several factors: (a) the sand portion used was so fine that the pressure deficiency (Keen, 1930, p. 109-128) necessary to drain was too great; (b) a permanent free water table was unavoidably maintained; (c) there was no possibility for capillary movement in the container (metal walled pail).

Except for a few modifications the technique just described is essentially the same as that used in the 1932 experiment. Clay pots placed inside the pails to hold the sand and sand-soil mixtures overcame the difficulty of the permanent free water table and allowed for the desired capillary movement. With this modification and by using coarser sand there was no evidence of marsh gas. Monel metal screens (Monel metal reacts only slightly with the nutrient solution) prevented the sand from running out the hole in the bottom of the clay pot into the pail. The clay pot interliners may be seen in Plate I showing above the pails, and in Plate II. The pots to be used for sand cultures were filled to a depth of 5 inches with number 4 Columbia silica sand which is angular in shape and much coarser than the Ottawa. A mixture of 3 parts by volume of Ottawa to 2 parts of the Columbia was used in the upper part of the pots. Drainage experiments proved this to be the best combination. The Columbia sand was used to mix with the soils and proved quite satisfactory.

The method of watering differed somewhat from that used in the 1931 Scots pine experiment. The quantity of water was increased to 3.5 liters as compared to 2.25. This measured amount was poured over the sand in the pot and allowed to drain free into the jug reservoir. The level in the jug was then marked, and since the sand would always retain the same quantity of water, the volume of the solution was kept constant by maintaining the water level in the jugs up to the mark. Only distilled water was used. Flushing the solution into the pots was greatly facilitated by the use of a multiple pumping arrangement. This consisted of a brass tube connecting 5 or more jugs so that air could be forced into them all in one operation (Plate III). Daily during the growing season the solution was flushed into the pots until the sand immediately surrounding the roots of the seedlings was flooded. It was kept there for approximately 3 hours during the hottest part of the day and then allowed to drain. In this way the watering technique differed from the 1931 experiment where a water table of 1½ inch was constantly maintained except when flushing. Evaporation from the sides of the clay pot interliners and from the bottom of the pails—bung not exactly flush with bottom so that all solution could drain out—had a cooling effect which tended to neutralize excessive temperatures on hot days.

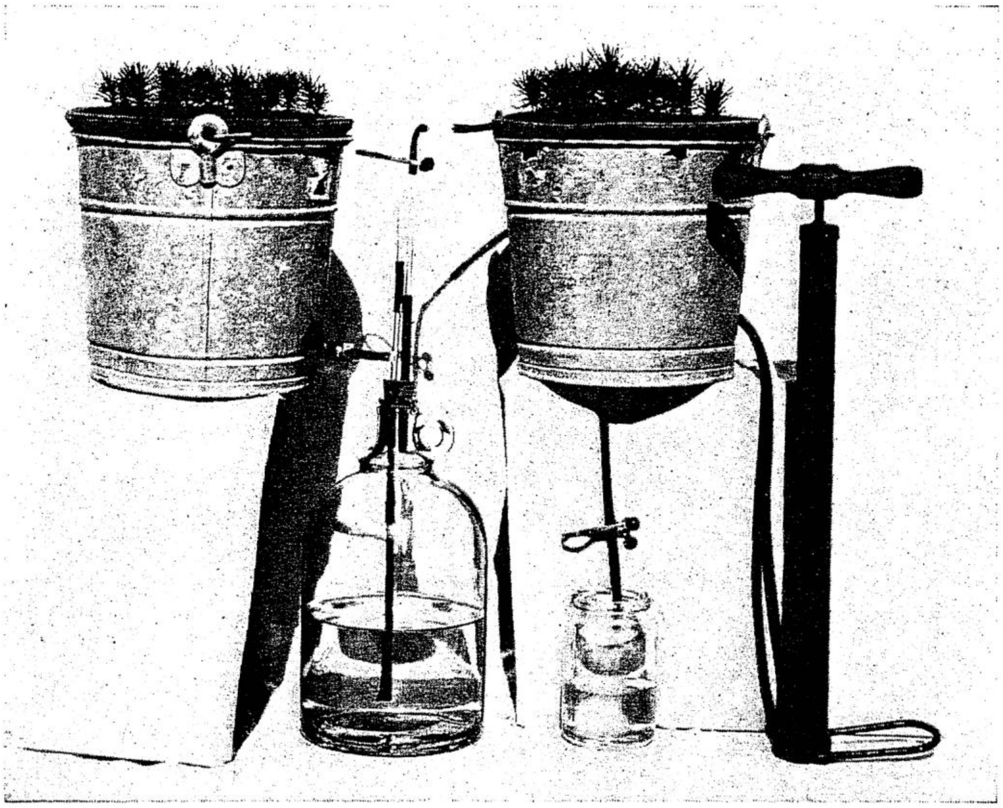

PLATE I. WATERING DEVICE: SOIL CULTURE (RIGHT), SAND CULTURE (LEFT).

Clay pot interliners are shown protruding above pails. Air pressure supplied by a hand pump forces the solution from jug to pail; usually five jugs are connected in parallel as in Plate III.

The arrangement shown in Plate I (right) was designed for watering the soil cultures. The bung in this case is in the bottom of the pail. One liter of water was poured over the sand-soil mixture and allowed to drain free into the mason jar directly beneath, and the level marked. Water lost by evaporation each day was replaced by distilled water supplied to the top through a fine spray until the solution level reached the mark. The solution in the jar was then poured over the top and allowed to drain.

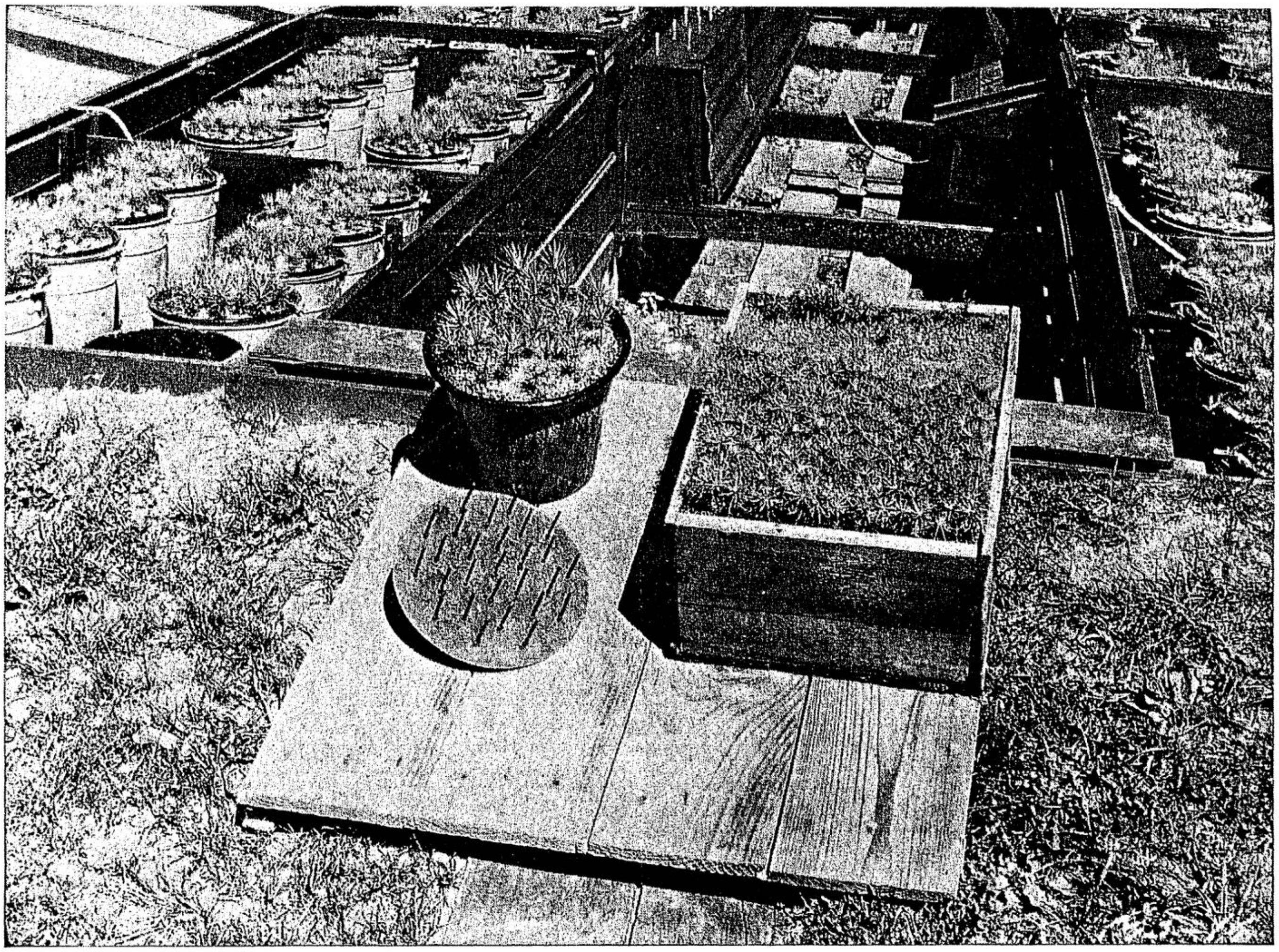

PLATE II. GERMINATING FLAT, CLAY POT INTERLINER AND PLANTING DIBBLE.

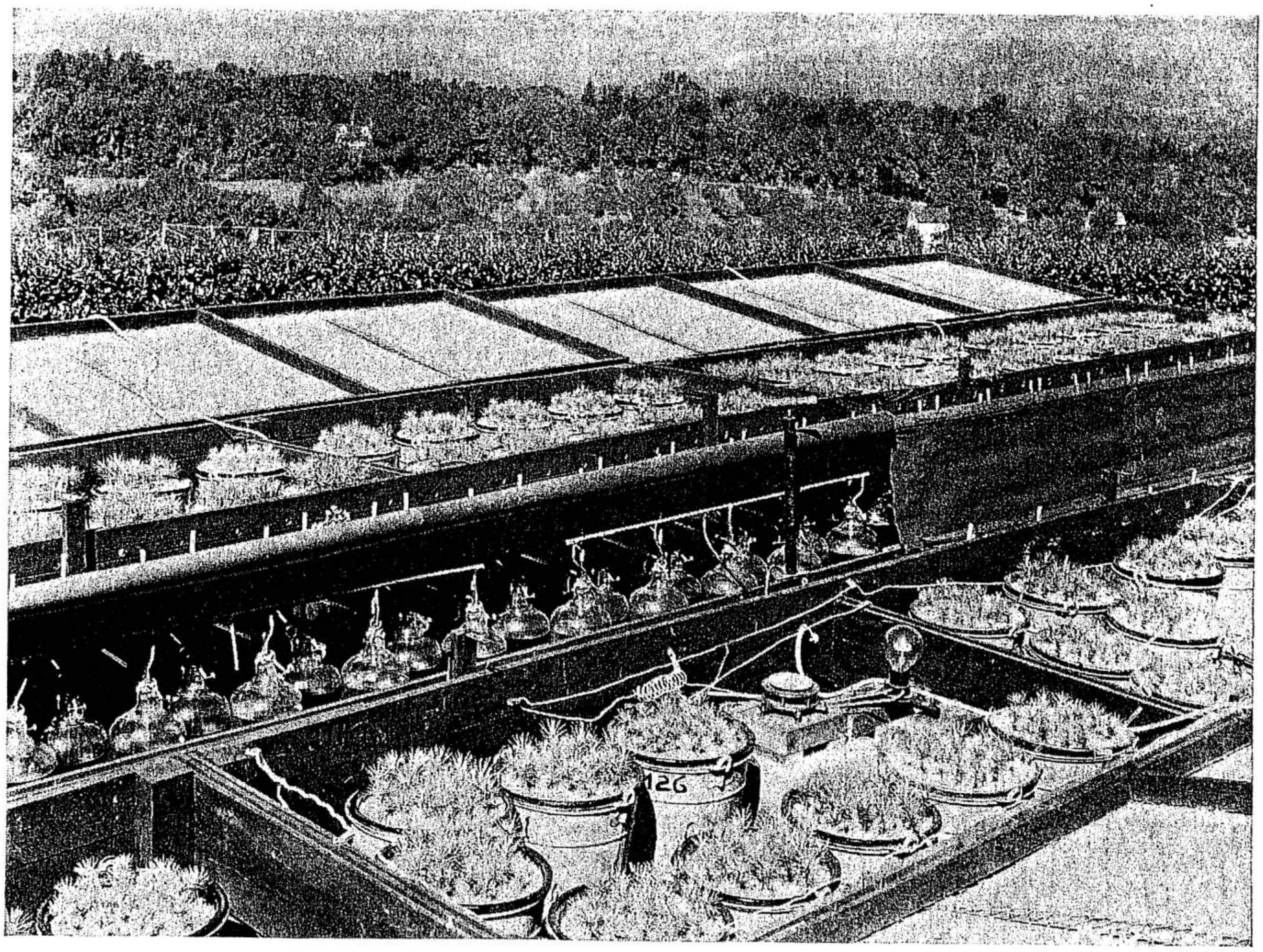

PLATE III. ARRANGEMENT OF POTS, PAILS AND JUGS IN PIT.

Multiple pumping device is shown with pump attached. Jugs are covered by cloth shades to protect nutrient solutions from the sun. Shades can be raised or lowered as shown. Pyrheliometer (right) and photronic cell are mounted in near box.

Soil Sampling and Mixing

Soil samples were taken from four of the most important forest types of the Black Rock Forest: Hardwood Cove, Mid-Slope (good), Mid-Slope (poor), and Ridge (Tryon, 1930). The Hardwood Slope type was divided into "good" and "poor." This distinction seemed necessary because the trees on certain areas (poor) were inferior in size to those of other areas (good), although of the same age; and the soil, elevation, and moisture conditions were apparently comparable. The various types are shown in Plates IV, V and VI, and a more complete description is given in Appendix III.

A quarter-acre permanent sample plot was established on each of the areas sampled. Soil was taken from approximately thirty places scattered over the plot to assure a good sample. Litter, duff and humus were removed and only soil from the dark brown horizon (Scholz, 1931) was taken. Since this is the layer in which most of the feeding roots are located it should be the best to use in testing fertility.

The soils were screened and bagged in the field. With one exception they were kept moist until the time of mixing. The Mid-Slope (poor) soil dried slightly more than the others. Just before the seedlings were ready to transplant the soils were mixed with sand and placed in pots. Columbia No. 4 sand was used; 3 parts of sand to 1 part soil by volume. During transplanting all pots were inoculated with a few grams of fresh soil from the plots. This was done to make sure that all microorganisms present in the natural soils were also present in the pots.

Pits and Screens

The arrangement of pots, pails and jugs in the pits may be seen in Plates II and III. The pits were shielded from rain by frames covered with Cello Glass as shown in Plate III. This was necessary because of the possibility of contamination by fixed atmospheric nitrogen brought down by the rain, and because of the necessity for accurate volume control of the solutions. Cello Glass—Cellophane precipitated in wire mesh—like glass transmits light, but has the added advantage of being much lighter and nearly unbreakable.

It was found that Scots pine seedlings may be exposed to full solar radiation directly following transplanting without any apparent ill effects on growth. But white pine seedlings subjected to the same treatment suffer rather severe injury; many die, and those surviving

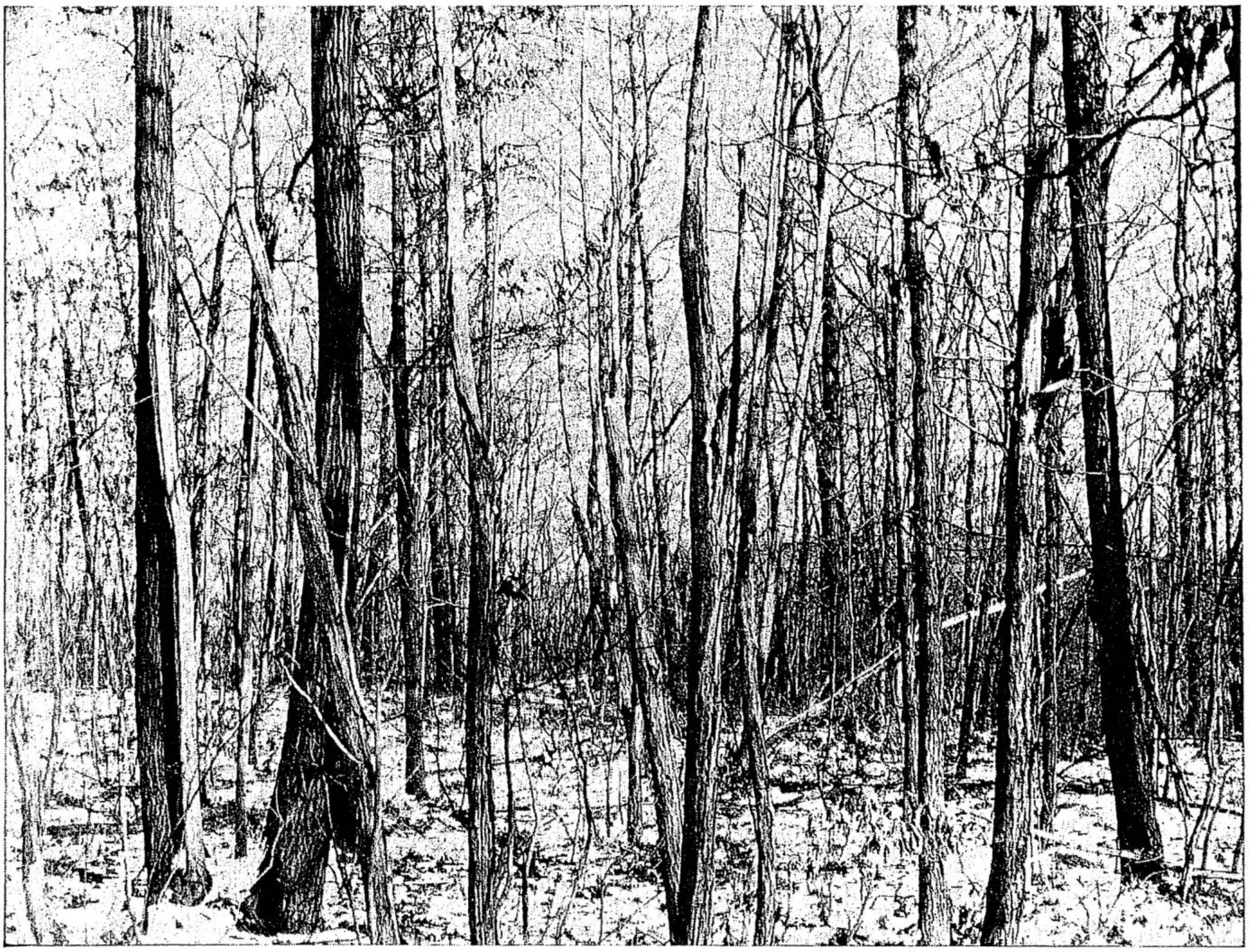

PLATE IV. A REPRESENTATIVE AREA OF THE UPPER HARDWOOD SLOPE TYPE (Chestnut Oak and Red Oak) AT THE 1210-FOOT LEVEL.

Compartment No. VI. February, 1930.

PLATE V. AN EXAMPLE OF THE HARDWOOD SLOPE TYPE AT ABOUT THE 1000-FOOT LEVEL.
Compartment No. VII. September, 1929.

PLATE VI. AN EXAMPLE OF THE HARDWOOD COVE TYPE (the Red Oak, Yellow Poplar, Yellow Birch mixture) AT THE 1100-FOOT LEVEL.

are very much retarded. In the 1932 white pine experiment it was found necessary to shade the seedlings just transplanted with lath screens (Plate VII) which cut the light intensity about 50%. The distance between the laths was gradually increased over a period of two weeks following transplanting. This procedure proved entirely satisfactory. White pine seedlings in this stage of their development, at least following transplanting, are apparently less tolerant of light than Scots pine.

Because of bird attack the quarter-inch mesh wire screens shown in Plate VII were necessary for about the first two weeks after transplanting.

NUTRIENT SOLUTIONS

Sand Cultures.—The basic nutrient solution supplied to each pail in the 1931 Scots pine experiment contained 2.5 grams of KH_2PO_4, 4 grams of $MgSO_4 \cdot 7H_2O$, 3 grams of $CaCl_2 \cdot 6H_2O$, and 0.045 grams of ferric citrate ("scales" U.S.P.). The total volume of the solution was 2.25 liters. The salts were added in two portions to avoid too sudden a change in the osmotic pressure of the solution surrounding the roots. This quantity of salts was considered sufficient for the complete development of 29 Scots pine seedlings, because it is approximately one half the quantity Aldrich-Blake (1930) found satisfactory for a pot of 52 Corsican pine seedlings. Nitrogen was varied as NH_4NO_3, one half the total quantity being supplied at the beginning, and the remainder about one month later.

The same basic nutrient solution was used in the 1932 white pine experiment. But the volume of the solution was increased to 3.5 liters. The total quantities of the chemicals used and the concentrations of the various nutrient elements in the solution are summarized in Table 1.[1] Application of the basic nutrient solution was again made in two portions, but the nitrogen was applied according to the schedule in Table 1.

Soil Cultures.—Seedlings were grown in each of the four soils under seven different nutrient conditions. The chemical treatments are summarized in Table 2. These nutrient applications were designed to supplement the nutrients already contained in the natural soils and not as a sole source of supply in themselves. In this way it was hoped to separate the effect of only a single element, since all others were kept optimum, or at least not limiting. The treatments were arranged to disclose soil deficiencies in either N, P, Ca and K; also to determine the effect on the seedlings of increasing nitrogen supply. Necessary nutrient solution division was made on the basis of weight. Usually stock solutions were made fresh when needed and never kept more than a week. The nutrient treatments in Table 2 were all made at one time, the beginning of the experiment.

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[1] See Appendix I for all tables referred to in text.

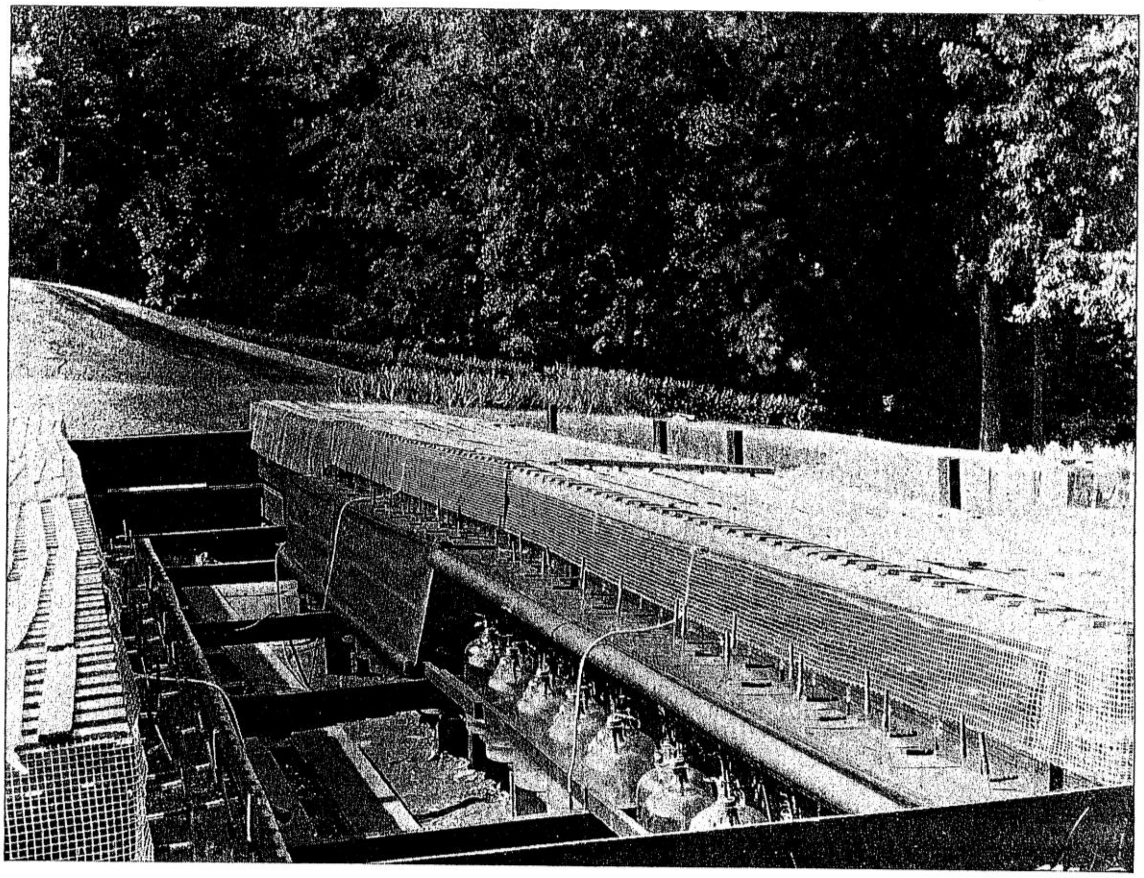

PLATE VII. SPECIAL SCREENS REQUIRED IMMEDIATELY AFTER TRANSPLANTING.

The lath screens control light; spacing is gradually increased until all are removed (about 15 days). Wire

DISCUSSION OF NUTRIENT SOLUTIONS

Basic Formula.—The Corsican pine experiment of Aldrich-Blake (1930) supplied the only data available on the nutrition of coniferous seedlings. Since his formula gave good results it was used, with only slight modifications, in these experiments. A basic solution was desired in which no nutrient element would be a limiting factor in the growth and development of the seedlings and, if possible, all would be very near the optimum value for maximum yield. By varying any single element, nitrogen in this case, its effect could be separated.

Data from later experiments (1933) have shown that the concentrations of phosphorus, potassium and calcium were certainly not limiting and, with the possible exception of calcium, were very near the experimentally determined optima. A concentration of calcium approximately one third of that used is recommended. The phosphorus and potassium nutrient treatments for 1933 are shown in Tables 3 and 4.

Effect of Abrupt Changes in Concentration.—Growth is considerably retarded by too rapid changes in the nutrient solution concentration. This is evident from the yields of Scots pine seedlings from the 1931 experiment. All pots in this experiment received the same basic nutrient solution, the total volume of which was 2.25 liters. Only nitrogen was varied. When all the chemicals had been added, in order to determine the importance of concentration, the volumes of the solutions in half the jugs (all treatments were made in duplicate) were allowed to decrease through evaporation until they were about one third that of the others. The decrease in water volume meant a proportional increase in the concentration of the nutrient elements in solution. Within two weeks many of the needles of the seedlings thus treated became deep purple and then brown. The concentrations were promptly returned to normal and about half the seedlings survived. But these were so retarded in their development that their final weights differed markedly from those grown in the continuously dilute solutions. Only the latter were used in calculating the final "yields" in Table 5. Important information was gained by this procedure for it was noticed that seedlings grown in the concentrated basic nutrient solution from which only nitrogen was absent—zero nitrogen treatment—no injury was evident. Apparently it was a case of nitrogen burning. The extent of injury was proportional to the increase in the quantity of nitrogen.

Profiting by this experience the nitrogen concentrations of the 1932 sand culture experiment (nitrogen series) were gradually increased at three day intervals as shown in the nitrogen application schedule, Table 1. A similar procedure was followed for gradually stepping up the concentrations of all nutrient elements in the 1933 sand culture N, P, K, and Ca series. The phosphorus application schedule (Table 6) shows in detail how this was accomplished.

Chlorine Variations.—Chlorine, from $CaCl_2$ was unavoidably varied in both the potassium and phosphorus series. But it is generally agreed (Miller, 1931) that the presence or absence of this element, except in extreme or abnormal cases, has little if any effect upon the growth of most plants. Because it was considered a non-nutrient, and unessential to pine seedlings, its variations of concentration were not included in Tables 3 and 4. Furthermore Jung (1922) found that, of the many plants examined, conifers were the only species that did not contain chlorine. Also data from other (unreported) experiments with pine seedlings show the chlorine variations used in the above series have no effect upon growth.

pH Variations.—The hydrogen-ion concentration of the soil and sand culture solutions, like chlorine, varied somewhat in the various nutrient series. The pH values are given in column 5, Tables 3 and 4; and in column 2, Tables 7, 8, 9, and 10. No pH readings were made of the 1932 sand culture nitrogen series (Table 1), but values for a similar series (1933) will serve equally well, if not better, since the concentration intervals (of N) over the range comparable to natural soils are more closely spaced. They are summarized in Table 11.

Wilde (1934), who investigated the effect of soil reaction on the germination and growth of coniferous seedlings, as well as other species, found that conifers would do well when planted in soils having a pH range of 4.5 to 7.0; but that the optimum range was slightly narrower: pH 5.0 to 6.0. Inspection of Tables 3, 4, 7, 8, 9, 10, and 11 reveals that the reactions of most of the solutions used in these experiments are well within the optimum range. Consequently pH is believed to be of minor significance in these experiments and, for all practical purposes, except in a few extreme instances—high acidity of the upper P concentrations (Table 3)—may be considered constant.

Seeds

Seeds used in these experiments were separated into weight classes. This permitted correction of plant weights at the time of harvesting for the original "capital" with which they started.

Seeds for the 1931 Scots pine experiment were separated into 0.5 milligram classes and the weights of the resulting seedlings were reduced with the aid of correction coefficients to an average weight equivalent to that of plants from a single seed size. Thus accurate comparisons have been made independent of the influence of seed weight. The exact method used in deriving correction coefficients is discussed on p. 31.

All seeds were sterilized with a 0.1% solution of bichloride of mercury, soaked in sterile water for one day, and then planted in washed sand contained in wooden flats (Plate II). When necessary, distilled water was applied with a fine spray gun, but the seedlings received no nutrients until after transplanting. Fifteen days after planting all but a few of the seedlings had shed their seed coats; they were then transplanted to the pails—except those to be used for determining the correction coefficients. Twenty-nine seedlings of a single weight class were placed in each pail. The planting dibble shown in Plate II assured even spacing.

Seeds for the 1932 white pine experiment were gathered from a small group of trees 40-50 years in age, growing on a good site near Petersham, Massachusetts. An effort was made to obtain sufficient seed from a single tree in order to eliminate as nearly as possible the genetic factor. But this proved impossible for 1931 was not an especially good seed year. The seeds were separated into 1.0 milligram classes. White pine seeds are approximately five times the weight of Scots pine; therefore a larger class interval may be used. Correction factors were again derived to reduce all final seedling weights to the equivalent of seedlings from a single seed size. The method employed differs slightly from that used for Scots pine (p. 32).

Untreated white pine seeds frequently do not have a high germination percentage, but this can be greatly improved by after-ripening. Seeds were sterilized with bichloride of mercury, stratified in moist filter paper contained in sterile flasks, and stored for six weeks at a constant temperature of + 5° C. Cold storage not only increases the germination percentage, but the uniformity of germination. At the end of this period they were planted in washed sand. The sand was treated with acetic acid as recommended by Doran (1932)—¾ of a quart of 0.8% acetic acid per square foot of seed bed at time of planting—and no damping off was noted. Like the Scots pine, they received no nutrients and were kept as dry as possible to prevent fungal infection. Twenty days from the time of planting, the seedlings, except those to be used for determining the correction coefficients, were transplanted to the pots. Only 27 seedlings were placed in each pot because the clay pot interliners reduced the available space (29 to the pail in the Scots pine experiment).

REPLACEMENTS

Whenever a seedling died it was replaced so that there were always the same number competing for the available water and nutrients in each pot. When such replacements were made, a waxed thread was tied about the seedling and it was discarded at the end of the summer.

HARVESTING

The seedlings for the 1931 experiment were transplanted to the pots on July 2 and grown for 105 days. Those for the 1932 experiment were transplanted July 6 and grown for 101 days. At the end of the growing period the contents of the pots were emptied on a screen and

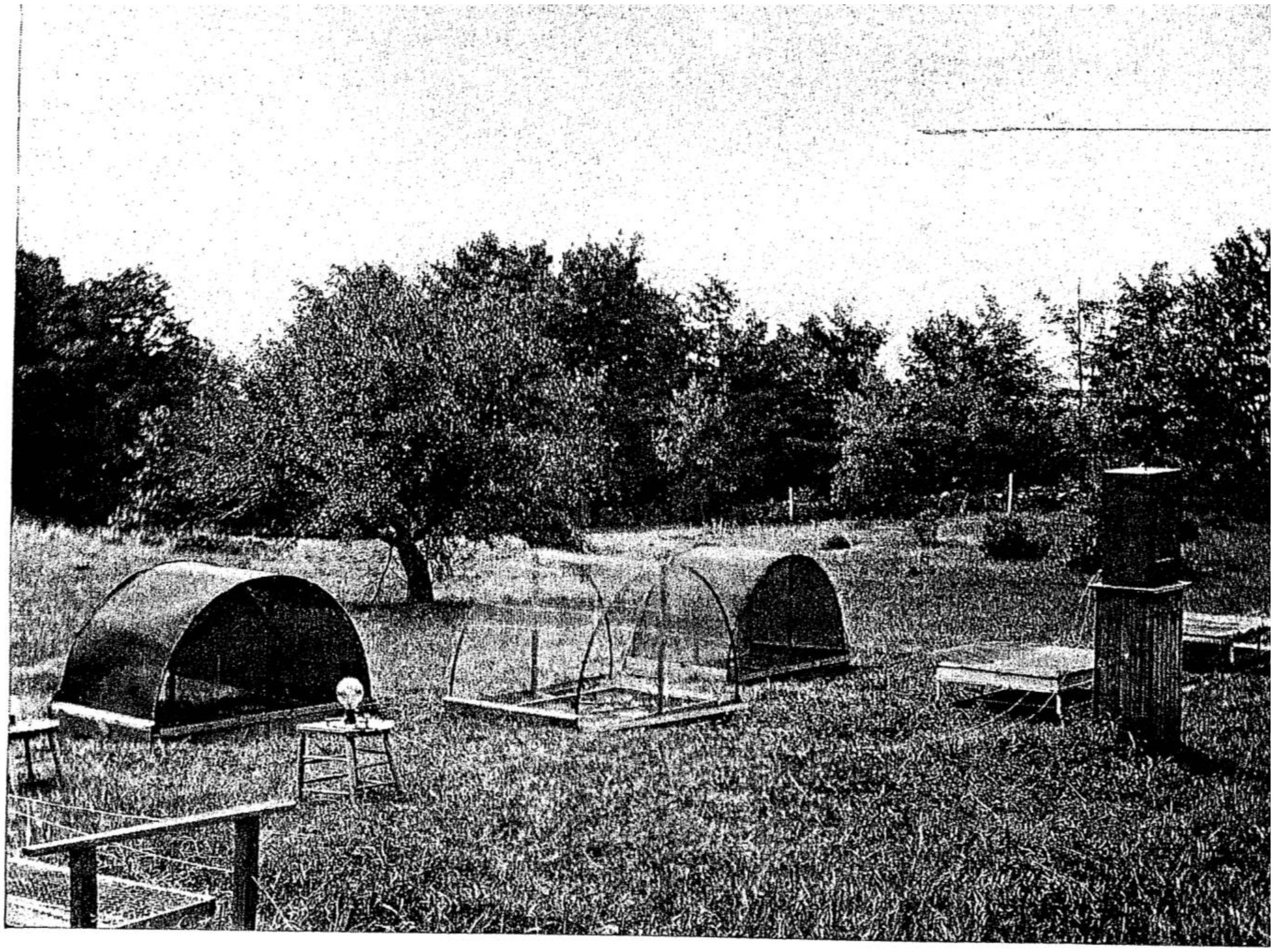

PLATE VIII. GENERAL VIEW OF 1931 EXPERIMENT, HARVARD FOREST, PETERSHAM, MAS

Each pit contains 12 pails of 29 seedlings each. Screens vary solar radiation. From left to right: "qu light, "full" light, "half" light and movable water screens. "Open" pyrheliometer left foreground, recordin croammeter in box at right.

the sand or sand-soil mixture was washed away from the roots by a small stream of water. Seedlings were separated in a tub of water to prevent breakage. Each root system was examined under a microscope, and an exceedingly small amount of root breakage was noted. A complete study of the mycorrhizal and other features of the root systems was made by Mr. A. B. Hatch (p. 81). At least one average seedling from each pot was preserved for reference, photograph and morphological study. The others were cut into two portions, root and shoot for ratio determinations, each part placed in a labeled glassine envelope, dried at 70° centigrade and weighed to ± 0.1 milligram.

Solar Radiation Measurements

Seedlings of the 1931 Scots pine experiment were grown under two light[1] intensities: "half light" and "full light."

Shading was accomplished by one layer of 18 x 18 mesh (wire diameter, 0.0617 inch, open area 49.7%) brass wire cloth placed over the half light pit. One layer of 1 inch mesh screen was placed over the full light pit to protect the seedlings from birds and animals. The arrangement is shown in Plate VIII. Radiation measurements were made with Eppley Weather Bureau Type Pyrheliometers, registering on a recording microammeter (Gast, 1930). Two pyrheliometers were used, one recording continuously in the open (left foreground, Plate VIII) and the other alternating between the pits. Table 12 shows a summary of the radiation measurements. The full light pit received during the summer 84.7% of the total radiation in the open. This was due mostly to the absorption by the Cello Glass screens during rainy weather and not to the one inch mesh screen. Corrections were made in each case for the number of hours the Cello Glass screens covered the pits. It will be noted (Table 12) that radiation was measured for only the last 83 days of the experiment—total length of experiment was 105 days. Probably a fair approximation of the radiation for the total period can be arrived at by extrapolation of the available data.

The white pine seedlings of the 1932 experiment were grown in full light only. Complete radiation records were not obtained during 1932; but a fairly accurate approximation has been calculated from available sources of information.

Complete measurements were made during the summer of 1933 over a comparable period. Radiation was again measured with the Eppley Weather Bureau Type Pyrheliometer but the recording was done by a Leeds and Northrup two point recording potentiometer (Micromax, equipped with special integrating device). One of the pyrheliometers

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[1] The word "light" is, in this report, used synonymously with solar radiation.

is shown in Plate III (right). The instrument to the immediate left is a photronic cell in weather-proof mounting. Comparative radiation measurements by months during 1932 and 1933 were obtained from the New York Weather Bureau Observatory in Central Park—about 60 miles south of Cornwall. Although the New York records, by months during 1933, differ slightly from those at Cornwall it is very probable that the ratios between the radiation received during comparable periods of 1932 and 1933 are relatively constant for either New York or Cornwall. By applying the ratios by months (determined from the N. Y. observations) to the 1933 Cornwall records, a fairly reliable measure of the radiation received at Cornwall during 1932 has been calculated. Thus it was found that the seedlings of the 1932 white pine experiment received a total of 38,887.0 gram calories per square centimeter from July 6, to October 15; an average of 385.0 per day.

The total radiation value is somewhat lower than that of the New York observatory over a comparable period. This is because corrections were made for the number of hours the seedlings were shielded from rain by the Cello Glass screens. These corrections are relatively accurate since the transmission factor of Cello Glass is easily determined and a record was kept of the time the seedlings were covered.

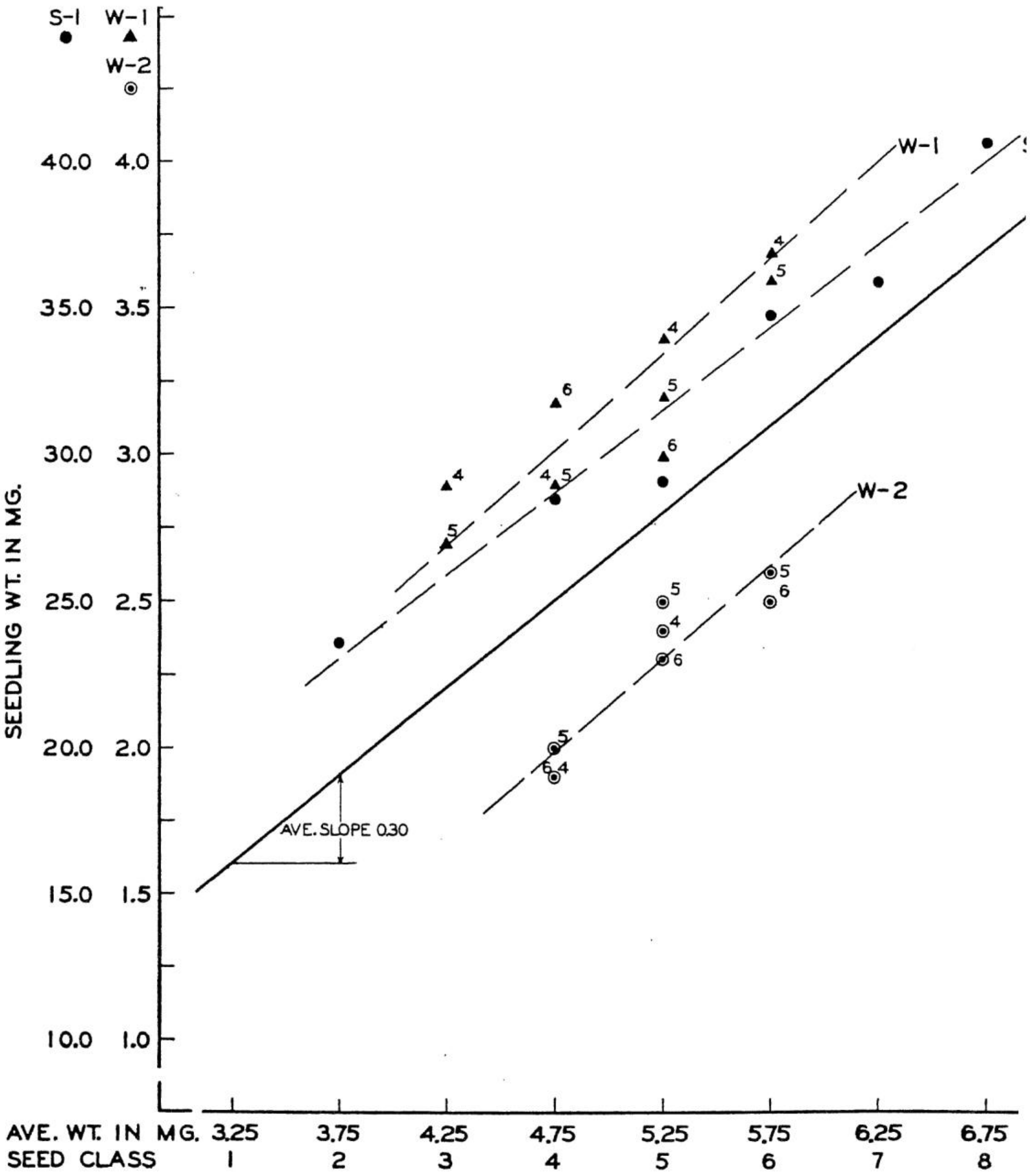
It will be noted that the mean total daily radiation received by the Scots pine (308.4, Table 12) of the 1931 experiment is somewhat lower than that received by white pine in 1932 (385.0) The significance of this difference will be referred to later. Also the total radiation over a comparable period (June to November included) was approximately 9% greater during 1932 than 1933. The data are summarized in Table 13.

NITROGEN DETERMINATIONS

From each pot at least four and up to twelve seedlings were analyzed, the number depending on the uniformity of the results. These seedlings were chosen on the basis of the average dry weight and the shoot-root ratio of the pot. For the 1931 sand culture experiment the analyses are summarized in Table 5, for the 1932 sand culture experiment in Table 14, for the 1932 soil culture experiment: the Ridge, Mid-slope (poor), Mid-slope (good) and Cove in Tables 7, 8, 9, 10 respectively.

For the determination of total nitrogen, a modification of the micro-Kjeldahl method described by Pregl (1930, p. 109) was used. Oxidation was carried out in a small decomposition flask using about 1 milliliter of concentrated sulphuric acid containing a small portion of salicylic acid (1 gram per 30 ml.) and a knife point of a mixture of 1 part by weight of potassium sulphate to 3 parts of mercuric sulphate. The contents of the flask were introduced into the distillation flask with 7 milliliters of 30% sodium hydroxide containing 5% of sodium thiosulphate. The ammonia was distilled into a standard N/100 solution of hydrochloric acid. The material must be fairly dry, for a small amount of water will dilute the sulphuric acid inhibiting nitration of the salicylic acid thus preventing all of the nitrate nitrogen from being included in the determination. In the case of the smaller seedlings, the whole seedling was used in the analysis. The larger seedlings were ground up and 40-90 milligram samples taken. The total milligram nitrogen content was computed from the dry weight of the seedling and the percentage nitrogen value. Table 15 shows the results of check determinations of the nitrogen in samples of the same seedling material. The method also checked very well with a macro-Kjeldahl using standard solutions of ammonium nitrate and urea.

Total nitrogen, ammonia nitrogen, and organic and ammoniacal nitrogen determinations were made of each of the four natural soils used in the experiment. The ordinary macro-Kjeldahl methods given in Official Methods (1925) were employed. Quantities of organic nitrogen in the soils were arrived at by subtraction (organic and ammoniacal nitrogen — ammonia nitrogen = organic nitrogen); and nitrates and nitrites were obtained in a similar way (total nitrogen — organic and ammoniacal nitrogen = nitrates and nitrites). Samples for analysis were taken from the screened soils just before mixing with the sand. They were treated with toluol to prevent chemical changes due to microbiological activity. The results of these determinations were consistent. They are summarized in Table 16.



TEXT FIG. 1. THE WEIGHTS OF SCOTS PINE SEEDLINGS GROWN FROM SEEDS VARIOUS WEIGHTS.

DISCUSSION OF RESULTS

The Relation of Seed Weight to Seedling Weight

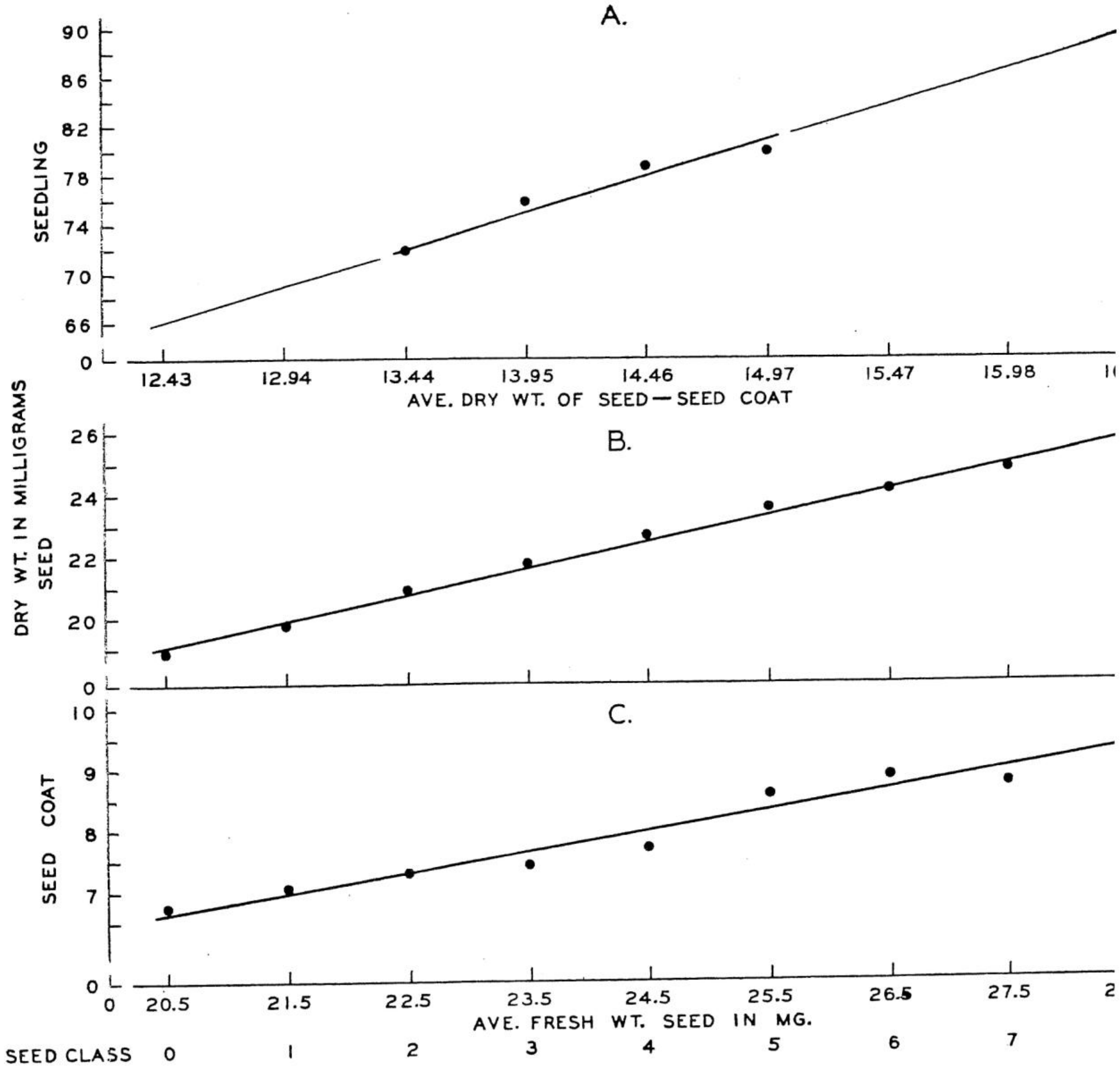
From the experience of Eytingen (1915), Korstian (1927), Aldrich-Blake (1930), McComb (1934), and Gast (data in Text Fig. 1), it is evident that the weight of the seed used has a decided influence upon the weight of the resulting seedlings. Since it is desired to study the effect of various nutrient combinations upon yield—all other growth factors remaining constant—it is necessary either to eliminate or correct for the influence of seed weight if accurate comparisons are to be made. Otherwise large deviations due to the use of seeds of various size would greatly lessen the precision of the experimental results. If it were practical to grow all seedlings from seeds of the same weight this effect would be eliminated. But it is tedious and impractical to accumulate sufficient seeds of a single weight. The second alternative—the use of correction factors—is preferable. Thus seeds of several weight classes may be used, and weights of the resulting seedlings can be corrected, by the use of factors, to an average weight equivalent to plants from a single seed size.

Three sets of data were used to obtain the linear relation between seed weight and seedling weight as shown in Text Fig. 1. Scots pine seeds for the 1931 experiment were separated into classes according to fresh weight. After germination the w-2 series was harvested as soon as the seedlings had shed their seed coats, and the w-1 series a few weeks later. The s-1 series grew for three months and were therefore much larger. All seedlings were grown in washed sand and received no nutrients. Before the dry weights were taken the seedlings of the w-1 and -2 series were classified according to the number of primary cotyledons (as indicated near each point). It was anticipated that some connection between this number and the weight of the seedlings might be found, but nothing consistent was observed. The heavy line represents the average slope of the three series of data. From this average relation coefficients were determined for correcting the weights of seedlings from various sized seeds to the equivalent of seedlings from a single sized seed. Thus the weights of seedlings from seed class 4 can be converted to weights equivalent to seedlings grown from seed class 5 by multiplying by 1.130; from class 6 to the equivalent of class 5 by multiplying by 0.896; and from class 7 to the equivalent of class 5 by multiplying by 0.812. For purposes of comparison all the seedling weights in this experiment were thus corrected and are reported as of seed class 5.

A slightly different method was used to calculate the correction coefficients for the 1932 white pine experiment. The procedure followed in 1931 (discussed above) was questionable because it assumed that seed coat thickness varied with seed size, and at the same rate. Although this assumption has since been substantiated (Table 17, Col. 5), there was, at the time, no evidence either way. If incorrect (seed coat thickness constant), then it was possible to demonstrate mathematically that the proportion of seed coat to total weight of seed would be higher in smaller than in larger seeds. Thus correction coefficients, calculated as in 1931, would be inaccurate; the total "effective weight" of the seeds in the smaller fresh weight classes would be proportionately smaller than in the larger classes. The term "effective weight" applies to a measure of the stored food contained in a seed, which is the important factor in determining the size of the resulting seedling. To avoid possible error the effect of seed coat thickness was eliminated from the calculations in 1932. Correction coefficients were derived from the average relation between the dry weight of the food material in the seeds and the dry weight of the resulting seedlings. A measure of the former was obtained by subtracting seed coat weight from seed weight for each fresh weight class.

Seeds to be used were separated according to fresh weight into nine classes, planted in washed sand contained in wooden flats, and grown for 51 days without nutrients. The seedlings and seed coats (shed soon after germination) were then harvested, dried and weighed. Average dry weights of the seeds from the various fresh weight classes were also obtained. All data are summarized in Table 17, and in Text Fig. 2. The average dry weights and standard errors of the seed coats, seeds, and seedlings from seeds of the various fresh weight classes are given in columns 3, 6, and 9 respectively. The average relations of (1) dry weight of seed, and (2) dry weight of seed coat, to the fresh weight of seed are shown in Text Fig. 2, B and C. The method of least mean squares was employed in the calculation of all linear relations. Average values calculated with the aid of the regression equations are given in columns 4 and 7 of Table 17.

Values representing the dry weight of the food material stored in the seeds of the various fresh weight classes were obtained by subtracting the values in column 4 from those in column 7 (dry weight of seed — dry weight of seed coat = dry weight of food material). The average relation between these values (stored food) and the dry weight of the resulting seedlings was obtained. This relation is shown in Text Fig. 2, A; the regression equation values in Table 17, column 10. The question may be raised as to whether a curve or a straight line is the better fit. From an inspection of the plotted points the curve appears the better. But use of the straight line seems justifiable since the same relation is unquestionably linear for Corsican pine (Aldrich Blake 1930), Scots pine (Text Fig. 1), and white pine in subsequent experiments.



TEXT FIG. 2. THE DRY WEIGHTS OF (A) WHITE PINE SEEDLINGS FROM SEEDS OF VARY
FOOD CONTENT, AND OF (B) SEEDS AND (C) SEED COATS FROM SEEDS OF THE VARI
FRESH WEIGHT CLASSES.

The average dry weight of the seed less the seed coat (B—C) is taken as a measure of the food in the s
of the various fresh weight classes.

Unfortunately the seedlings from the size classes below 2 and above 5 were lost. Their inclusion would no doubt have borne out the conclusions drawn from other experiments.

The validity of the method used for determining the values upon which the seedling weights were plotted may also be questioned. It will be remembered that the average (calculated) values of seed coats and seed weights were used in the subtractions. The procedure used is justified as follows: values obtained by the direct least mean squares of the difference between the experimentally determined values (columns 3 and 6) are essentially the same as those obtained by the method used (column 8).

Only seed classes 2, 3, 4, and 5 were used in the 1932 experiment. From the average relation between the dry weight of the stored food in the seeds of the various fresh weight classes, and the dry weight of the resulting seedlings, coefficients were derived for converting the weights of seedlings from seeds of various size to the equivalent of seedlings from a single seed size. All seedling weights were corrected as of class 5. Correction coefficients are given in Table 17, column 11. Thus the weights of seedlings from seed class 2 were converted to weights equivalent to seedlings grown from class 5 by multiplying by 1.123, from 3 to 5 by 1.079, and from 4 to 5 by 1.038. In all tables of basic data, the average weights, seed size used, and the corrected weights are given. Only weights thus corrected enter into the comparisons and calculations.

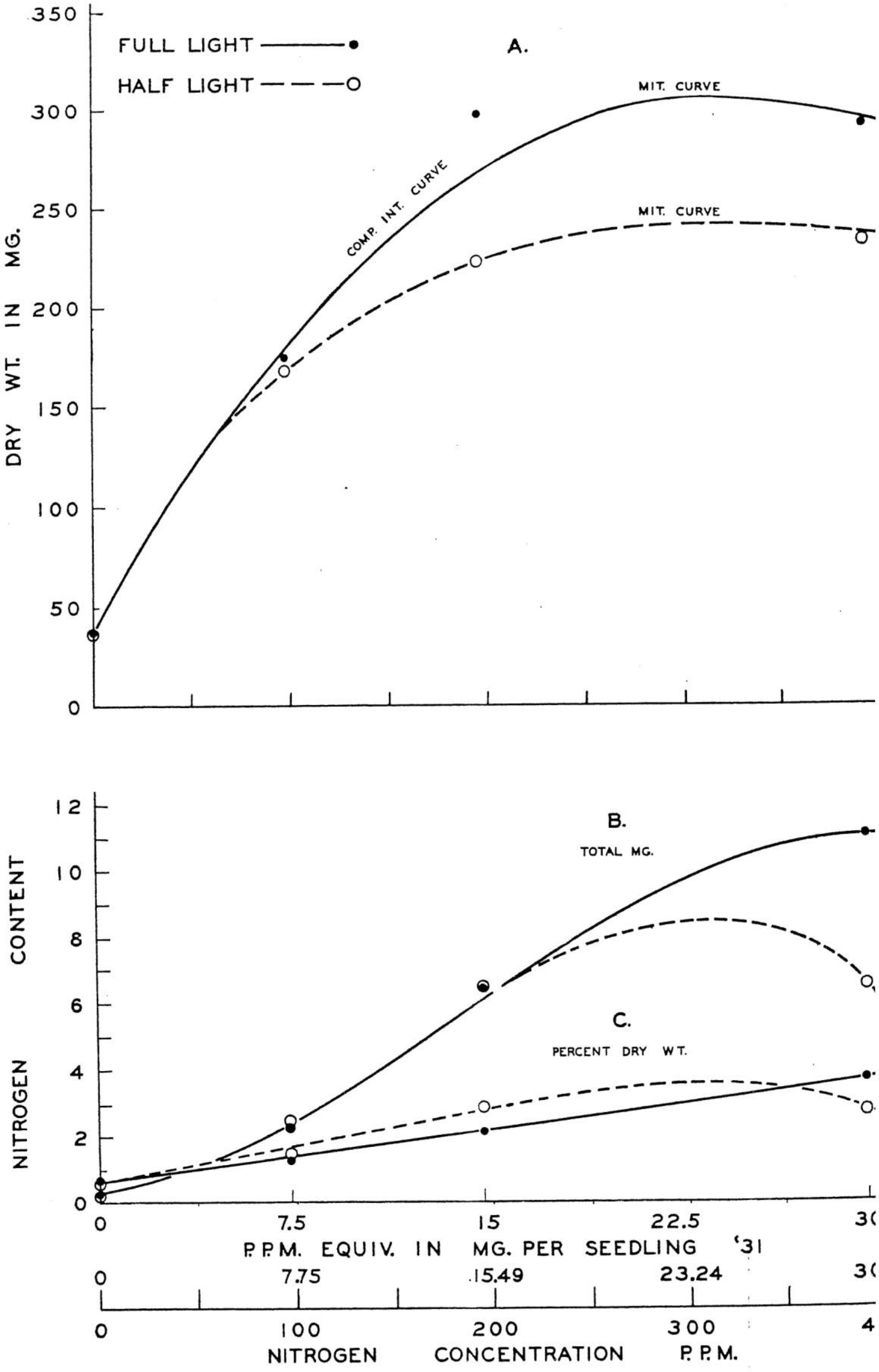
The extra work of the procedure used in deriving the correction coefficients—compared to 1931—may seem somewhat unnecessary since seed coat thickness apparently varies with seed size, and at approximately the same rate. This is evidenced by the ratios of seed coat weight to total dry weight of seed (Table 17, column 5). But there is a slight variation—the ratios (column 5) increase slightly with seed size. Any variations in these ratios indicate that seed coat thickness does not vary at the same rate as seed size; and perfect agreement is necessary if the correction factors are to be strictly accurate, that is, unless the necessary precautions (1932) are taken. The coefficients as derived (1932) are independent of seed coat or moisture content variations. Therefore the slight extra work of the method used seems more than justified by the increased assurance of accuracy.

The question has been raised as to how long the influence of seed weight is apparent in the seedling weight. From the data just presented it is certain for one growing season. From the data in Text Fig. 1, since the relation of seed weight to seedling weight remains nearly constant throughout the first growing season (the slope of the lines representing the weights of the seedlings harvested at different times after planting is nearly the same in all cases), it seems reasonable to expect that at least some of the influence of seed weight would be noticeable for several years.

The investigation of Paton (1929) is of interest in this connection. Experimental conditions were as follows: *"seedlings of Corsican pine, Scotch pine, white pine, Norway spruce, and white spruce were selected from the 2-year old seed beds. Trees were chosen from the upper, middle, and lower height classes, each tree numbered with an aluminum tag, and then transplanted into rows 8 inches apart and 2 inches apart in the rows."*

Heights were measured at the time of transplanting, the following autumn, and the autumn of the succeeding year. The next spring all were transplanted to a field covered with light sod and heights were again measured in the fall. The data and curves presented (*loc. cit.*, p. 193) show that relative height differences (between height classes) were approximately the same at the end of the experiment as at the beginning—curves of height against time for each height class are nearly parallel in each case. The author concludes that height variations in the seed bed were due to differences in "inherent vigor," and that the smaller seedlings will probably always be "weaker" than those in the upper and middle groups. But in the light of later investigations (Aldrich-Blake, Gast, McComb, and the present study) it seems probable that seedling size variations (in the seed bed as well as later) were due to differences in original "capital"—seed size, and later, plant size—rather than inherent vigor. If this is true, then the experiment of Paton shows that seed size influences seedling height for at least 6 years (2 years in seed bed, 3 in transplant bed, and 1 in the field).

The influence of seed weight on seedling weight, at least for the first year, is clearly demonstrated by the data presented, and is further confirmed by later experiments (in preparation). If the experiment of Paton (*loc. cit.*) may be used as evidence the time can be extended to 6 years. In all, several thousand seedlings of various species of pine have been used in the determinations here reported. This adds to the significance of the conclusions. Corrections for the influence of seed weight often amount to 25% of the dry weight of the seedlings. Inaccuracies resulting from the failure to make such corrections are thus apparent. Grading the seeds to size with the aid of a set of accurately sized screens is not recommended for use in experiments where a high degree of accuracy is required. Anyone weighing individually 5000 or 6000 seeds, and endeavoring to select as nearly as possible seeds of the same weight, will soon discover that the correlation between size and weight is far from perfect even though light seeds have been eliminated with a blower.



TEXT FIG. 3. WEIGHTS AND NITROGEN CONTENT, IN MILLIGRAMS AND AS PER CE OF SCOTS PINE SEEDLINGS GROWN IN SAND CULTURE IN TWO LIGHT INTENSIT WITH VARIED NITROGEN SUPPLY.

1931 AND 1932 SAND CULTURE EXPERIMENTS

The Effect of Nitrogen Supply on Growth

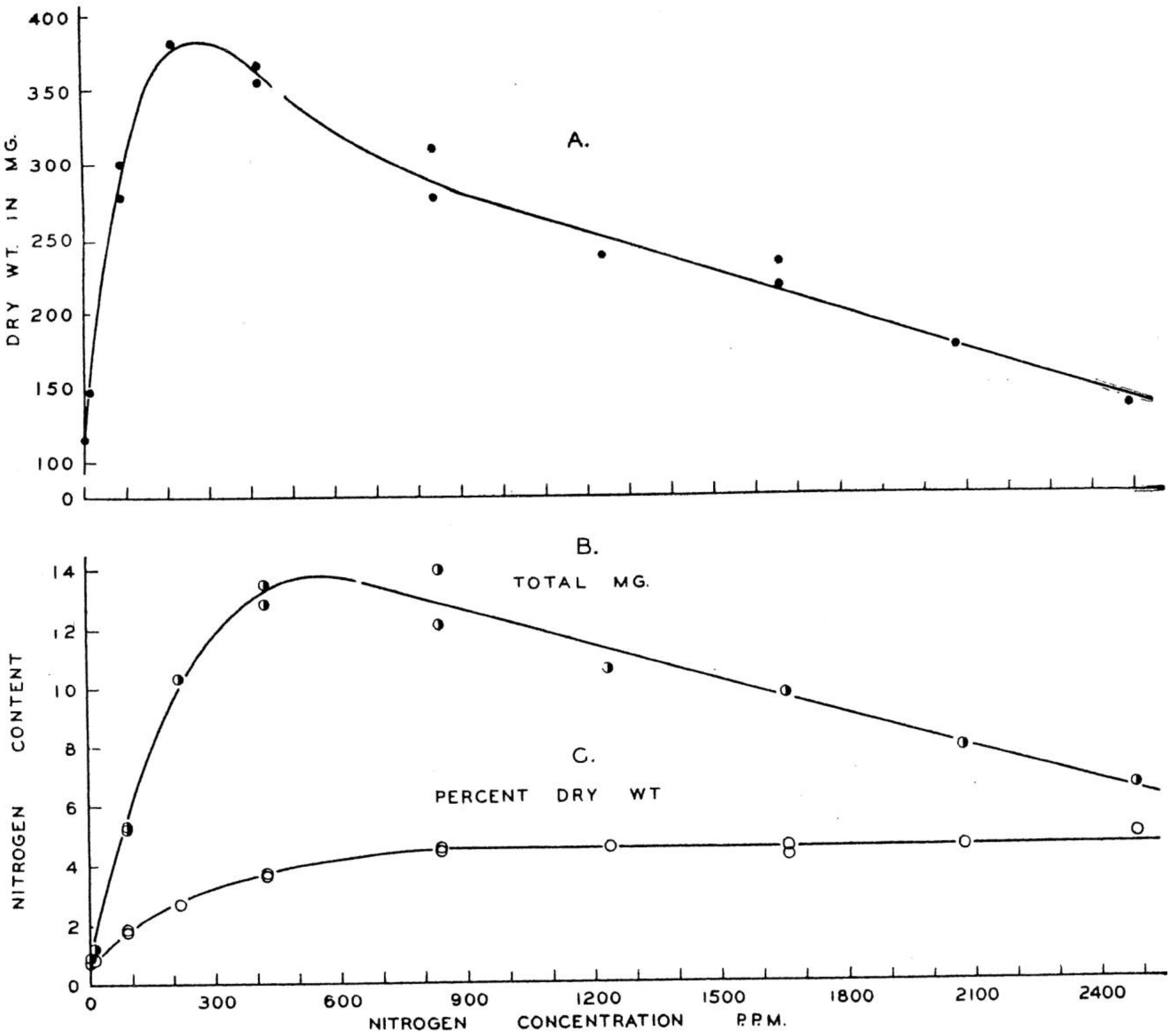
The dry weights of three-months-old Scots and white pine seedlings vary with the nitrogen concentration of the nutrient solution (Text Figs. 3, A and 4, A; Tables 5 and 14). The optimum concentration for both species is approximately 300 p.p.m. But white pine grown for the same period are the larger (Text Fig. 5, A). The difference in size is nearly constant throughout the nitrogen range. This variation may have been due to radiation conditions rather than to any inherent differences between the two species. The average daily total radiation during the Scots pine experiment was 308.4 gram calories per square centimeter (Table 12), as compared to 385.0 for white pine in 1932.

The common finding of all reported experiments (Mitscherlich, 1928; and Willcox, 1930) show that plant growth is stimulated by the addition of nitrogen until a certain point is reached; if further additions are made, the effect of the nitrogen becomes depressing rather than stimulating. Phosphorus, potassium, and calcium were found to have a similar effect on yield (1933 sand culture experiment). The Mitscherlich growth formula expressing the relation of nitrogen to yield has been successfully used in calculating the yields of various field and garden crops and was therefore employed in the calculation of these data.

A brief discussion of the formula will be necessary before proceeding with the growth data. The normal Mitscherlich yield equation is

$$y = A \cdot (1 - 10^{-c[x+b]}),$$

in which $y =$ the yield, $x =$ a growth factor (in this case, nitrogen), $A =$ the maximum theoretical yield that may be obtained with an infinite amount of x, $c =$ the "efficiency" constant for the added growth factor, and $b =$



TEXT FIG. 4. WEIGHTS AND NITROGEN CONTENT IN MILLIGRAMS AND AS PER CENT. OF the "x" equivalent contained in the seed, soil, or both. If a large quantity of a single growth factor is supplied to a plant, the action of the growth factor may become simultaneously both positive and negative. To express the negative action of a growth factor in the equation, a "depression constant" k, must be added to the normal equation, which then becomes

$$y = A \cdot (1 - 10^{-c[x+b]}) \cdot 10^{-kx^2}.$$

This formula was used in calculating the yield curves in Text Figs. 3, 4, 5 and 6. Calculated and experimentally determined yields are compared in Table 18 (Scots pine), and Table 19 (white pine). The use of a depression constant in each instance seemed necessary because it is evident from the low yields found at 387 p.p.m. (Scots pine), and 425 p.p.m. (white pine) that the curves reached a maximum at a nitrogen concentration of approximately 300 p.p.m. Table 20 gives a comparison of the calculated yields of the two species. The constants of each formula are given in Appendix II. It will be seen that the positive effect cx is dominant for the smaller additions of nitrogen, and that the depression effect, k, does not become important until the higher concentrations are reached. Then, however, it acts rapidly with each addition of nitrogen (kx^2) and a maximum is reached. Further additions of nitrogen past the concentration of maximum yield give dominance to the depression effect, thus causing the yield curve to drop. The region near the maximum of the yield curve—concentrations of 200—300 p.p.m. N—where the positive and negative action of the nitrogen are about equal and are working against each other will be known hereafter as the "region of tension." The region of small concentrations may be designated the "minimum region," in the case of Scots and white pine, 0 to 50 p.p.m. N. Above this is the "working region," concentrations 50 to 200 p.p.m. N. The "region of injury" is at concentrations above 300.

The Scots pine yield curve, taken alone, is not very convincing because of the lack of experimentally determined points, especially at its maximum. That the Mitscherlich yield formula is a relatively good expression of the average relation is evidenced by the favorable correlation index (measure of degree of relationship between the two variables) of .992, and standard error (measure of curve accuracy) of 14.1. Even though these statistical indexes are favorable they do not necessarily prove the curve significant. But its importance is greatly increased because subsequent investigators (Gast, personal communication) have confirmed the optimum and general shape; also because of its similarity to the white pine yield curve based upon more numerous data.

The white pine yield curve for a nitrogen concentration range of 0 to 425 p.p.m. was also calculated with the aid of the Mitscherlich formula. The calculated and experimentally determined values are in good agreement (Table 19). Reliability of the curve is further evidenced by the correlation index of .994 and standard error of 7.4. Since natural soils seldom supply nitrogen equivalent to more than 150 p.p.m., the lower portion of the yield curve is of the more practical value. This concentration range was duplicated in the 1933 experiment, but the nitrogen concentrations were spaced at intervals of only 25 p.p.m. up to 100, and 50 p.p.m. intervals from there to 300. The results of this experiment are in almost perfect agreement with those presented. This confirmation in addition to the relatively numerous data presented here, gives further proof of the reliability of the calculated average relation between the two variables. For purposes of discussion and for comparisons it is convenient to calculate yields at concentrations above 425 p.p.m. Although of no immediate practical value, they are nevertheless of physiological interest. A brief discussion of the calculation will suffice.

Data are presented (p. 46) to show that the nitrogen content of the seedlings, both percent and total milligrams, is proportional to the nitrogen supply. Formulæ were calculated to express these relations. Thus, either total milligrams or percent nitrogen content may be determined for any nitrogen concentration. Then by dividing the total milligrams content (N_p) by the percent nitrogen content ($N_{\%}$) at the various concentrations, yields may be calculated

$$\frac{N_p}{N_{\%}} \times 100 = \mathbf{y}.$$

Yields above nitrogen concentration 450 p.p.m. were calculated in this way. They agree very well with the experimentally determined values (Table 19). The correlation index and standard error for the yield curve over the entire nitrogen concentration range are .992 and 10.6 respectively.

It was necessary to use two formulæ to express the entire curve because yields calculated with the Mitscherlich formula do not agree with those experimentally determined above a nitrogen concentration of 450 p.p.m. The "Mitscherlich" calculated curve falls much too rapidly. This may be due to: (1) experimental error, (2) possibly the formula was not designed to express yields at such unusually high nitrogen concentrations, or (3) because the formula has been derived from, and applied to, plants which pass through both vegetative and fruiting phases annually. A discussion of results obtained by several workers will clarify the latter point.

The accumulation of nitrogen in fruits is at the expense of the nitrogen content of the vegetative portions of the plant—leaf, stem, and roots—whose development slows when fruiting starts. In a study of the growth of barley

Gregory (1926) shows that the rate of photosynthesis in plants receiving nitrogen supplies differing by 400% is almost identical, but that their final yields, nitrogen content, and maximum leaf areas differ widely. From this he concludes that the function of nitrogen is to stimulate vegetative growth resulting in a larger photosynthetic area, thus enabling a greater total assimilation without a change in the rate of photosynthesis. This explains nicely the mechanism by which nitrogen increases yield and is in agreement with later investigations.

Armstrong and Albert (1931), studying the nitrogen relations of cotton plants, found that early in the season 85-90% of the total nitrogen in the plants was contained in the leaves and stalks; but that near the end of the growing season approximately 50% of the total nitrogen in the plants was concentrated in the bolls. They also show that the plants receiving the larger nitrogen supply attain a larger final yield in dry weight and contain a greater quantity of nitrogen. Working independently, Eaton (1931) discovered that by removing the floral buds early in the season, cotton plants thus treated attained a size approximately three times that of the controls. This seems to indicate that by preventing an accumulation of nitrogen in the bolls, vegetative growth is continued. Blackman (1919) quotes evidence showing that the growth rate of *Helianthus, Connabis,* and *Nicotiana* falls off sharply at the beginning of the reproductive period when inflorescence first appears, and Gregory (*loc. cit.*) found it necessary to divide the development of barley into two periods, before and after flowering. For this reason perennial plants, such as pine seedlings, because of the absence of the fruiting phase in early life, should be better material to use in the study of vegetative growth (dry weight increase) than annual plants that fruit each season. It is altogether possible that the Mitscherlich equation, because it was derived from and applied to the prediction of the yield of crop plants, cannot fit the yield of purely vegetative development over the whole range of nitrogen concentrations studied in the 1932 white pine experiment.

Two methods other than the Mitscherlich formula were employed in calculating yields: (1) the use of calculated nitrogen content values, and (2) the compound interest formula.

The use of nitrogen content values

$$\frac{N_p}{N_{\%}} \times 100 = y$$

for calculating white pine yields has been discussed. This method was also employed in calculating Scots pine yields (Table 21).

The compound interest formula was used in calculating Scots pine yields because plant growth may be compared with money accumulating at compound interest (Blackman, 1919). Thus the original seed weight (*S*) represents the capital. The rate of increase, which becomes greater with increased nitrogen concentration (N), represents the interest rate. The analogy is perfect if the compounding is continuous instead of periodic—quarterly, semi-annually, etc.—as is business practice. The simple equation for yield (*y*) obtained by continuous compounding is

$$y = S \times \text{antiln}_e\ (c + k \cdot \log_{10} N)$$

where c is a constant equal to the $ln_e y$ when nitrogen is not supplied ($N = O$), and k is the efficiency coefficient of nitrogen use. In practical calculation, the experimentally determined dry weights were corrected to weights as of plants from 5 mg. seeds. Values of the constants were obtained by the method of least mean squares, using common instead of natural logarithms. ''Calculated weights'' of plants from 5 mg. seeds grown in full radiation were obtained from the equation

$$y_5 = \text{antilog}_{10}\ (1.729 + 0.6516 \log_{10} N).$$

Stated in natural logarithms and in a general form explicit for all seed weights when used with the correction factor (*f*), the equation becomes

$$y = \frac{s}{f} \cdot \text{antiln}_e \, (2.372 + 1.418 \log_{10} \cdot N).$$

The values calculated with the aid of the formula are given in Table 21 and shown as a curve in Text Fig. 3, A (Comp. Int. Curve). They agree well with the found values and those computed by the Mitscherlich equation. Examination of the Aldrich-Blake data on Corsican pine (1929 culture experiment) reveals (Gast, personal communication) that in the minimum and working ranges of nitrogen concentration—the region of tension was not reached in the experiment—the continuously compound interest formula applies better than the Mitcherlich equation. In the 1931 Scots pine experiment the compound interest formula fits the data fairly well up to a nitrogen concentration of 200 p.p.m. Prediction in the regions of tension and injury might be obtained by the introduction of a depression constant.

The Effect of Nitrogen Supply on the Nitrogen Content of Seedlings

The nitrogen content of both white and Scots pine seedlings varies with the nitrogen concentration of the nutrient solution. Nitrogen content has been expressed in two ways: as total milligrams, and as a percent of dry weight. The use of the following symbols will facilitate further discussion:

N=Nitrogen concentration of sand or soil culture solution—external concentration. Usually expressed as p.p.m. (parts per million $\Bumpeq$ milligrams per liter). All formulæ expressing the Scots pine relations require N in terms of milligrams of nitrogen per seedling (29 per pot). But for purposes of comparison the equivalents in terms of p.p.m. are given in all tables.

$N_{\%}$=Nitrogen content of the seedling expressed as a percent of dry weight—internal concentration.

N_s=The quantity of nitrogen (total milligrams) supplied by the seed.

N_a=The quantity of nitrogen (total milligrams) absorbed by a seedling from the nutrient media.

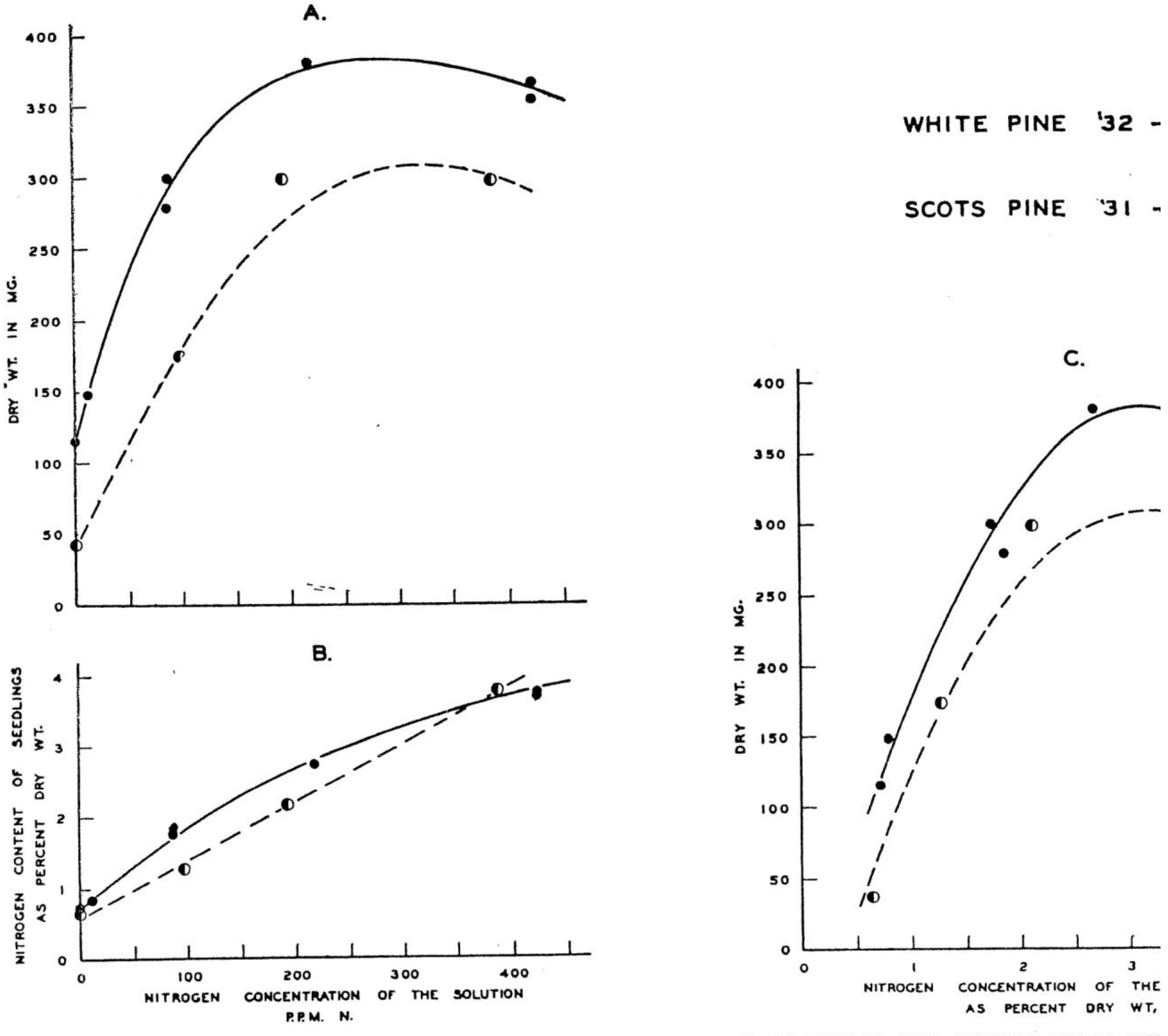
N_p=Total milligrams of nitrogen contained by a plant ($N_s+N_a=N_p$).

Percent Nitrogen Content.—Scots pine seedlings grown in sand culture for three months increased in $N_{\%}$ with increases in N (Text Figs. 3 and 5; Table 5). The rate of increase was constant over the range of N supplied, and the average relation (Text Figs. 3 and 5) is therefore linear. The regression equation was calculated by the method of least mean squares. The average relation between $N_{\%}$ and N is represented by the formula

$$N_{\%} = 0.106 \cdot N + 0.56.$$

Calculated values are in good agreement with those experimentally determined (Table 18).

White pine seedlings—grown under similar conditions but with a much larger range of N—increase in $N_{\%}$ with increases of N up to 900 p.p.m. $N_{\%}$ remains constant the rest of the range (Text Figs. 4, 5 and 6; Table 14). The calculated line of average relation over a comparable range of N, is slightly curvilinear for white pine and linear for Scots pine (Fig. 5; Table 20). Lack of perfect agreement is probably due to the difference in watering technique used in the two experiments. A smaller volume of nutrient solution was used in the Scots pine experiment (2.25 compared to 3.5 liters). The greater the total volume of the solution, the less the small amounts of nitrogen removed by the seedlings lowers the effective nitrogen concentration of the solution. The quantities removed by the Scots pine would therefore lower the effective concentration proportionately more than the quantities removed by the white pine from a solution of greater volume. This correction, if made, gives better concord. Since it is not feasible in these experiments to change the nutrient solutions, the advisability of using



TEXT FIG. 5. WEIGHTS AND PER CENT NITROGEN CONTENT OF SCOTS AND WHITE PINE SE
IN SAND CULTURE WITH VARIED NITROGEN SUPPLY; ALSO (C), WEIGHTS PLOTTED AG
(SEEDLING) NITROGEN CONCENTRATION.

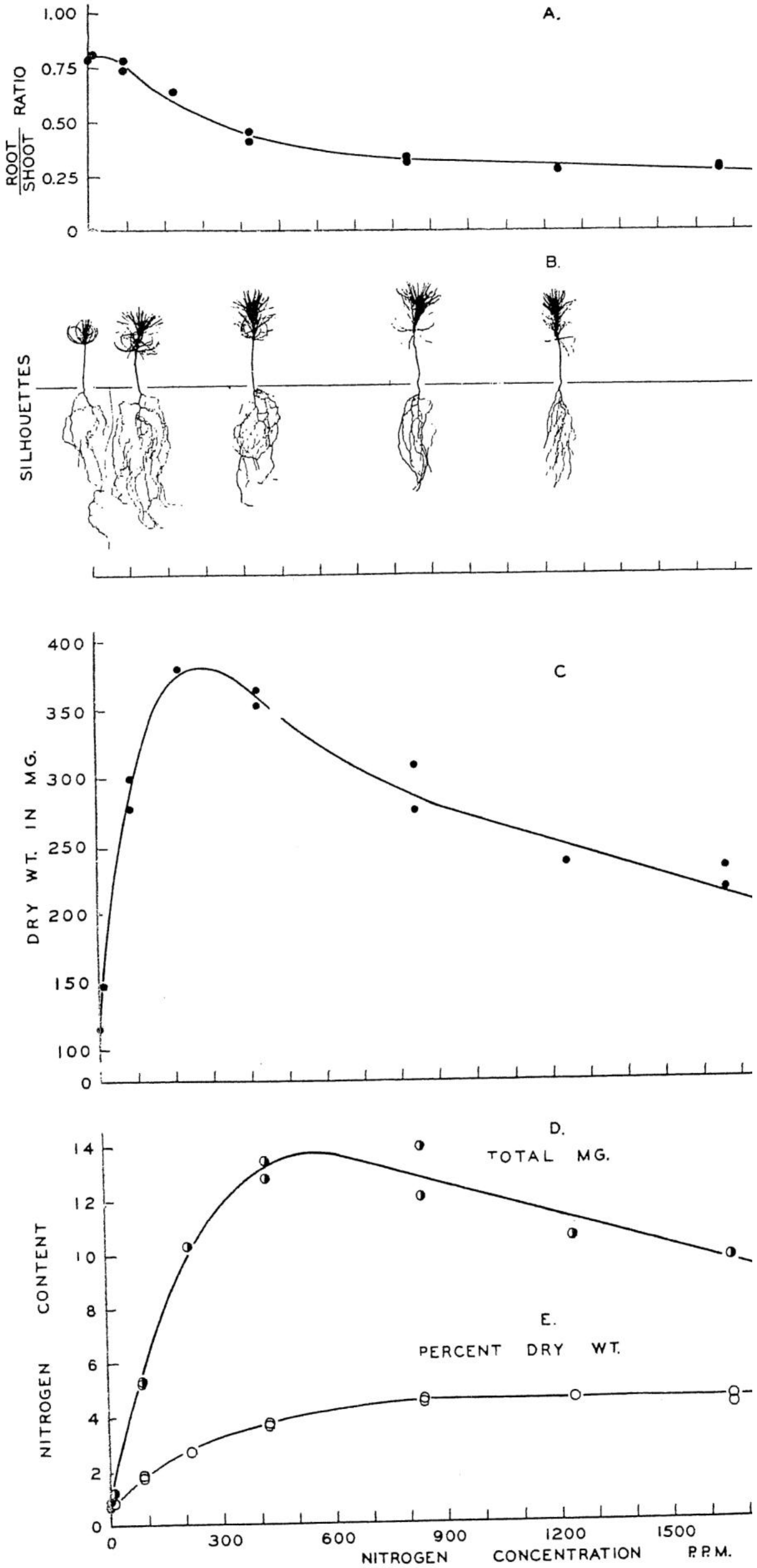
large volumes is apparent. However, the small difference in the shape of the curves is of no great importance to the present study. More significant is the fact that the percent nitrogen content of the two species very nearly corresponds at the nitrogen concentration of maximum yield (300 p.p.m.). Calculated $N_{\%}$ values of the two species are compared in Table 20.

The Mitscherlich type equation was used to calculate the average relation between N and $N_{\%}$ for white pine. The normal equation is

$$N_{\%} = A \cdot (1 - 10^{-c[N+b]}).$$

Although ordinarily applied to yield a formula of the same type serves equally well to express the average relation between N and $N_{\%}$. Thus the formula is solved for $N_{\%}$ instead of y of the normal yield equation. Therefore A becomes the maximum theoretical $N_{\%}$ that may be obtained with an infinite supply of N, $c =$ the "efficiency" constant for the added growth factor (N), and $b =$ the N equivalent in the seed. Since the curve did not reach a maximum no depression constant was necessary. This formula proved entirely satisfactory for predicting $N_{\%}$ (calculated and experimentally determined values are compared in Table 19). The correlation index over the whole range of nitrogen concentrations is .995, and the standard error 0.14. Numerical values of the constants are given in Appendix II.

Quantitative evaluation of the available nitrogen in the four soils under consideration depends chiefly upon this relation as determined in sand culture. Therefore it is important to establish its reliability. Since natural soils seldom supply nitrogen equivalent to more than 150 p.p.m., it is this lower range with which we are most concerned. The average relation between the two variables over a concentration range of 0 to 600 p.p.m. N is shown in Text Fig. 7, A. The correlation index for this range is .997 and the standard error 0.08; more favorable than



TEXT FIG. 6. ROOT-SHOOT RATIOS, SILHOUETTES, WEIGHTS A
MILLIGRAMS AND AS PER CENT, OF WHITE PINE SEEDLINGS

are very much retarded. In the 1932 white pine experiment it was found necessary to shade the seedlings just transplanted with lath screens (Plate VII) which cut the light intensity about 50%. The distance between the laths was gradually increased over a period of two weeks following transplanting. This procedure proved entirely satisfactory. White pine seedlings in this stage of their development, at least following transplanting, are apparently less tolerant of light than Scots pine.

Because of bird attack the quarter-inch mesh wire screens shown in Plate VII were necessary for about the first two weeks after transplanting.

NUTRIENT SOLUTIONS

Sand Cultures.—The basic nutrient solution supplied to each pail in the 1931 Scots pine experiment contained 2.5 grams of KH_2PO_4, 4 grams of $MgSO_4 \cdot 7H_2O$, 3 grams of $CaCl_2 \cdot 6H_2O$, and 0.045 grams of ferric citrate ("scales" U.S.P.). The total volume of the solution was 2.25 liters. The salts were added in two portions to avoid too sudden a change in the osmotic pressure of the solution surrounding the roots. This quantity of salts was considered sufficient for the complete development of 29 Scots pine seedlings, because it is approximately one half the quantity Aldrich-Blake (1930) found satisfactory for a pot of 52 Corsican pine seedlings. Nitrogen was varied as NH_4NO_3, one half the total quantity being supplied at the beginning, and the remainder about one month later.

The same basic nutrient solution was used in the 1932 white pine experiment. But the volume of the solution was increased to 3.5 liters. The total quantities of the chemicals used and the concentrations of the various nutrient elements in the solution are summarized in Table 1.[1] Application of the basic nutrient solution was again made in two portions, but the nitrogen was applied according to the schedule in Table 1.

Soil Cultures.—Seedlings were grown in each of the four soils under seven different nutrient conditions. The chemical treatments are summarized in Table 2. These nutrient applications were designed to supplement the nutrients already contained in the natural soils and not as a sole source of supply in themselves. In this way it was hoped to separate the effect of only a single element, since all others were kept optimum, or at least not limiting. The treatments were arranged to disclose soil deficiencies in either N, P, Ca and K; also to determine the effect on the seedlings of increasing nitrogen supply. Necessary nutrient solution division was made on the basis of weight. Usually stock solutions were made fresh when needed and never kept more than a week. The nutrient treatments in Table 2 were all made at one time, the beginning of the experiment.

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[1] See Appendix I for all tables referred to in text.

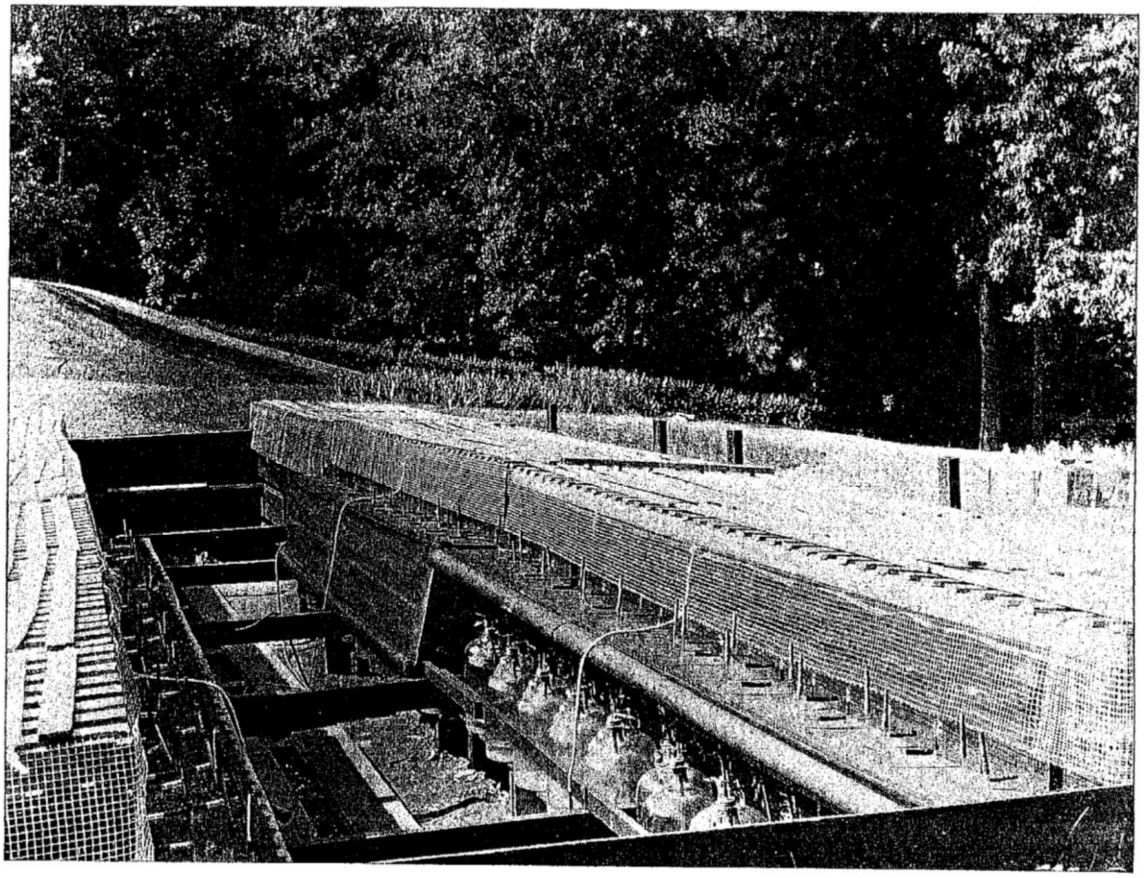

PLATE VII. SPECIAL SCREENS REQUIRED IMMEDIATELY AFTER TRANSPLANTING.

The lath screens control light; spacing is gradually increased until all are removed (about 15 days). Wire

DISCUSSION OF NUTRIENT SOLUTIONS

Basic Formula.—The Corsican pine experiment of Aldrich-Blake (1930) supplied the only data available on the nutrition of coniferous seedlings. Since his formula gave good results it was used, with only slight modifications, in these experiments. A basic solution was desired in which no nutrient element would be a limiting factor in the growth and development of the seedlings and, if possible, all would be very near the optimum value for maximum yield. By varying any single element, nitrogen in this case, its effect could be separated.

Data from later experiments (1933) have shown that the concentrations of phosphorus, potassium and calcium were certainly not limiting and, with the possible exception of calcium, were very near the experimentally determined optima. A concentration of calcium approximately one third of that used is recommended. The phosphorus and potassium nutrient treatments for 1933 are shown in Tables 3 and 4.

Effect of Abrupt Changes in Concentration.—Growth is considerably retarded by too rapid changes in the nutrient solution concentration. This is evident from the yields of Scots pine seedlings from the 1931 experiment. All pots in this experiment received the same basic nutrient solution, the total volume of which was 2.25 liters. Only nitrogen was varied. When all the chemicals had been added, in order to determine the importance of concentration, the volumes of the solutions in half the jugs (all treatments were made in duplicate) were allowed to decrease through evaporation until they were about one third that of the others. The decrease in water volume meant a proportional increase in the concentration of the nutrient elements in solution. Within two weeks many of the needles of the seedlings thus treated became deep purple and then brown. The concentrations were promptly returned to normal and about half the seedlings survived. But these were so retarded in their development that their final weights differed markedly from those grown in the continuously dilute solutions. Only the latter were used in calculating the final **"yields"** in Table 5. Important information was gained by this procedure for it was noticed that seedlings grown in the concentrated basic nutrient solution from which only nitrogen was absent—zero nitrogen treatment—no injury was evident. Apparently it was a case of nitrogen burning. The extent of injury was proportional to the increase in the quantity of nitrogen.

Profiting by this experience the nitrogen concentrations of the 1932 sand culture experiment (nitrogen series) were gradually increased at three day intervals as shown in the nitrogen application schedule, Table 1. A similar procedure was followed for gradually stepping up the concentrations of all nutrient elements in the 1933 sand culture N, P, K, and Ca series. The phosphorus application schedule (Table 6) shows in detail how this was accomplished.

Chlorine Variations.—Chlorine, from $CaCl_2$ was unavoidably varied in both the potassium and phosphorus series. But it is generally agreed (Miller, 1931) that the presence or absence of this element, except in extreme or abnormal cases, has little if any effect upon the growth of most plants. Because it was considered a non-nutrient, and unessential to pine seedlings, its variations of concentration were not included in Tables 3 and 4. Furthermore Jung (1922) found that, of the many plants examined, conifers were the only species that did not contain chlorine. Also data from other (unreported) experiments with pine seedlings show the chlorine variations used in the above series have no effect upon growth.

pH Variations.—The hydrogen-ion concentration of the soil and sand culture solutions, like chlorine, varied somewhat in the various nutrient series. The pH values are given in column 5, Tables 3 and 4; and in column 2, Tables 7, 8, 9, and 10. No pH readings were made of the 1932 sand culture nitrogen series (Table 1), but values for a similar series (1933) will serve equally well, if not better, since the concentration intervals (of N) over the range comparable to natural soils are more closely spaced. They are summarized in Table 11.

Wilde (1934), who investigated the effect of soil reaction on the germination and growth of coniferous seedlings, as well as other species, found that conifers would do well when planted in soils having a pH range of 4.5 to 7.0; but that the optimum range was slightly narrower: pH 5.0 to 6.0. Inspection of Tables 3, 4, 7, 8, 9, 10, and 11 reveals that the reactions of most of the solutions used in these experiments are well within the optimum range. Consequently pH is believed to be of minor significance in these experiments and, for all practical purposes, except in a few extreme instances—high acidity of the upper P concentrations (Table 3)—may be considered constant.

Seeds

Seeds used in these experiments were separated into weight classes. This permitted correction of plant weights at the time of harvesting for the original "capital" with which they started.

Seeds for the 1931 Scots pine experiment were separated into 0.5 milligram classes and the weights of the resulting seedlings were reduced with the aid of correction coefficients to an average weight equivalent to that of plants from a single seed size. Thus accurate comparisons have been made independent of the influence of seed weight. The exact method used in deriving correction coefficients is discussed on p. 31.

All seeds were sterilized with a 0.1% solution of bichloride of mercury, soaked in sterile water for one day, and then planted in washed sand contained in wooden flats (Plate II). When necessary, distilled water was applied with a fine spray gun, but the seedlings received no nutrients until after transplanting. Fifteen days after planting all but a few of the seedlings had shed their seed coats; they were then transplanted to the pails—except those to be used for determining the correction coefficients. Twenty-nine seedlings of a single weight class were placed in each pail. The planting dibble shown in Plate II assured even spacing.

Seeds for the 1932 white pine experiment were gathered from a small group of trees 40-50 years in age, growing on a good site near Petersham, Massachusetts. An effort was made to obtain sufficient seed from a single tree in order to eliminate as nearly as possible the genetic factor. But this proved impossible for 1931 was not an especially good seed year. The seeds were separated into 1.0 milligram classes. White pine seeds are approximately five times the weight of Scots pine; therefore a larger class interval may be used. Correction factors were again derived to reduce all final seedling weights to the equivalent of seedlings from a single seed size. The method employed differs slightly from that used for Scots pine (p. 32).

Untreated white pine seeds frequently do not have a high germination percentage, but this can be greatly improved by after-ripening. Seeds were sterilized with bichloride of mercury, stratified in moist filter paper contained in sterile flasks, and stored for six weeks at a constant temperature of + 5° C. Cold storage not only increases the germination percentage, but the uniformity of germination. At the end of this period they were planted in washed sand. The sand was treated with acetic acid as recommended by Doran (1932)—¾ of a quart of 0.8% acetic acid per square foot of seed bed at time of planting—and no damping off was noted. Like the Scots pine, they received no nutrients and were kept as dry as possible to prevent fungal infection. Twenty days from the time of planting, the seedlings, except those to be used for determining the correction coefficients, were transplanted to the pots. Only 27 seedlings were placed in each pot because the clay pot interliners reduced the available space (29 to the pail in the Scots pine experiment).

REPLACEMENTS

Whenever a seedling died it was replaced so that there were always the same number competing for the available water and nutrients in each pot. When such replacements were made, a waxed thread was tied about the seedling and it was discarded at the end of the summer.

HARVESTING

The seedlings for the 1931 experiment were transplanted to the pots on July 2 and grown for 105 days. Those for the 1932 experiment were transplanted July 6 and grown for 101 days. At the end of the growing period the contents of the pots were emptied on a screen and

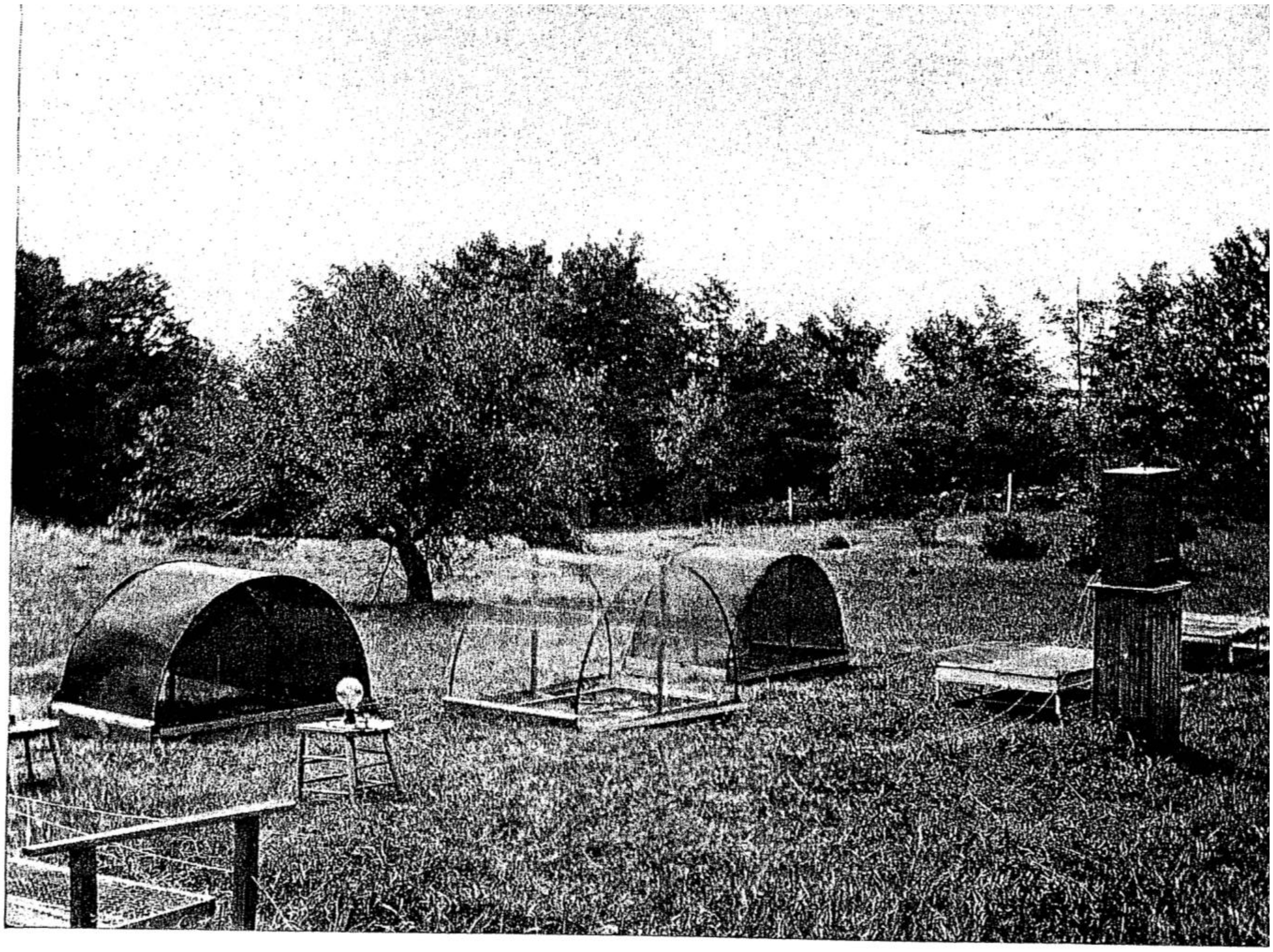

PLATE VIII. GENERAL VIEW OF 1931 EXPERIMENT, HARVARD FOREST, PETERSHAM, MAS

Each pit contains 12 pails of 29 seedlings each. Screens vary solar radiation. From left to right: "qu
light, "full" light, "half" light and movable water screens. "Open" pyrheliometer left foreground, recordin
croammeter in box at right.

the sand or sand-soil mixture was washed away from the roots by a small stream of water. Seedlings were separated in a tub of water to prevent breakage. Each root system was examined under a microscope, and an exceedingly small amount of root breakage was noted. A complete study of the mycorrhizal and other features of the root systems was made by Mr. A. B. Hatch (p. 81). At least one average seedling from each pot was preserved for reference, photograph and morphological study. The others were cut into two portions, root and shoot for ratio determinations, each part placed in a labeled glassine envelope, dried at 70° centigrade and weighed to ± 0.1 milligram.

Solar Radiation Measurements

Seedlings of the 1931 Scots pine experiment were grown under two light[1] intensities: "half light" and "full light."

Shading was accomplished by one layer of 18 x 18 mesh (wire diameter, 0.0617 inch, open area 49.7%) brass wire cloth placed over the half light pit. One layer of 1 inch mesh screen was placed over the full light pit to protect the seedlings from birds and animals. The arrangement is shown in Plate VIII. Radiation measurements were made with Eppley Weather Bureau Type Pyrheliometers, registering on a recording microammeter (Gast, 1930). Two pyrheliometers were used, one recording continuously in the open (left foreground, Plate VIII) and the other alternating between the pits. Table 12 shows a summary of the radiation measurements. The full light pit received during the summer 84.7% of the total radiation in the open. This was due mostly to the absorption by the Cello Glass screens during rainy weather and not to the one inch mesh screen. Corrections were made in each case for the number of hours the Cello Glass screens covered the pits. It will be noted (Table 12) that radiation was measured for only the last 83 days of the experiment—total length of experiment was 105 days. Probably a fair approximation of the radiation for the total period can be arrived at by extrapolation of the available data.

The white pine seedlings of the 1932 experiment were grown in full light only. Complete radiation records were not obtained during 1932; but a fairly accurate approximation has been calculated from available sources of information.

Complete measurements were made during the summer of 1933 over a comparable period. Radiation was again measured with the Eppley Weather Bureau Type Pyrheliometer but the recording was done by a Leeds and Northrup two point recording potentiometer (Micromax, equipped with special integrating device). One of the pyrheliometers

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[1] The word "light" is, in this report, used synonymously with solar radiation.

is shown in Plate III (right). The instrument to the immediate left is a photronic cell in weather-proof mounting. Comparative radiation measurements by months during 1932 and 1933 were obtained from the New York Weather Bureau Observatory in Central Park—about 60 miles south of Cornwall. Although the New York records, by months during 1933, differ slightly from those at Cornwall it is very probable that the ratios between the radiation received during comparable periods of 1932 and 1933 are relatively constant for either New York or Cornwall. By applying the ratios by months (determined from the N. Y. observations) to the 1933 Cornwall records, a fairly reliable measure of the radiation received at Cornwall during 1932 has been calculated. Thus it was found that the seedlings of the 1932 white pine experiment received a total of 38,887.0 gram calories per square centimeter from July 6, to October 15; an average of 385.0 per day.

The total radiation value is somewhat lower than that of the New York observatory over a comparable period. This is because corrections were made for the number of hours the seedlings were shielded from rain by the Cello Glass screens. These corrections are relatively accurate since the transmission factor of Cello Glass is easily determined and a record was kept of the time the seedlings were covered.

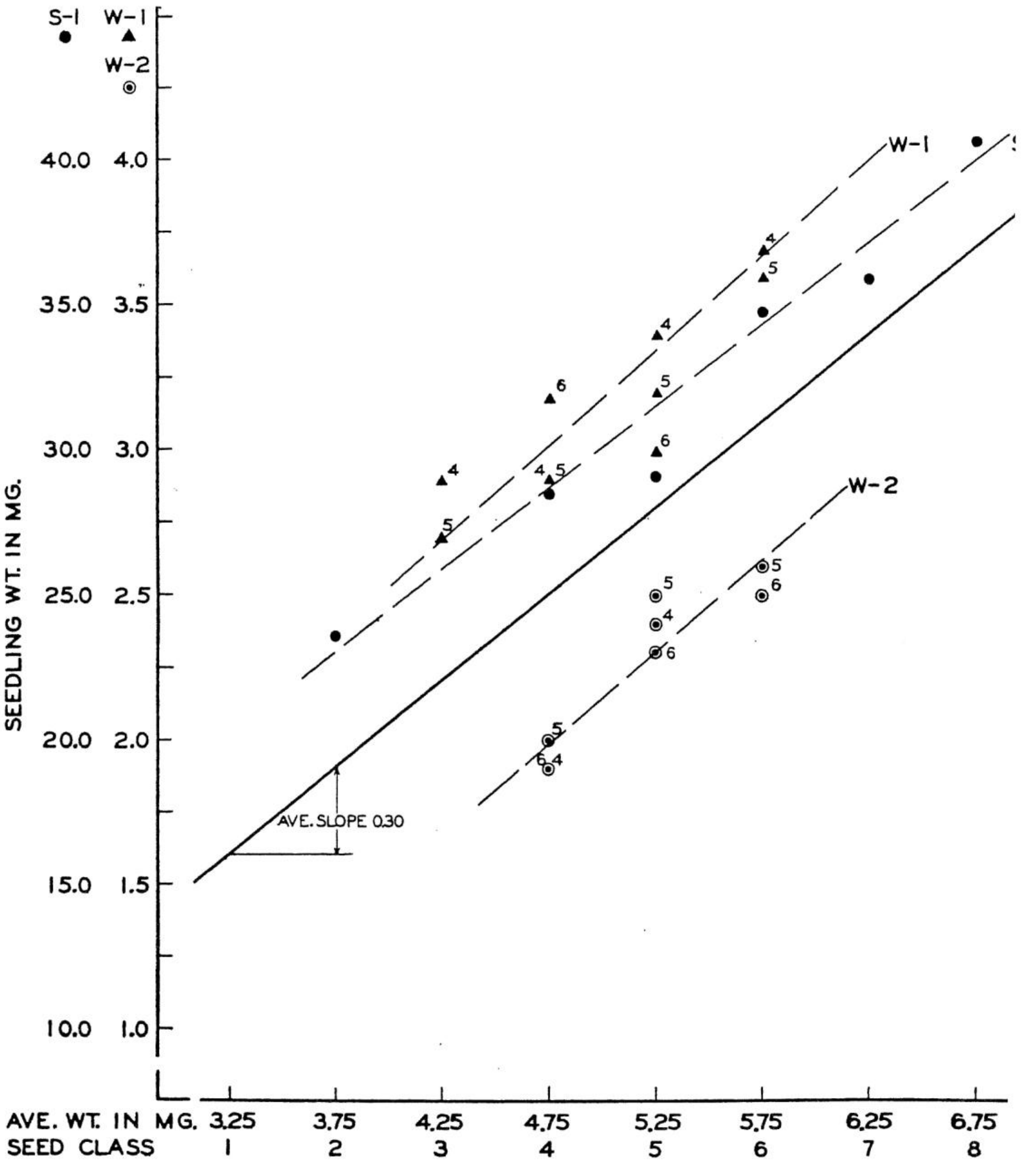
It will be noted that the mean total daily radiation received by the Scots pine (308.4, Table 12) of the 1931 experiment is somewhat lower than that received by white pine in 1932 (385.0) The significance of this difference will be referred to later. Also the total radiation over a comparable period (June to November included) was approximately 9% greater during 1932 than 1933. The data are summarized in Table 13.

NITROGEN DETERMINATIONS

From each pot at least four and up to twelve seedlings were analyzed, the number depending on the uniformity of the results. These seedlings were chosen on the basis of the average dry weight and the shoot-root ratio of the pot. For the 1931 sand culture experiment the analyses are summarized in Table 5, for the 1932 sand culture experiment in Table 14, for the 1932 soil culture experiment: the Ridge, Mid-slope (poor), Mid-slope (good) and Cove in Tables 7, 8, 9, 10 respectively.

For the determination of total nitrogen, a modification of the micro-Kjeldahl method described by Pregl (1930, p. 109) was used. Oxidation was carried out in a small decomposition flask using about 1 milliliter of concentrated sulphuric acid containing a small portion of salicylic acid (1 gram per 30 ml.) and a knife point of a mixture of 1 part by weight of potassium sulphate to 3 parts of mercuric sulphate. The contents of the flask were introduced into the distillation flask with 7 milliliters of 30% sodium hydroxide containing 5% of sodium thiosulphate. The ammonia was distilled into a standard N/100 solution of hydrochloric acid. The material must be fairly dry, for a small amount of water will dilute the sulphuric acid inhibiting nitration of the salicylic acid thus preventing all of the nitrate nitrogen from being included in the determination. In the case of the smaller seedlings, the whole seedling was used in the analysis. The larger seedlings were ground up and 40-90 milligram samples taken. The total milligram nitrogen content was computed from the dry weight of the seedling and the percentage nitrogen value. Table 15 shows the results of check determinations of the nitrogen in samples of the same seedling material. The method also checked very well with a macro-Kjeldahl using standard solutions of ammonium nitrate and urea.

Total nitrogen, ammonia nitrogen, and organic and ammoniacal nitrogen determinations were made of each of the four natural soils used in the experiment. The ordinary macro-Kjeldahl methods given in Official Methods (1925) were employed. Quantities of organic nitrogen in the soils were arrived at by subtraction (organic and ammoniacal nitrogen — ammonia nitrogen = organic nitrogen); and nitrates and nitrites were obtained in a similar way (total nitrogen — organic and ammoniacal nitrogen = nitrates and nitrites). Samples for analysis were taken from the screened soils just before mixing with the sand. They were treated with toluol to prevent chemical changes due to microbiological activity. The results of these determinations were consistent. They are summarized in Table 16.



TEXT FIG. 1. THE WEIGHTS OF SCOTS PINE SEEDLINGS GROWN FROM SEEDS VARIOUS WEIGHTS.

DISCUSSION OF RESULTS

The Relation of Seed Weight to Seedling Weight

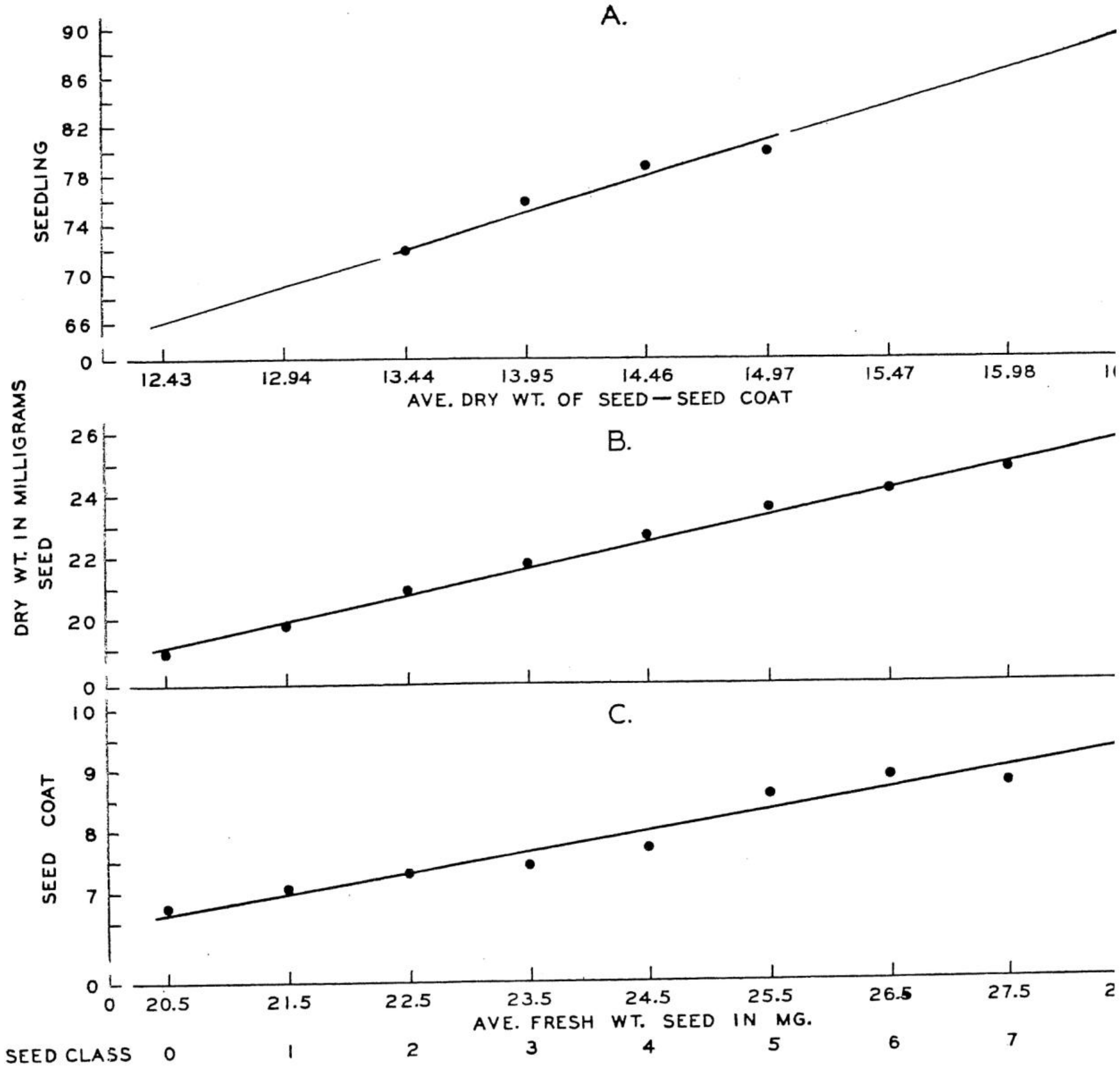
From the experience of Eytingen (1915), Korstian (1927), Aldrich-Blake (1930), McComb (1934), and Gast (data in Text Fig. 1), it is evident that the weight of the seed used has a decided influence upon the weight of the resulting seedlings. Since it is desired to study the effect of various nutrient combinations upon yield—all other growth factors remaining constant—it is necessary either to eliminate or correct for the influence of seed weight if accurate comparisons are to be made. Otherwise large deviations due to the use of seeds of various size would greatly lessen the precision of the experimental results. If it were practical to grow all seedlings from seeds of the same weight this effect would be eliminated. But it is tedious and impractical to accumulate sufficient seeds of a single weight. The second alternative—the use of correction factors—is preferable. Thus seeds of several weight classes may be used, and weights of the resulting seedlings can be corrected, by the use of factors, to an average weight equivalent to plants from a single seed size.

Three sets of data were used to obtain the linear relation between seed weight and seedling weight as shown in Text Fig. 1. Scots pine seeds for the 1931 experiment were separated into classes according to fresh weight. After germination the w-2 series was harvested as soon as the seedlings had shed their seed coats, and the w-1 series a few weeks later. The s-1 series grew for three months and were therefore much larger. All seedlings were grown in washed sand and received no nutrients. Before the dry weights were taken the seedlings of the w-1 and -2 series were classified according to the number of primary cotyledons (as indicated near each point). It was anticipated that some connection between this number and the weight of the seedlings might be found, but nothing consistent was observed. The heavy line represents the average slope of the three series of data. From this average relation coefficients were determined for correcting the weights of seedlings from various sized seeds to the equivalent of seedlings from a single sized seed. Thus the weights of seedlings from seed class 4 can be converted to weights equivalent to seedlings grown from seed class 5 by multiplying by 1.130; from class 6 to the equivalent of class 5 by multiplying by 0.896; and from class 7 to the equivalent of class 5 by multiplying by 0.812. For purposes of comparison all the seedling weights in this experiment were thus corrected and are reported as of seed class 5.

A slightly different method was used to calculate the correction coefficients for the 1932 white pine experiment. The procedure followed in 1931 (discussed above) was questionable because it assumed that seed coat thickness varied with seed size, and at the same rate. Although this assumption has since been substantiated (Table 17, Col. 5), there was, at the time, no evidence either way. If incorrect (seed coat thickness constant), then it was possible to demonstrate mathematically that the proportion of seed coat to total weight of seed would be higher in smaller than in larger seeds. Thus correction coefficients, calculated as in 1931, would be inaccurate; the total ''effective weight'' of the seeds in the smaller fresh weight classes would be proportionately smaller than in the larger classes. The term ''effective weight'' applies to a measure of the stored food contained in a seed, which is the important factor in determining the size of the resulting seedling. To avoid possible error the effect of seed coat thickness was eliminated from the calculations in 1932. Correction coefficients were derived from the average relation between the dry weight of the food material in the seeds and the dry weight of the resulting seedlings. A measure of the former was obtained by subtracting seed coat weight from seed weight for each fresh weight class.

Seeds to be used were separated according to fresh weight into nine classes, planted in washed sand contained in wooden flats, and grown for 51 days without nutrients. The seedlings and seed coats (shed soon after germination) were then harvested, dried and weighed. Average dry weights of the seeds from the various fresh weight classes were also obtained. All data are summarized in Table 17, and in Text Fig. 2. The average dry weights and standard errors of the seed coats, seeds, and seedlings from seeds of the various fresh weight classes are given in columns 3, 6, and 9 respectively. The average relations of (1) dry weight of seed, and (2) dry weight of seed coat, to the fresh weight of seed are shown in Text Fig. 2, B and C. The method of least mean squares was employed in the calculation of all linear relations. Average values calculated with the aid of the regression equations are given in columns 4 and 7 of Table 17.

Values representing the dry weight of the food material stored in the seeds of the various fresh weight classes were obtained by subtracting the values in column 4 from those in column 7 (dry weight of seed — dry weight of seed coat = dry weight of food material). The average relation between these values (stored food) and the dry weight of the resulting seedlings was obtained. This relation is shown in Text Fig. 2, A; the regression equation values in Table 17, column 10. The question may be raised as to whether a curve or a straight line is the better fit. From an inspection of the plotted points the curve appears the better. But use of the straight line seems justifiable since the same relation is unquestionably linear for Corsican pine (Aldrich Blake 1930), Scots pine (Text Fig. 1), and white pine in subsequent experiments.



TEXT FIG. 2. THE DRY WEIGHTS OF (A) WHITE PINE SEEDLINGS FROM SEEDS OF VARY
FOOD CONTENT, AND OF (B) SEEDS AND (C) SEED COATS FROM SEEDS OF THE VARI
FRESH WEIGHT CLASSES.

The average dry weight of the seed less the seed coat (B—C) is taken as a measure of the food in the s
of the various fresh weight classes.

Unfortunately the seedlings from the size classes below 2 and above 5 were lost. Their inclusion would no doubt have borne out the conclusions drawn from other experiments.

The validity of the method used for determining the values upon which the seedling weights were plotted may also be questioned. It will be remembered that the average (calculated) values of seed coats and seed weights were used in the subtractions. The procedure used is justified as follows: values obtained by the direct least mean squares of the difference between the experimentally determined values (columns 3 and 6) are essentially the same as those obtained by the method used (column 8).

Only seed classes 2, 3, 4, and 5 were used in the 1932 experiment. From the average relation between the dry weight of the stored food in the seeds of the various fresh weight classes, and the dry weight of the resulting seedlings, coefficients were derived for converting the weights of seedlings from seeds of various size to the equivalent of seedlings from a single seed size. All seedling weights were corrected as of class 5. Correction coefficients are given in Table 17, column 11. Thus the weights of seedlings from seed class 2 were converted to weights equivalent to seedlings grown from class 5 by multiplying by 1.123, from 3 to 5 by 1.079, and from 4 to 5 by 1.038. In all tables of basic data, the average weights, seed size used, and the corrected weights are given. Only weights thus corrected enter into the comparisons and calculations.

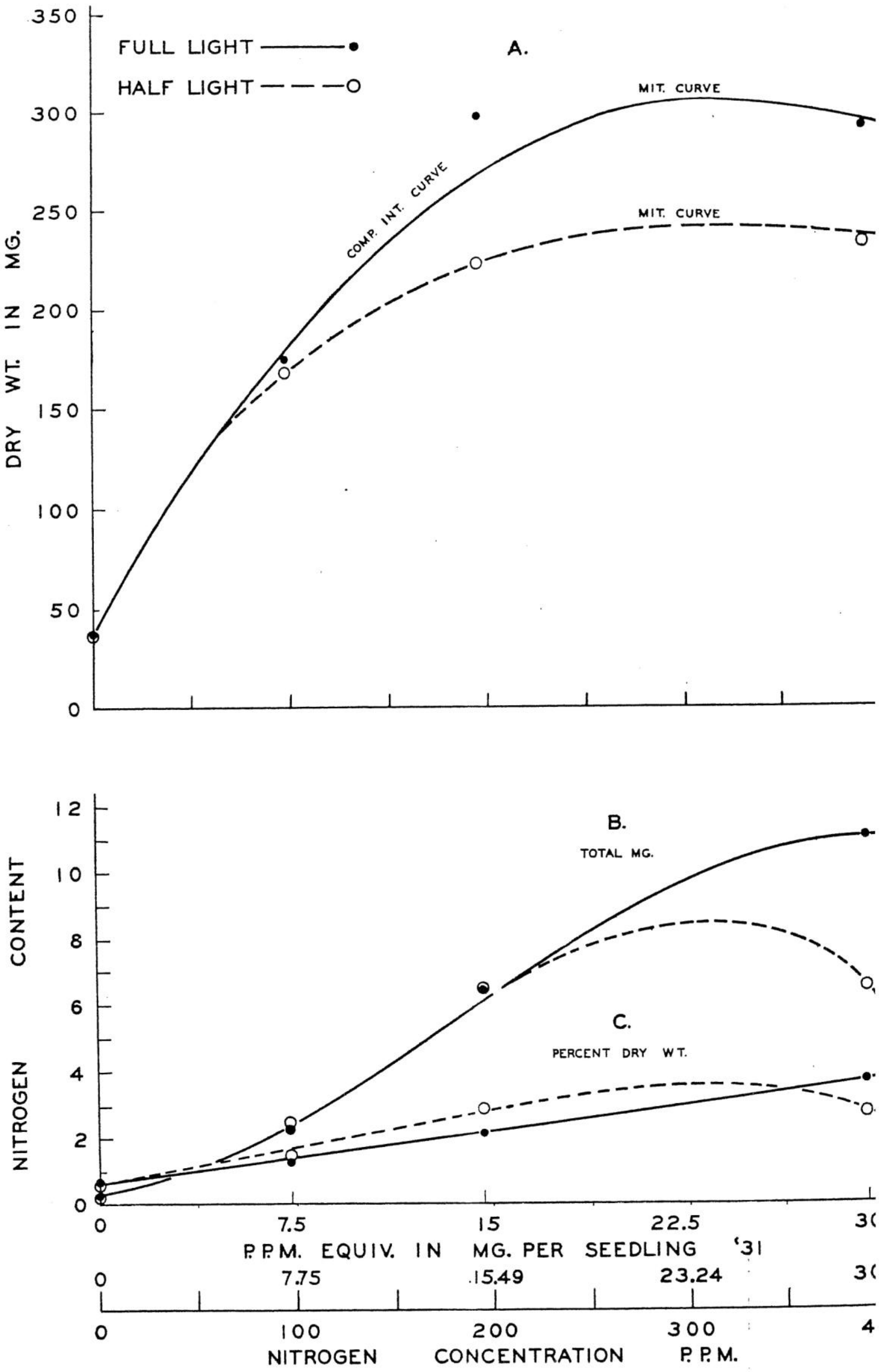
The extra work of the procedure used in deriving the correction coefficients—compared to 1931—may seem somewhat unnecessary since seed coat thickness apparently varies with seed size, and at approximately the same rate. This is evidenced by the ratios of seed coat weight to total dry weight of seed (Table 17, column 5). But there is a slight variation—the ratios (column 5) increase slightly with seed size. Any variations in these ratios indicate that seed coat thickness does not vary at the same rate as seed size; and perfect agreement is necessary if the correction factors are to be strictly accurate, that is, unless the necessary precautions (1932) are taken. The coefficients as derived (1932) are independent of seed coat or moisture content variations. Therefore the slight extra work of the method used seems more than justified by the increased assurance of accuracy.

The question has been raised as to how long the influence of seed weight is apparent in the seedling weight. From the data just presented it is certain for one growing season. From the data in Text Fig. 1, since the relation of seed weight to seedling weight remains nearly constant throughout the first growing season (the slope of the lines representing the weights of the seedlings harvested at different times after planting is nearly the same in all cases), it seems reasonable to expect that at least some of the influence of seed weight would be noticeable for several years.

The investigation of Paton (1929) is of interest in this connection. Experimental conditions were as follows: *"seedlings of Corsican pine, Scotch pine, white pine, Norway spruce, and white spruce were selected from the 2-year old seed beds. Trees were chosen from the upper, middle, and lower height classes, each tree numbered with an aluminum tag, and then transplanted into rows 8 inches apart and 2 inches apart in the rows."*

Heights were measured at the time of transplanting, the following autumn, and the autumn of the succeeding year. The next spring all were transplanted to a field covered with light sod and heights were again measured in the fall. The data and curves presented (*loc. cit.*, p. 193) show that relative height differences (between height classes) were approximately the same at the end of the experiment as at the beginning—curves of height against time for each height class are nearly parallel in each case. The author concludes that height variations in the seed bed were due to differences in "inherent vigor," and that the smaller seedlings will probably always be "weaker" than those in the upper and middle groups. But in the light of later investigations (Aldrich-Blake, Gast, McComb, and the present study) it seems probable that seedling size variations (in the seed bed as well as later) were due to differences in original "capital"—seed size, and later, plant size—rather than inherent vigor. If this is true, then the experiment of Paton shows that seed size influences seedling height for at least 6 years (2 years in seed bed, 3 in transplant bed, and 1 in the field).

The influence of seed weight on seedling weight, at least for the first year, is clearly demonstrated by the data presented, and is further confirmed by later experiments (in preparation). If the experiment of Paton (*loc. cit.*) may be used as evidence the time can be extended to 6 years. In all, several thousand seedlings of various species of pine have been used in the determinations here reported. This adds to the significance of the conclusions. Corrections for the influence of seed weight often amount to 25% of the dry weight of the seedlings. Inaccuracies resulting from the failure to make such corrections are thus apparent. Grading the seeds to size with the aid of a set of accurately sized screens is not recommended for use in experiments where a high degree of accuracy is required. Anyone weighing individually 5000 or 6000 seeds, and endeavoring to select as nearly as possible seeds of the same weight, will soon discover that the correlation between size and weight is far from perfect even though light seeds have been eliminated with a blower.



Text Fig. 3. WEIGHTS AND NITROGEN CONTENT, IN MILLIGRAMS AND AS PER CE OF SCOTS PINE SEEDLINGS GROWN IN SAND CULTURE IN TWO LIGHT INTENSIT WITH VARIED NITROGEN SUPPLY.

1931 and 1932 Sand Culture Experiments

The Effect of Nitrogen Supply on Growth

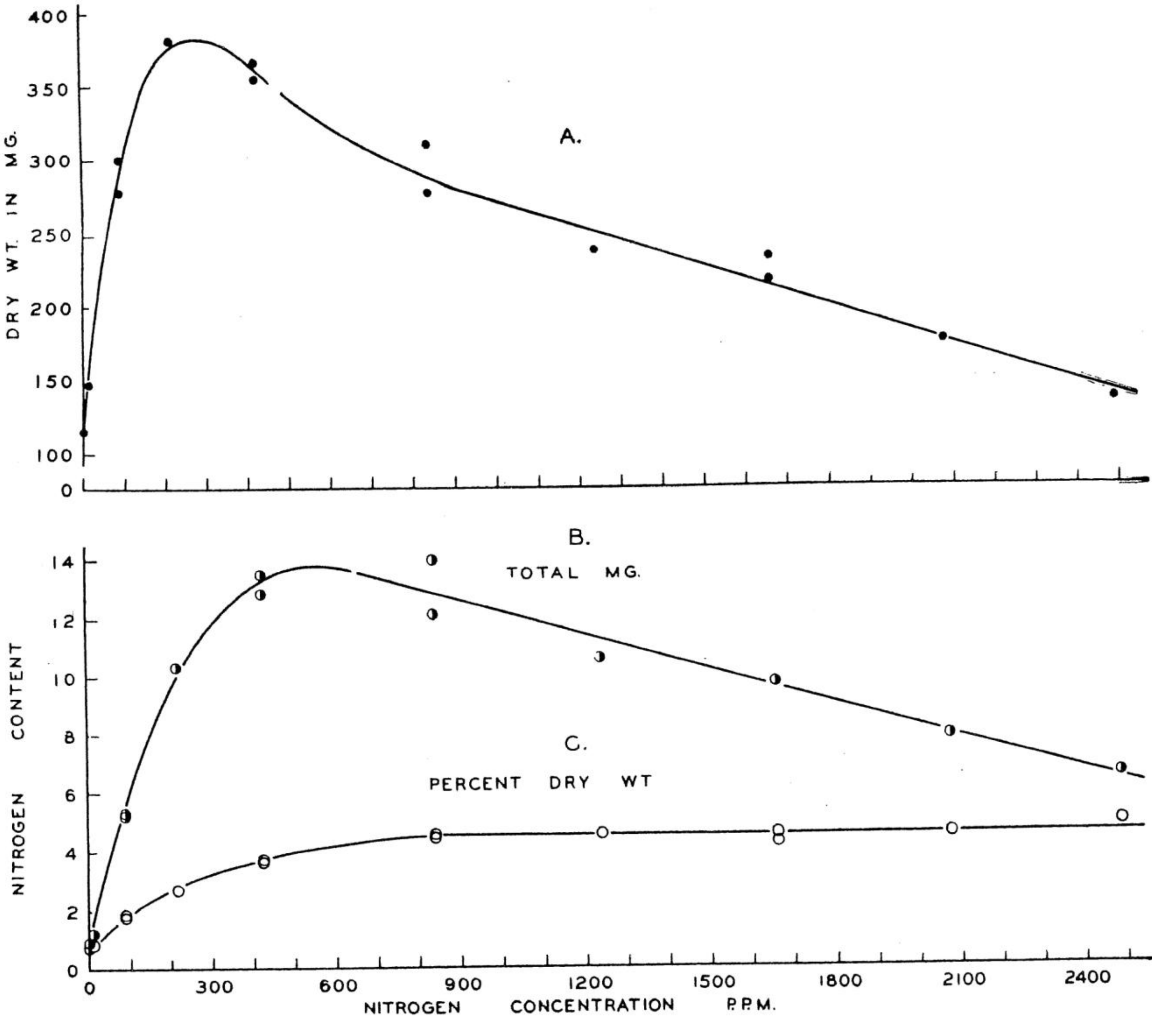
The dry weights of three-months-old Scots and white pine seedlings vary with the nitrogen concentration of the nutrient solution (Text Figs. 3, A and 4, A; Tables 5 and 14). The optimum concentration for both species is approximately 300 p.p.m. But white pine grown for the same period are the larger (Text Fig. 5, A). The difference in size is nearly constant throughout the nitrogen range. This variation may have been due to radiation conditions rather than to any inherent differences between the two species. The average daily total radiation during the Scots pine experiment was 308.4 gram calories per square centimeter (Table 12), as compared to 385.0 for white pine in 1932.

The common finding of all reported experiments (Mitscherlich, 1928; and Willcox, 1930) show that plant growth is stimulated by the addition of nitrogen until a certain point is reached; if further additions are made, the effect of the nitrogen becomes depressing rather than stimulating. Phosphorus, potassium, and calcium were found to have a similar effect on yield (1933 sand culture experiment). The Mitscherlich growth formula expressing the relation of nitrogen to yield has been successfully used in calculating the yields of various field and garden crops and was therefore employed in the calculation of these data.

A brief discussion of the formula will be necessary before proceeding with the growth data. The normal Mitscherlich yield equation is

$$y = A \cdot (1 - 10^{-c[x+b]}),$$

in which y = the yield, x = a growth factor (in this case, nitrogen), A = the maximum theoretical yield that may be obtained with an infinite amount of x, c = the "efficiency" constant for the added growth factor, and b =



TEXT FIG. 4. WEIGHTS AND NITROGEN CONTENT IN MILLIGRAMS AND AS PER CENT. OF the "x" equivalent contained in the seed, soil, or both. If a large quantity of a single growth factor is supplied to a plant, the action of the growth factor may become simultaneously both positive and negative. To express the negative action of a growth factor in the equation, a "depression constant" k, must be added to the normal equation, which then becomes

$$y = A \cdot (1 - 10^{-c[x+b]}) \cdot 10^{-kx^2}.$$

This formula was used in calculating the yield curves in Text Figs. 3, 4, 5 and 6. Calculated and experimentally determined yields are compared in Table 18 (Scots pine), and Table 19 (white pine). The use of a depression constant in each instance seemed necessary because it is evident from the low yields found at 387 p.p.m. (Scots pine), and 425 p.p.m. (white pine) that the curves reached a maximum at a nitrogen concentration of approximately 300 p.p.m. Table 20 gives a comparison of the calculated yields of the two species. The constants of each formula are given in Appendix II. It will be seen that the positive effect cx is dominant for the smaller additions of nitrogen, and that the depression effect, k, does not become important until the higher concentrations are reached. Then, however, it acts rapidly with each addition of nitrogen (kx^2) and a maximum is reached. Further additions of nitrogen past the concentration of maximum yield give dominance to the depression effect, thus causing the yield curve to drop. The region near the maximum of the yield curve—concentrations of 200—300 p.p.m. N—where the positive and negative action of the nitrogen are about equal and are working against each other will be known hereafter as the "region of tension." The region of small concentrations may be designated the "minimum region," in the case of Scots and white pine, 0 to 50 p.p.m. N. Above this is the "working region," concentrations 50 to 200 p.p.m. N. The "region of injury" is at concentrations above 300.

The Scots pine yield curve, taken alone, is not very convincing because of the lack of experimentally determined points, especially at its maximum. That the Mitscherlich yield formula is a relatively good expression of the average relation is evidenced by the favorable correlation index (measure of degree of relationship between the two variables) of .992, and standard error (measure of curve accuracy) of 14.1. Even though these statistical indexes are favorable they do not necessarily prove the curve significant. But its importance is greatly increased because subsequent investigators (Gast, personal communication) have confirmed the optimum and general shape; also because of its similarity to the white pine yield curve based upon more numerous data.

The white pine yield curve for a nitrogen concentration range of 0 to 425 p.p.m. was also calculated with the aid of the Mitscherlich formula. The calculated and experimentally determined values are in good agreement (Table 19). Reliability of the curve is further evidenced by the correlation index of .994 and standard error of 7.4. Since natural soils seldom supply nitrogen equivalent to more than 150 p.p.m., the lower portion of the yield curve is of the more practical value. This concentration range was duplicated in the 1933 experiment, but the nitrogen concentrations were spaced at intervals of only 25 p.p.m. up to 100, and 50 p.p.m. intervals from there to 300. The results of this experiment are in almost perfect agreement with those presented. This confirmation in addition to the relatively numerous data presented here, gives further proof of the reliability of the calculated average relation between the two variables. For purposes of discussion and for comparisons it is convenient to calculate yields at concentrations above 425 p.p.m. Although of no immediate practical value, they are nevertheless of physiological interest. A brief discussion of the calculation will suffice.

Data are presented (p. 46) to show that the nitrogen content of the seedlings, both percent and total milligrams, is proportional to the nitrogen supply. Formulæ were calculated to express these relations. Thus, either total milligrams or percent nitrogen content may be determined for any nitrogen concentration. Then by dividing the total milligrams content (N_p) by the percent nitrogen content ($N_{\%}$) at the various concentrations, yields may be calculated

$$\frac{N_p}{N_{\%}} \times 100 = y.$$

Yields above nitrogen concentration 450 p.p.m. were calculated in this way. They agree very well with the experimentally determined values (Table 19). The correlation index and standard error for the yield curve over the entire nitrogen concentration range are .992 and 10.6 respectively.

It was necessary to use two formulæ to express the entire curve because yields calculated with the Mitscherlich formula do not agree with those experimentally determined above a nitrogen concentration of 450 p.p.m. The "Mitscherlich" calculated curve falls much too rapidly. This may be due to: (1) experimental error, (2) possibly the formula was not designed to express yields at such unusually high nitrogen concentrations, or (3) because the formula has been derived from, and applied to, plants which pass through both vegetative and fruiting phases annually. A discussion of results obtained by several workers will clarify the latter point.

The accumulation of nitrogen in fruits is at the expense of the nitrogen content of the vegetative portions of the plant—leaf, stem, and roots—whose development slows when fruiting starts. In a study of the growth of barley

Gregory (1926) shows that the rate of photosynthesis in plants receiving nitrogen supplies differing by 400% is almost identical, but that their final yields, nitrogen content, and maximum leaf areas differ widely. From this he concludes that the function of nitrogen is to stimulate vegetative growth resulting in a larger photosynthetic area, thus enabling a greater total assimilation without a change in the rate of photosynthesis. This explains nicely the mechanism by which nitrogen increases yield and is in agreement with later investigations.

Armstrong and Albert (1931), studying the nitrogen relations of cotton plants, found that early in the season 85-90% of the total nitrogen in the plants was contained in the leaves and stalks; but that near the end of the growing season approximately 50% of the total nitrogen in the plants was concentrated in the bolls. They also show that the plants receiving the larger nitrogen supply attain a larger final yield in dry weight and contain a greater quantity of nitrogen. Working independently, Eaton (1931) discovered that by removing the floral buds early in the season, cotton plants thus treated attained a size approximately three times that of the controls. This seems to indicate that by preventing an accumulation of nitrogen in the bolls, vegetative growth is continued. Blackman (1919) quotes evidence showing that the growth rate of *Helianthus, Connabis,* and *Nicotiana* falls off sharply at the beginning of the reproductive period when inflorescence first appears, and Gregory (*loc. cit.*) found it necessary to divide the development of barley into two periods, before and after flowering. For this reason perennial plants, such as pine seedlings, because of the absence of the fruiting phase in early life, should be better material to use in the study of vegetative growth (dry weight increase) than annual plants that fruit each season. It is altogether possible that the Mitscherlich equation, because it was derived from and applied to the prediction of the yield of crop plants, cannot fit the yield of purely vegetative development over the whole range of nitrogen concentrations studied in the 1932 white pine experiment.

Two methods other than the Mitscherlich formula were employed in calculating yields: (1) the use of calculated nitrogen content values, and (2) the compound interest formula.

The use of nitrogen content values

$$\frac{N_p}{N_{\%}} \times 100 = y$$

for calculating white pine yields has been discussed. This method was also employed in calculating Scots pine yields (Table 21).

The compound interest formula was used in calculating Scots pine yields because plant growth may be compared with money accumulating at compound interest (Blackman, 1919). Thus the original seed weight (S) represents the capital. The rate of increase, which becomes greater with increased nitrogen concentration (N), represents the interest rate. The analogy is perfect if the compounding is continuous instead of periodic—quarterly, semi-annually, etc.—as is business practice. The simple equation for yield (y) obtained by continuous compounding is

$$y = S \times \text{antiln}_e\ (c + k \cdot \log_{10} N)$$

where c is a constant equal to the $ln_e y$ when nitrogen is not supplied ($N = O$), and k is the efficiency coefficient of nitrogen use. In practical calculation, the experimentally determined dry weights were corrected to weights as of plants from 5 mg. seeds. Values of the constants were obtained by the method of least mean squares, using common instead of natural logarithms. "Calculated weights" of plants from 5 mg. seeds grown in full radiation were obtained from the equation

$$y_5 = \text{antilog}_{10}\ (1.729 + 0.6516 \log_{10} N).$$

Stated in natural logarithms and in a general form explicit for all seed weights when used with the correction factor (*f*), the equation becomes

$$y = \frac{s}{f} \cdot \text{antiln}_e \, (2.372 + 1.418 \log_{10} \cdot N).$$

The values calculated with the aid of the formula are given in Table 21 and shown as a curve in Text Fig. 3, A (Comp. Int. Curve). They agree well with the found values and those computed by the Mitscherlich equation. Examination of the Aldrich-Blake data on Corsican pine (1929 culture experiment) reveals (Gast, personal communication) that in the minimum and working ranges of nitrogen concentration—the region of tension was not reached in the experiment—the continuously compound interest formula applies better than the Mitcherlich equation. In the 1931 Scots pine experiment the compound interest formula fits the data fairly well up to a nitrogen concentration of 200 p.p.m. Prediction in the regions of tension and injury might be obtained by the introduction of a depression constant.

The Effect of Nitrogen Supply on the Nitrogen Content of Seedlings

The nitrogen content of both white and Scots pine seedlings varies with the nitrogen concentration of the nutrient solution. Nitrogen content has been expressed in two ways: as total milligrams, and as a percent of dry weight. The use of the following symbols will facilitate further discussion:

N=Nitrogen concentration of sand or soil culture solution—external concentration. Usually expressed as p.p.m. (parts per million $\Bumpeq$ milligrams per liter). All formulæ expressing the Scots pine relations require N in terms of milligrams of nitrogen per seedling (29 per pot). But for purposes of comparison the equivalents in terms of p.p.m. are given in all tables.

$N_{\%}$=Nitrogen content of the seedling expressed as a percent of dry weight—internal concentration.

N_s=The quantity of nitrogen (total milligrams) supplied by the seed.

N_a=The quantity of nitrogen (total milligrams) absorbed by a seedling from the nutrient media.

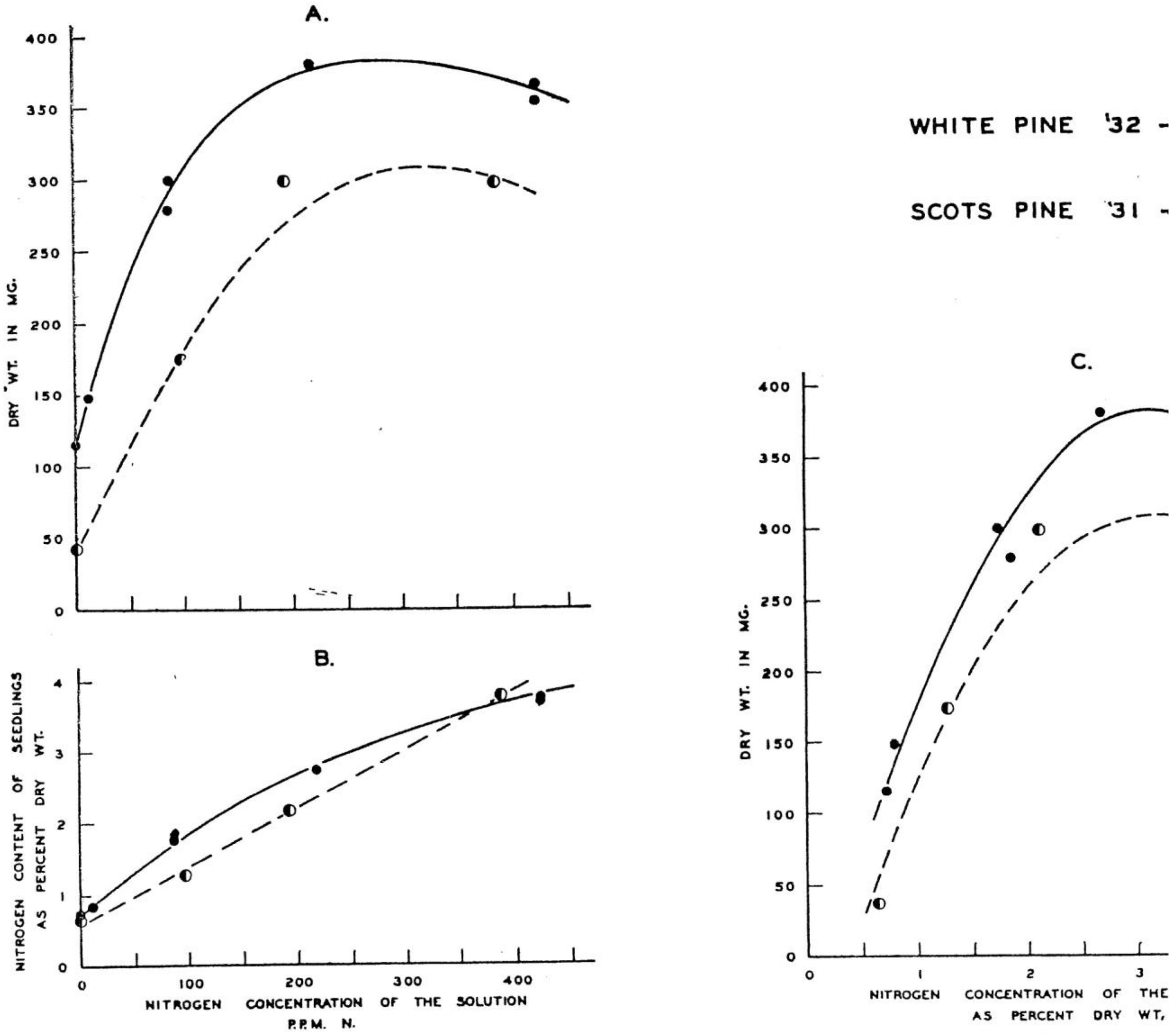
N_p=Total milligrams of nitrogen contained by a plant ($N_s+N_a=N_p$).

Percent Nitrogen Content.—Scots pine seedlings grown in sand culture for three months increased in $N_{\%}$ with increases in N (Text Figs. 3 and 5; Table 5). The rate of increase was constant over the range of N supplied, and the average relation (Text Figs. 3 and 5) is therefore linear. The regression equation was calculated by the method of least mean squares. The average relation between $N_{\%}$ and N is represented by the formula

$$N_{\%} = 0.106 \cdot N + 0.56.$$

Calculated values are in good agreement with those experimentally determined (Table 18).

White pine seedlings—grown under similar conditions but with a much larger range of N—increase in $N_{\%}$ with increases of N up to 900 p.p.m. $N_{\%}$ remains constant the rest of the range (Text Figs. 4, 5 and 6; Table 14). The calculated line of average relation over a comparable range of N, is slightly curvilinear for white pine and linear for Scots pine (Fig. 5; Table 20). Lack of perfect agreement is probably due to the difference in watering technique used in the two experiments. A smaller volume of nutrient solution was used in the Scots pine experiment (2.25 compared to 3.5 liters). The greater the total volume of the solution, the less the small amounts of nitrogen removed by the seedlings lowers the effective nitrogen concentration of the solution. The quantities removed by the Scots pine would therefore lower the effective concentration proportionately more than the quantities removed by the white pine from a solution of greater volume. This correction, if made, gives better concord. Since it is not feasible in these experiments to change the nutrient solutions, the advisability of using



TEXT FIG. 5. WEIGHTS AND PER CENT NITROGEN CONTENT OF SCOTS AND WHITE PINE SE IN SAND CULTURE WITH VARIED NITROGEN SUPPLY; ALSO (C), WEIGHTS PLOTTED AG (SEEDLING) NITROGEN CONCENTRATION.

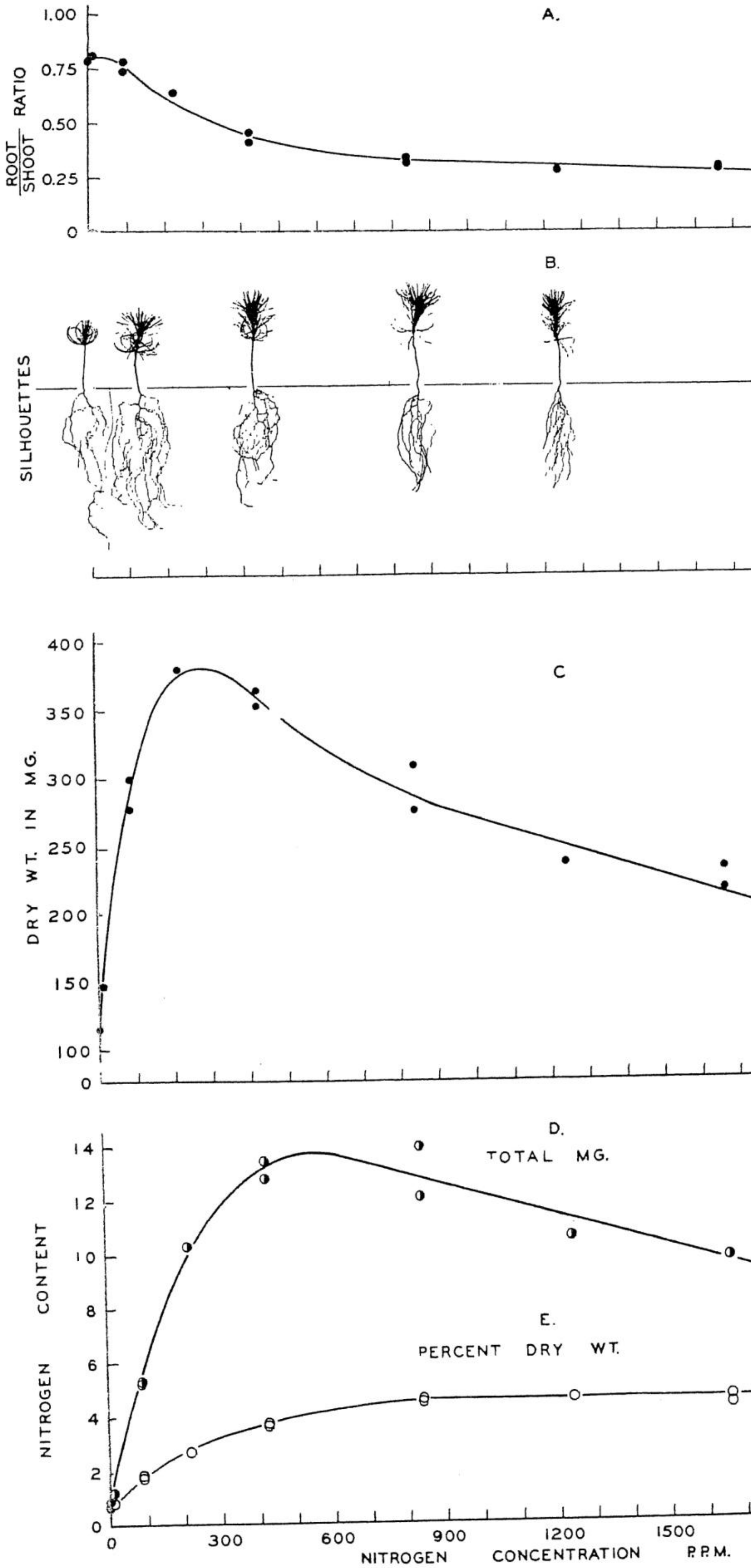
large volumes is apparent. However, the small difference in the shape of the curves is of no great importance to the present study. More significant is the fact that the percent nitrogen content of the two species very nearly corresponds at the nitrogen concentration of maximum yield (300 p.p.m.). Calculated $N_{\%}$ values of the two species are compared in Table 20.

The Mitscherlich type equation was used to calculate the average relation between N and $N_{\%}$ for white pine. The normal equation is

$$N_{\%} = A \cdot (1 - 10^{-c[N+b]}).$$

Although ordinarily applied to yield a formula of the same type serves equally well to express the average relation between N and $N_{\%}$. Thus the formula is solved for $N_{\%}$ instead of y of the normal yield equation. Therefore A becomes the maximum theoretical $N_{\%}$ that may be obtained with an infinite supply of N, $c =$ the "efficiency" constant for the added growth factor (N), and $b =$ the N equivalent in the seed. Since the curve did not reach a maximum no depression constant was necessary. This formula proved entirely satisfactory for predicting $N_{\%}$ (calculated and experimentally determined values are compared in Table 19). The correlation index over the whole range of nitrogen concentrations is .995, and the standard error 0.14. Numerical values of the constants are given in Appendix II.

Quantitative evaluation of the available nitrogen in the four soils under consideration depends chiefly upon this relation as determined in sand culture. Therefore it is important to establish its reliability. Since natural soils seldom supply nitrogen equivalent to more than 150 p.p.m., it is this lower range with which we are most concerned. The average relation between the two variables over a concentration range of 0 to 600 p.p.m. N is shown in Text Fig. 7, A. The correlation index for this range is .997 and the standard error 0.08; more favorable than



TEXT FIG. 6. ROOT-SHOOT RATIOS, SILHOUETTES, WEIGHTS A
MILLIGRAMS AND AS PER CENT, OF WHITE PINE SEEDLINGS
WITH VARIED NITROGEN SUPPLY

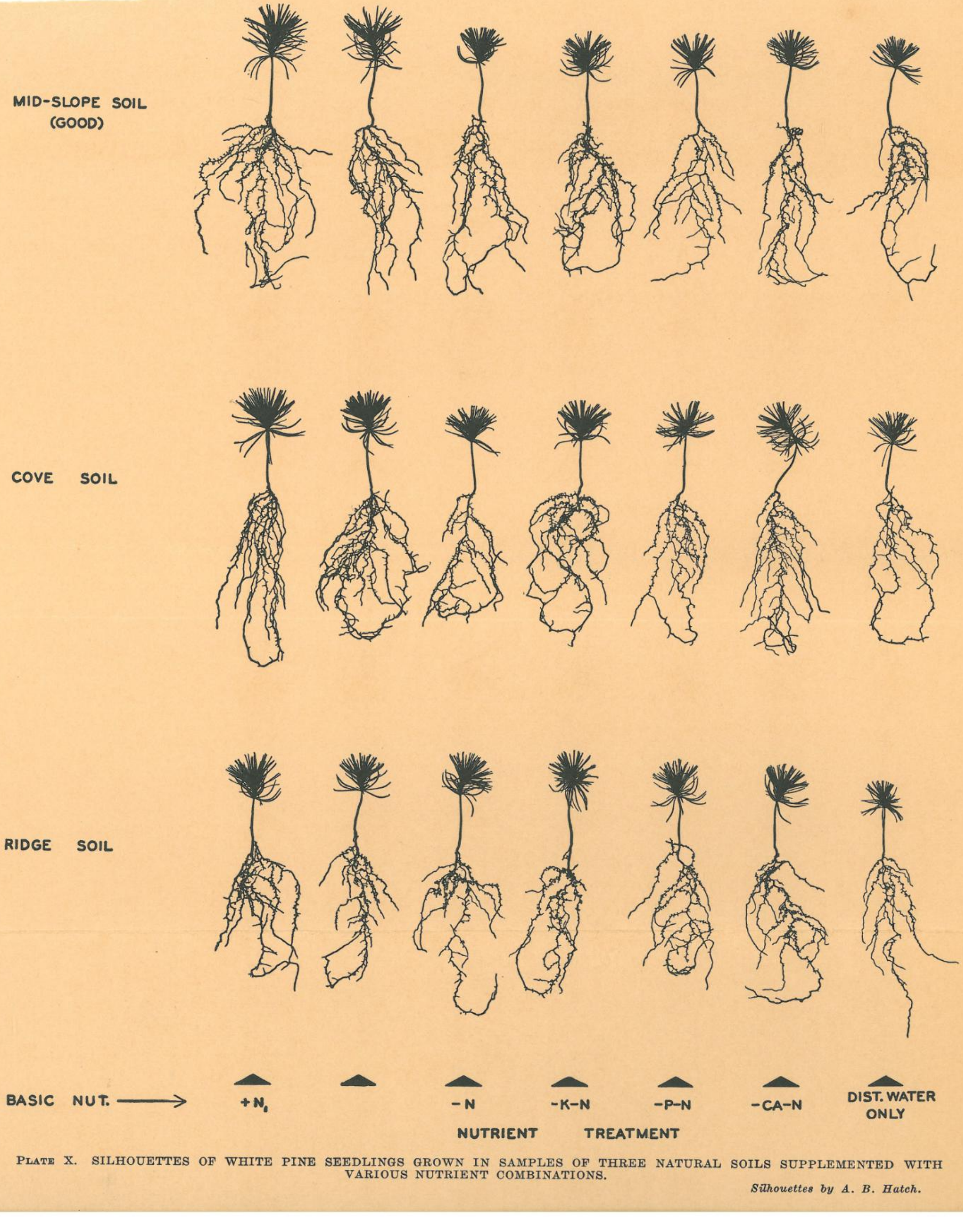


PLATE X. SILHOUETTES OF WHITE PINE SEEDLINGS GROWN IN SAMPLES OF THREE NATURAL SOILS SUPPLEMENTED WITH VARIOUS NUTRIENT COMBINATIONS.

Silhouettes by A. B. Hatch.

should be larger (dry weight) than those of seedlings grown in soils rich in all nutrients. But the root systems of soil-grown seedlings do not always respond in this way (Col. 4, Tables 7, 8, 9 and 10; Plate X). Probably the best examples of this discrepancy are the relatively low root-shoot ratios of seedlings grown in any of the four soils receiving the treatment Basic Nut. — N — P. In this case lack of sufficient phosphorus is definitely a limiting factor in the growth of the seedlings. Yet the seedlings have a lower root-shoot ratio and smaller roots (weight) than those of any other treatment.

There may be several explanations for the lack of agreement between the root response of seedlings grown in the two environments (sand and soil cultures) to changes in nutrient concentration. Although it is not the purpose of this report to discuss at length the morphological characteristics of root systems, or the mechanism of nutrient absorption, certain observations have been made that seem to facilitate interpretation of the data and should therefore be outlined briefly. A study of the mycorrhizal and other features of the root systems of seedlings from the 1931 and 1932 experiments was made by Mr. A. B. Hatch, in collaboration with whom the following paragraphs have been written.

In general Hatch (1932) found that the occurrence and development of mycorrhizæ tended to vary with the fertility of the soil. Mycorrhizæ were few on seedlings grown in the fertile Cove soil under favorable nutrient conditions: treatment Basic Nut. or + N_1. The same was true for the other soils except the relatively infertile Ridge. But mycorrhizæ tended to be abundant and well developed on seedlings from all soils when nutrient conditions were less favorable: treatments Basic Nut. — N — P, — N — K, — N — Ca, and Distilled Water only. In all soils, especially the infertile Ridge, seedlings grown in the poorest nutrient environment (Basic Nut. — N — P) had the most numerous and best developed mycorrhizæ.

This is significant since all Black Rock Forest soils are deficient in available phosphorus. Apparently the short roots of soil-grown seedlings react to nutrient deficiencies and to an unbalanced nutrient environment by becoming mycorrhizal.

The common assumption that attacks by mycorrhizal fungi retard root elongation has been shown by Hatch and Doak (1933) to be incorrect. The erroneous assumption was based on experiments in which the elongation rates of mycorrhizal short roots were compared with those of non-mycorrhizal long roots. Since short roots under any condition elongate more slowly than long roots, and because short roots alone become mycorrhizal, it is impossible to obtain from such a comparison evidence to show that mycorrhizal fungi attack retards root elongation. In sand culture (Plate IX) short roots were 1-3 mm. long and unbranched, while those of seedlings grown in soils deficient in P were, when mycorrhizal, 8-10 mm. long and profusely branched. Hatch interprets the attack as one which increases the absorbing surface area of the short roots. This, if true, is in effect a reaction to nutrient concentration similar to that of sand-culture-grown seedlings. But the response in the case of soil-grown seedlings is limited to short roots only. These roots are so small and succulent that they have little influence on dry weights. Therefore the root response of soil-grown seedlings to changes in nutrient environment, although it may be in effect comparable to that of the sand culture seedlings, is not disclosed by either total root weight or root-shoot ratio.

This is a wholly new interpretation of the phenomenon of mycotrophism in conifers, but apparently it is the only one that explains the results obtained. Recent mathematical analysis of the effect of mycorrhizæ on the dry weight increase of these seedlings (Hatch, 1934) have apparently demonstrated, by simple correlation procedures, that the relationship is not detrimental to seedling growth. However, it was not shown that mycorrhizæ increased dry weights. Such an increase would, according to theory, be masked by the conditions of these experiments where a uniform source of inoculum is available to all seedlings. The mycorrhizal phase of these experiments will be discussed more fully by Hatch in a subsequent publication.

QUANTITATIVE EVALUATION OF THE AVAILABLE NITROGEN IN NATURAL SOILS

VARIOUS experimental data fundamental to the second objective—quantitative evaluation of the available nitrogen in forest soils—has been presented and discussed and may now be assembled.

METHOD EMPLOYED

The necessary information may be briefly summarized. From the sand cultures it was found that both yield and the nitrogen contents of the seedlings were proportional to the nitrogen concentration of the nutrient solution (Text Figs. 4 and 6). Ammonium nitrate was used as a source of supply in these experiments because available information indicates that the nitrogen of this compound is readily available to the plants. Since radiation, temperature and water were maintained constant, and all other nutrient elements were supplied as pure chemicals, readily available and in quantities certainly not limiting, and according to later investigations very nearly optimal, the effect of only nitrogen has been separated. The average relations determined in this way are capable of mathematical expression. The accuracy and applicability of the equations were tested statistically and the constants have been confirmed by subsequent experiments. Consequently they may be considered reliable.

Thus either yield or nitrogen content—total or percent—may be calculated if the nitrogen concentration of the nutrient solution is known. Evidence has also been given to show that the formula expressing the relation between internal and external nitrogen concentration may be used to predict either variable with equal accuracy (Text Fig. 7).

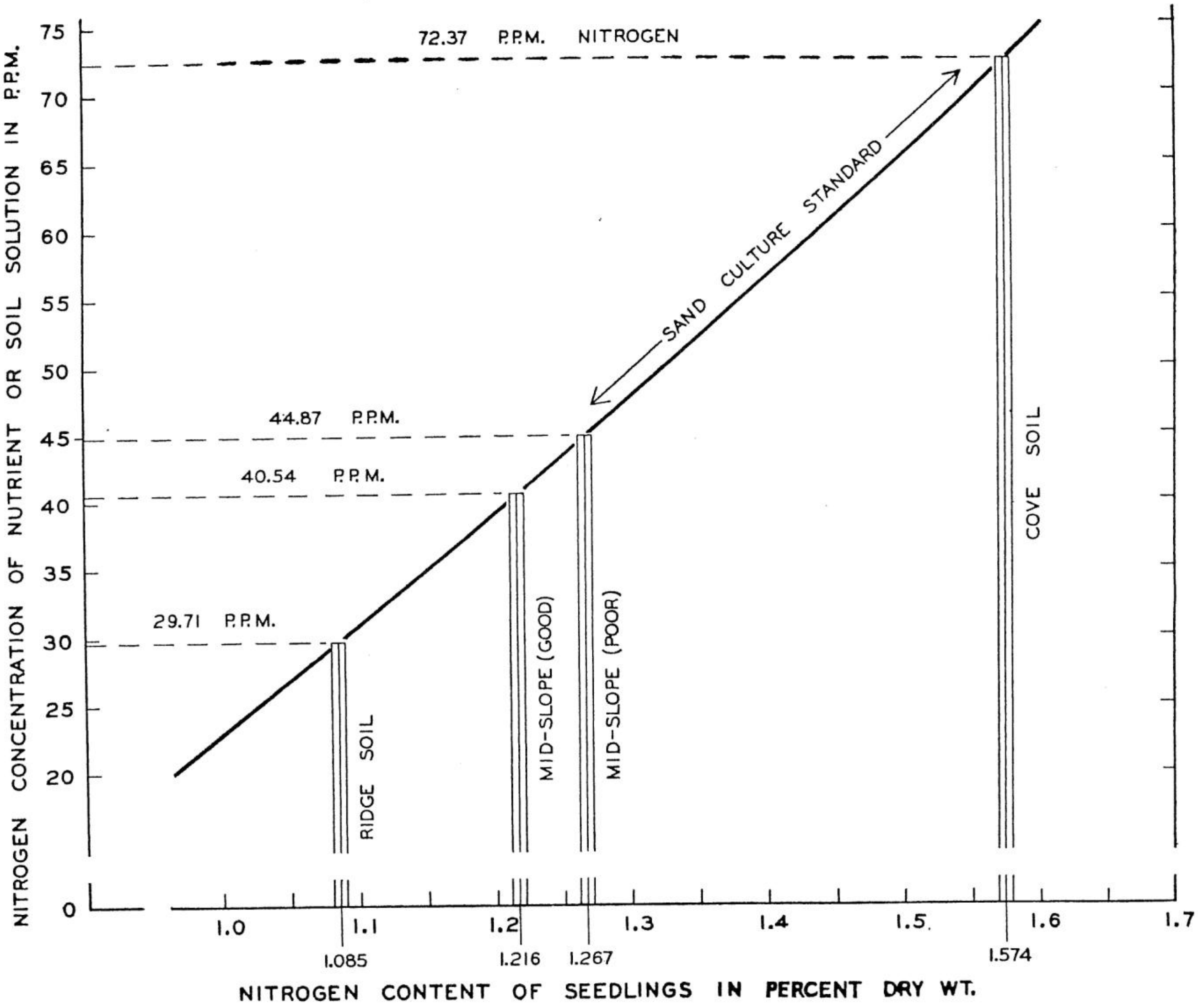
Seedlings grown in samples from the natural soils varied in nitrogen content with the soils (Text Fig. 9). They were grown for the same length of time under radiation, temperature, and moisture conditions comparable to the sand culture seedlings. Those receiving treatment Basic Nut. — N were supplied a supplement of all nutrient elements except nitrogen. No other element was limiting or lacking. The nitrogen of the soil was the sole source of this element. Under these conditions yield and nitrogen absorption are limited only by the nitrogen supply. Therefore either yield or the nitrogen content of the seedlings since both are proportional to the supply (sand culture experiment), may be considered a measure of the available nitrogen in the soil.

The seedlings from the four soils receiving treatment Basic Nut. — N contain nitrogen as follows:

Soil	*Percent Nitrogen Content of Seedlings*
Ridge	1.085
Mid-Slope (good)	1.216
Mid-Slope (poor)	1.267
Cove	1.574

Since nitrogen content is proportional to the supply the soils may be rated in the same order for increasing nitrogen availability. Now that the order is established relative comparisons will be considered.

Quantitative determinations and comparisons can be made by utilizing information gained from the sand culture study. This method takes into account the degree of the relation between the two variables. The procedure is shown diagrammatically in Text Fig. 10. The line of average relation (sand culture standard) is repeated with exactly the same ordinates as in Text Fig. 7, B. It represents the calculated relation between the nitrogen content of the seedlings and the nitrogen concentration of the nutrients solution as determined in sand culture; an inverted image of Text Fig. 7, A, or the lower portion of



TEXT FIG. 10. QUANTITATIVE EVALUATION OF THE AVAILABLE NITROGEN SUPPLY OF FOUR NATURAL SOILS.

$N_{\%}$ is the fertility index. Interpolation is based on the sand culture standard.

Text Fig. 4, C. The nitrogen contents of the seedlings from the various soils are represented by bars in their proper relative positions on the abscissa. Parallel lines are drawn from the points at which the bars intercept the line of average relation, and relative values in terms of N may be read from the ordinate scale. The same values may be calculated with the aid of the formula (Text Fig. 7). This is simpler and more accurate than interpolating from the diagram.

It will be observed that the best soil (Cove) supplied nitrogen equivalent to only 72.37 p.p.m. (Text Fig. 10). But the experimentally determined optimum nitrogen concentration was found to be 300 p.p.m. (Text Figs. 4, 5, 6 and 7). Although it is very doubtful if any natural soil could supply nitrogen equivalent to this concentration it is nevertheless used as a basis for comparisons. Consequently the range is sufficiently wide to compare any natural soils or even fertilizers. The available nitrogen equivalents of the soils, as determined by this method (Text Fig. 10), are expressed as a percent of optimum. It seems the logical procedure to compare them with the experimentally determined "perfect" nitrogen supply. Their percentage ratings are as follows: Ridge, 9.9%; Mid-Slope (good), 13.5%; Mid-Slope (poor), 15.0%; Cove, 24.1% of optimum. Or, to compare them to each other, they are in the ratio: 4.1:5.6: 6.2 : 10.0.

Yield or total milligrams (N_p), since they also are proportional to external supply, may be used to measure the nitrogen availability of the soils. $N_{\%}$ was chosen as the fertility index because it is more convenient than N_p and more accurate than yield.

Proposed Method Compared With Other Procedures

Biological Methods

The better known biological methods based on nutrient extraction by plants (Neubauer, 1925, 1926 and 1929; Gilbert and Harden, 1927; McCool and Weldon, 1928; Hoffer, 1930; Pettinger, 1931; Emmert, 1932; and Thornton, 1932 and 1933) were designed primarily to diagnose the nutrient deficiencies of agricultural soils. In this respect they have in general proved capable, as evidenced by the results of both pot tests and field trials. These methods have also provided a sound basis for intelligent fertilization, and in some cases have even been employed to test the availability of commercial fertilizers. Some have been sufficiently developed to establish limit values for deficiencies of various nutrients. Probably all may be used with equal accuracy to rate natural soils in the proper order of fertility. But relative quantitative comparisons cannot be made without some sort of reference scale or standard. Furthermore these methods depend upon the nutrient extraction powers of various field and garden crops which are not necessarily comparable to those of tree species.

At present it is not economically profitable to fertilize forest crops. For this reason there is no particular need to establish, for tree species, limit values for deficiencies in various nutrient elements—similar to those for field crops under farming conditions. Forest crops can be fertilized, but only indirectly through the effect of cultural treatment (thinnings, etc.) on the soil. What the forester needs is a graduated scale with which soil nutrient variations—due either to natural agencies, or artificial (cultural) treatment—can be evaluated quantitatively; something finer and more precise than limit values. The proposed method by using the sand nutrient culture as a standard of comparison supplies such a scale or "meter stick." And since the method is based upon nutrient extraction by tree species (pine seedlings) rather than field crops, difficulties resulting from possible differences in the absorptive powers of the two are eliminated.

Other biological procedures such as the soil-plaque method (Sackett and Stewart, 1931) and the *Aspergillus niger* method (Niklas, 1930), like those referred to above, lack the necessary precision. Also there is no evidence to show that the bacterial genus *Azotobacter,* or the fungus *Aspergillus niger,* react to various nutrient sources in exactly the same way as tree species. This can be determined only by experiment. But if such evidence can be obtained, then these two methods as well as some of the others mentioned, may prove useful indicators—but not exact quantitative measures—of the chemical fertility of forest soils.

The Mitscherlich method takes into account the relative effect of a nutrient element on yield and, in fertilization experiments, allows for the original quantities of that nutrient supplied by the soil and by the seed. These relations may be reduced to a mathematical formula. The formula has been discussed in connection with the white and Scots pine yield curves. If a soil is treated with varying amounts of a fertilizer, and the Mitscherlich formula applied to the yields, the average relation between the fertilizer and yield may be obtained (Willcox, 1930). This establishes a standard of comparison which may be used to evaluate and compare the available nutrients in natural soils. In this respect it is more exact than the other biological methods mentioned above. The chief objection to this procedure is the fact that yield is used as a measure of chemical fertility. Evidence has been given to show that the mean deviation of seedling yield is relatively greater than either total nitrogen or nitrogen percent. Consequently the latter are the more accurate measures to use. Also yield is very sensitive to variations in environment (radiation, moisture, nutrients); more so than total nitrogen. Therefore, yield variations might be influenced by environmental factors other than the one under consideration. This is especially important in field application where moisture and nutrient conditions are difficult to control. Total nitrogen is more independent of such variations, and is therefore superior to yield as a measure of soil nitrogen. Nitrogen percent, like yield, is very sensitive to environmental variations, but was used in this experiment because environmental factors other than nitrogen were easily controlled.

Electrodialysis and Extraction Methods

Electrodialysis or some of the soil extraction methods give promise of developing an adequate technique for determining the available nutrients in natural soils. But it is questionable whether the "available" nutrients as determined by these methods are actually available to plants. With reference to phosphorus availability Thornton (1932) sums up this difficulty as follows: *"No one of these methods is entirely satisfactory as no solvent has been found which will give a true indication of the availability of soil phosphorus under all conditions. Inability to find such a solvent to imitate the extractive and absorptive powers of plants under their natural environments has been the chief factor in limiting the usefulness of many of the proposed chemical methods. At the present time this difficulty seems to be as insurmountable as ever. There appears little reason to suppose that there is necessarily any relation between the amounts of nutrients extracted by chemical reagents in the laboratory and the amounts taken up by plants themselves."*

Apparently the more reasonable procedure involves utilizing plant reactions to distinguish between available and nonavailable nutrients and then, if possible, adjusting the sensitivity of the chemical methods to conform.

Direct Chemical Analysis

The quantity of nitrogen—in various forms and as total nitrogen—was determined by direct chemical analysis of the four soils. Results of these analyses are summarized in Table 16. Apparently the chief value of these determinations is to furnish excellent data with which to prove the futility of direct chemical analysis as a quantitative method for determining the available nitrogen in soils. This conclusion is in agreement with the opinion of soil chemists in general. Nevertheless some comparisons are of interest. If the nitrogen availability is measured indirectly through its effect on white pine seedlings, as in the proposed method, the soils are rated in the order: Ridge, Mid-Slope (good), Mid-Slope (poor), Cove; and in the ratio: 4.1; 5.6; 6.2; 10.0. But according to total nitrogen, by direct chemical analysis of the soils, they rate Mid-Slope (good), Mid-Slope (poor), Ridge, Cove; and in the ratio: 4.0; 5.2; 5.3; 10.0. Assuming the former rating to be correct, and evidence has been given to substantiate this assumption, the error of the second is apparent. Not even the order agrees. Although the Ridge soil actually contains a total quantity of nitrogen second only to the Cove, and greater than the two Mid-Slope soils, the "effective" quantity in the Ridge soil has been shown to be definitely less than that of the other three; both yield and the nitrogen content of seedlings from that soil are substantially lower than the others. Such a comparison is hardly fair because direct analysis measures the total or potential supply, while the proposed method measures the effective supply; the amount immediately available to plants. But the latter is plainly the best measure to use in comparing soil fertility, for crop yield varies with the available and not the potential supply.

Classifications based on the organic nitrogen, nitrates and nitrites, or the ammonia nitrogen content of the soils are not much more illuminating than those arranged according to total nitrogen. From the data in Table 16 the soils may be arranged as follows:

Basis of Classification	*Order of Increasing Nitrogen Content*	*Ratio*
Total nitrogen	Mid-Slope (good), Mid-Slope (poor), Ridge, Cove	4.0 :5.2 :5.3 :10.0
Ammonia nitrogen	Mid-Slope (good), Ridge, Mid-Slope (poor), Cove	2.4 :3.0 :7.4 :10.0
Nitrate and nitrite nitrogen	Ridge, Mid-Slope (poor), Cove, Mid-Slope (good)	6.2 :6.5 :8.7 :10.0
Organic nitrogen	Mid-Slope (good), Mid-Slope (poor) Ridge, Cove	3.5 :4.8 :5.1 :10.0
Available[1] nitrogen	Ridge, Mid-Slope (Good), Mid-Slope (poor), Cove	4.1 :5.6 :6.2 :10.0

[1] As determined by the proposed method.

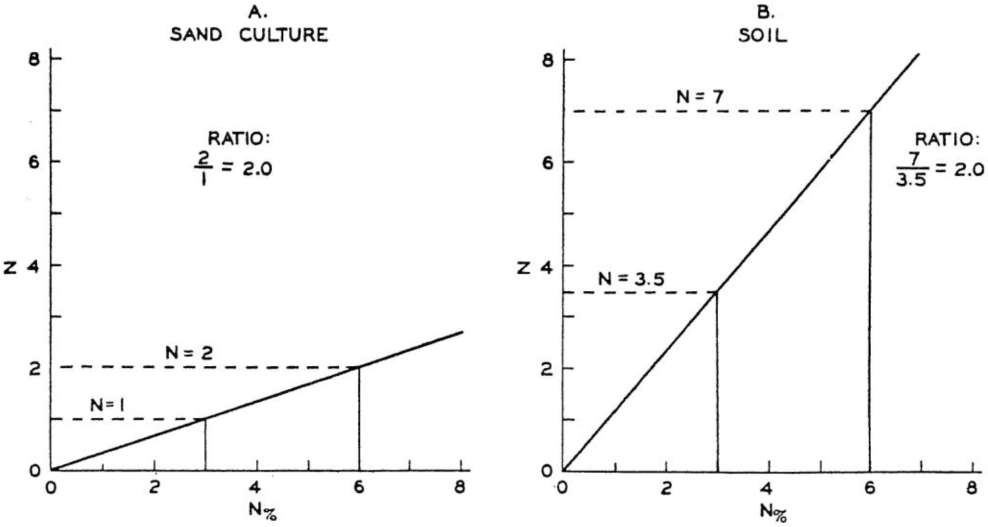
In only two cases—total, and organic nitrogen—is the order the same, and no ratios agree. None of the classifications based on direct chemical analysis even approximate either in arrangement or the ratio the one based on available nitrogen. Consequently, if a measure of the effective or available nitrogen in a soil is desired, the ordinary methods of direct analysis are not adequate.

Discussion of Proposed Method

The average relation between nitrogen supply and the percent nitrogen content of white pine seedlings was obtained from the results of the sand culture experiment. An equation was derived to express this correlation and evidence has been presented to show that the same equation may be used to predict either variable with equal accuracy (Text Fig. 7). A measure of the available nitrogen supply of the four natural soils was obtained by applying this formula (from sand cultures), to the percent nitrogen content of seedlings grown in the soils (Text Fig. 10). This procedure has been subject to criticism. But, as will be shown, the basis for the objection is illusory. Superficially the method may appear to be based upon the assumption that the association between the two variables is identical under either condition (soil or sand culture); and that the equation expressing the relation in one case (sand culture), is therefore equally applicable to the other (soil). If the success of the proposed method were actually dependent upon the truth of this assumption, then the method would be open to severe criticism; for the assumption, as stated above, is undoubtedly incorrect. Although the sand culture technique attempts to simulate nature it is well known that the synthetic nutrient environment of the sand culture is not exactly comparable to that of a natural soil. The degree of success would be difficult to determine. But contrary to the apparent basis, as stated above, perfect agreement is not essential to the success of the proposed method provided the relation between the variables—N and $N_{\%}$—can be shown to be essentially linear in both environments (sand and soil culture). Evidence may be found to substantiate this statement.

This relation was found in sand culture to be very nearly linear over the working range of nitrogen supplies (Text Figs. 7, B and 10); the range comparable to natural soils. Similar results were obtained by Adams (1928) from pine seedlings grown in the untreated soil of a plantation. Apparently the same relation is essentially linear for conifers in either environment. Consequently the only difference will be in the rate of increase—steepness of slope. Granted that the rate varies with environment. But relative quantitative comparisons according to the proposed method can be shown to be independent of rate as long as the relation between N and $N_{\%}$ is approximately linear in either environment—soil or sand culture. This is demonstrated by Text Fig. 11.

Let *A* represent the relation as determined by the sand culture technique (comparable to Text Fig. 10), and *B* the same relation in a natural soil. Both are hypothetical but will serve to illustrate the point. The ordinate scales are graduated 1-8 in any convenient units of nitrogen supply, and the abscissa in each case is graduated 1-8 in units of $N_{\%}$. Both are linear but there is a marked difference in slope, or rate of increase. Assume that the reference seedlings from two natural soils have a percent nitrogen content of 3% and 6%. To interpolate, using the hypothetical sand culture standard, *A,* as in Text Fig. 10, the two soils are found to have a nitrogen supply equivalent to 1 and 2 respectively. But according to the theoretical relation, as from a soil (*B*), they have N supplies of 3.5 and 7 respectively. Although the numerical N equivalents vary with the slope of the standard to which the $N_{\%}$ values are compared, the relative comparison (ratio = 2.0) between the respective nitrogen equivalents remains constant since the standard in either case is linear. The same principle applies to the procedure followed in this investigation. For this reason the relative quantitative rating (ratio) of the available nitrogen supply of the four soils is considered an accurate comparison, even though the sand culture standard is not an exact duplication of nature.



TEXT FIG. 11. INTERPOLATION FROM TWO (HYPOTHETICAL) LINEAR RELATIONS OF DIFFERENT SLOPES.

Even a wholly arbitrary standard such as *A* in the above illustration could probably be used to make relative comparisons as well as the sand culture standard. But the numerical equivalents (Cove soil = 72 p.p.m. N, from Text Fig. 10) would not be as significant. The significance of the equivalents increases with the agreement between the sand culture technique and nature. Hence the use of the sand culture method as the best now available for studying plant nutrition.

APPLICATION OF PROPOSED METHOD

The soil analysis technique presented in this report is to be used to study the effect of various silvicultural treatments on the chemical fertility of the Black Rock Forest soils. Successive measures should disclose both favorable and unfavorable trends and thus serve as a guide to future management policy.

Practical application of the proposed method is not as complicated as it may at first appear. It should be emphasized that once the sand culture standard has been established it is not necessary to repeat that part of the procedure every time the soils are to be tested. Also it is no more difficult to analyze seedlings than soils; and evidence has been given to show that more reliable information can be obtained from the former.

Several modifications tending to simplify, and widen the range of applicability of the proposed method are being tested. Both pots and soil sampling can be eliminated if the reference seedlings are grown in the field in a natural soil profile. The results will probably not be exactly comparable to pot tests, but the relative ratings of the soils (ratios) should remain the same. If $N_{\%}$ is used as the fertility index care must be taken that environmental factors other than nitrogen supply are not limiting. These precautions are not so necessary in the case of N_p which tends to be independent of such variations.

Another possibility is that of using only the needles of the reference seedlings. Some evidence has been obtained to show that such a procedure is possible. From 18 seedlings tested, it was found that the $N_{\%}$ of the whole seedling was proportional to the $N_{\%}$ of the needles (Table 23). Although the data are not sufficiently numerous to be conclusive, they nevertheless serve to indicate a valuable possibility. More data will be obtained and, if the correlation proves sufficiently good, the sand culture standard will be calculated on this basis.

It is believed that further investigation will lead to the development of additional modifications even less complicated than those suggested. Simplified tests based upon the plant extraction principle (Emmert, 1932; Thornton, 1932 and 1933) are now available for diagnosing nutrient deficiencies in various crop plants. Perhaps similar field tests can be applied to tree species to measure the available nutrients in forest soils. From the experience with pine seedlings it is probable that there is a relation between the nutrient content of the leaves, needles, branches or sap of mature trees, and the nutrient conditions of the soils in which they grow. If such relations exist, then soil nutrient conditions will be reflected in the chemical composition of the part or parts where the association is most pronounced. Fertilization experiments in various mature stands of the Black Rock Forest are now in progress to determine the extent and reliability of these relations. If sufficiently good they may form a basis for rapid and fairly accurate soil fertility tests in the field.

SUMMARY

TECHNIQUE

IN THE experiments reported, a sand culture technique with inorganic nutrient solutions was used. For this, a pail coated with acid resistant paint and fitted with a clay pot interliner, a glass jug for reservoir, and a pumping device for watering was arranged. Natural soils admixed with sand were also used. For these, mason jars were substituted for the jugs, and the solutions were drained directly from the pails into the jars beneath. Only distilled water was used. All pails were shielded from rain by frames covered with Cello Glass—Cellophane precipitated in wire cloth. This was done to prevent contamination by fixed atmospheric nitrogen and because it was necessary to maintain accurate nutrient volume control. Solar radiation variations were obtained with various layers of brass wire cloth of the proper open area. Total solar radiation was recorded continuously.

PHYSIOLOGICAL OBSERVATIONS

Seed weight is an important factor in determining the size attained by one-year-old Scots and white pine seedlings. Consequently all seeds used in these experiments were weighed individually. Since it was impractical to accumulate sufficient seeds of a single weight class, several classes were used. Correction factors were derived for converting the weights of seedlings from seeds of various size to a weight equivalent to seeds of a single size.

The yields of Scots and white pine seedlings grown in sand cultures watered with a basic nutrient, but with varied nitrogen supplies, were found to vary with the nitrogen concentration of the nutrient solution. In either case maximum yield (total dry weight) was attained at a nitrogen concentration of 300 p.p.m. N—the optimum supply. Further increases depressed growth. These relations between growth and nitrogen supply were tested statistically, expressed by mathematical formulæ and confirmed by subsequent experiments.

Like yield, the nitrogen absorption of these two species measured as a percent of dry weight ($N_{\%}$), and as total milligrams (N_P), varied with the nitrogen concentration of the nutrient solution—the external supply (N). The internal nitrogen concentration (as percent of dry weight) at the point of maximum yield (300 p.p.m. N) was found to be approximately 3.2% for both species. Apparently further increases in the external supply result in toxic internal nitrogen concentrations. These relations between the external supply and the nitrogen absorption were expressed by equations whose constants have been confirmed in later experiments.

Because of the close correlation between the internal nitrogen concentration and the yields of both species (Scots and white pine) it is believed that internal nitrogen concentration plays a more important role in determining yield than does the external supply. Thus, although the internal concentration varies with the external supply, the effect upon yield of the former is direct while that of the latter is indirect. Consequently internal concentration is an excellent measure of the availability of the external supply, since any nitrogen absorbed is necessarily available. This measure was utilized to evaluate the available nitrogen supplied by several natural soils.

Due to the toxic effect of high internal nitrogen concentrations resulting from too rapid increases in the external supply, it was found necessary to increase gradually the external concentration of the nutrient solutions. Thus 300 p.p.m. N when applied at once resulted in severe injury, but when attained gradually produced maximum growth.

Needle color of white pine seedlings varied with the nitrogen supply from a yellow-green at zero nitrogen to an unusually deep blue-green at 2490 p.p.m. No sharp change was noted; rather, a gradual transition from the yellow to the blue-green with increasing nitrogen supply. Relatively accurate quantitative estimates of available nitrogen supply were made on the basis of needle color.

Seedlings grown in soils or sand nutrient cultures deficient in phosphorus developed a distinct purple color of the lower needles. This color reaction may be used as a specific indicator since it is apparently associated only with extreme phosphorus deficiencies and is independent of other nutrient conditions.

The root systems of white pine seedlings grown in sand nutrient cultures were found to vary in size and development with the external nitrogen supply. Maximum root weight occurred at the concentration of maximum total yield (root + shoot) — 300 p.p.m. N. But the proportion of root to shoot (root-shoot ratio) reached a maximum at a lower supply (50 p.p.m.). Above this point the ratios decreased with increasing nitrogen concentration. Likewise root development—measured by the number and branching of laterals and secondary laterals; also the number of short roots—after attaining a slight maximum, varied inversely as the nitrogen concentration. If root size and development may be taken as a measure of absorbing area, this area can be said to decrease as nitrogen becomes more readily available.

The root systems of seedlings grown in samples of four natural soils receiving various nutrient supplements did not respond to nutrient concentration in exactly the same way as the roots of those grown in sand culture. Soils and treatments definitely deficient in one or more nutrient elements did not, as might be expected, produce seedlings with the largest (weight) roots or root-shoot ratios. This may have been due to the introduction of an additional factor, mycorrhizæ.

Mycorrhizæ were few on seedlings grown in the more fertile soils under favorable nutrient conditions, but tended to be abundant and well developed on seedlings grown under less favorable nutrient conditions—infertile soils. It has been suggested that, since the mycorrhizal structure undoubtedly increases the total surface area of the roots, and may form a more efficient absorbing mechanism than short roots or root hairs, the response (to nutrient environment) may be, in effect, comparable to that of sand-culture-grown-seedlings. But because these structures are so small and succulent they are not disclosed by the dry weight of the roots.

The yields of Scots pine seedlings grown in sand cultures watered with a basic nutrient solution, but with varied light and nitrogen supply, varied with both light and nitrogen. Those that received either light intensity —''half'' or ''full'' solar radiation—increased in size with the nitrogen supply up to the optimum of 300 p.p.m. N. The rate of increase was identical up to 55 p.p.m. N, but became greater in full light above this point. Consequently the difference in size between the seedlings grown in the two light values increased with the nitrogen supply from 55 p.p.m. N to the optimum. Relatively high nitrogen supplies were necessary to bring out the effect on yield of high light intensities.

The 50% difference in solar radiation had little effect upon the total nitrogen absorption except at unusually high nitrogen supplies. But the percent nitrogen content of the seedlings grown in half ''light'' was higher than those grown in full light. This follows since the former had approximately the same total quantity of nitrogen to be distributed through a smaller seedling.

Scots pine seedlings transplanted directly from the germination flats to the sand nutrient cultures were exposed immediately to full solar radiation without any apparent ill effects. But white pine, it was found, must be shaded and the light increased gradually over a period of about two weeks. Evidently the latter are, in this stage of their development, less tolerant of high light intensities.

In attempting to duplicate these experiments it was found essential to measure and record the total solar radiation received during the growing period. This factor, which is one of the more important in determining the growth of plants, is apt to vary from year to year over a comparable period in the same location. Thus, if no measurements are made, growth variations (due to radiation differences) may be attributed to entirely the wrong cause.

DETECTING SOIL NUTRIENT DEFFICIENCIES

Soils used in these experiments were taken from, and named for, four of the major forest types of the Black Rock Forest: Ridge, Mid-Slope (divided into good and poor on the basis of tree growth) and Cove hardwoods. Samples were obtained from permanent plots, the soils admixed with sand, placed in pots into which white pine seedlings were transplanted, and the seedlings grown for the same length of time as those in the sand nutrient cultures. Soils were supplemented with basic inorganic nutrient solutions with omissions of either P, N, K, or Ca. By observing seedling growth responses (to nutrient treatment) and comparing yields, it was possible to detect deficiencies of any of these elements in the four soils used. Because seedling yields proved very sensitive to all environmental changes, only relatively large variations and consistent trends were considered significant in interpreting the results.

The four soils were found to contain relatively abundant supplies of available calcium and potassium and, with the exception of the Ridge soil, the same was true of nitrogen. But all exhibited a marked deficiency of available phosphorus.

Analysis showed that the nitrogen absorbed by the soil-grown seedlings varied with the available supply. Moreover the absorption, when measured as a total quantity (N_p), tended to be more independent than $N_{\%}$, of other (than nitrogen) nutrient variations.

QUANTITATIVE EVALUATION OF THE AVAILABLE NITROGEN IN NATURAL SOILS

Either the yields (y) or the nitrogen contents (N_p and $N_{\%}$) of white pine seedlings, since both are proportional to the nitrogen supply (N), may be used to measure the available nitrogen in natural soils. As the fertility index, $N_{\%}$ was selected because it is a more reliable measure than yield, and more easily determined than N_p.

The calculated average relation (determined in sand nutrient cultures) between the nitrogen supply and the $N_{\%}$ of white pine seedlings serves as a standard of comparison. By interpolation based upon this standard or graduated ''meter stick,'' and fitting in the $N_{\%}$ values of seedlings grown in soils of unknown nitrogen supplying capacity, relative nitrogen fertility equivalents may be obtained for each soil. Thus it was found that the Ridge soil supplied to the seedlings a quantity of available nitrogen equivalent in effect to a continuous supply of 29.71 p.p.m. N as NH_4NO_3; the Mid-Slope (good), 40.54; the Mid-Slope (poor), 44.87; and the Cove soil, 72.37.

Since the experimentally determined optimum nitrogen supply was equal to 300 p.p.m. N as NH_4NO_3, the nitrogen supplying powers of the soils were expressed in each case as a percent of optimum (300). With the soils in the same order as above, these percentage values are: 9.9; 13.5; 15.0; and 24.1 percent of optimum. Compared to each other on this basis they are in the ratio: 4.1: 5.6: 6.2: 10. These relative measures depend upon the nutrient extractive and absorptive powers of coniferous seedlings rather than those of chemical solutions of various solvent qualities—not necessarily the same. Consequently the fertility equivalents, as determined, are of necessity measures of available nitrogen only. The relative merits of this and other methods (actual data on direct chemical analysis) are discussed in the text.

This proposed technique, because of the standard (sand culture "meter stick"), is capable of relative quantitative comparisons. As such it is of aid to ecological investigations concerned with identifying and evaluating the soil nutrient changes that invariably accompany natural forest succession or conversion by artificial means. Several modifications tending to simplify the method, *i.e.,* growing reference species in the field in a natural soil profile thus eliminating the pots, are suggested.

COMMENT

By the use of pot culture tests such as have been described in this paper our knowledge of the seedling stages of tree species can be advanced greatly. In such work none of the factors of the environment can be ignored. The investigator may be concerned with the effect of only a single variable: the concentration of one of the several nutrient elements, radiation, the soil temperature, air temperature or relative humidity. Yet neglect to key the other measurable factors into the structure may make it impossible to account for failure to duplicate the results of successive experiments.

In the description of these experiments the reader may have observed the omission of the factors of soil and air temperature. Records of these were made. But good agreement between two years' experiments on the basis of radiation equality indicates that sufficient precision was thus obtained.

Seedlings of approximately the same size remove from the growth medium very nearly the same amounts of nutrients. The factor of radiation exerts the primary control on the use of the food-forming elements supplied. In the case of Scots pine, increasing the radiation from half value to full "light" increases by one-fourth the dry weight reached at the end of three months. In the case of two trials with white pine, equal weights were attained when the cumulative energies received during the two growth periods in successive years were equal.

As the supply of nitrogen is increased the dry weight increases until an optimum is reached at an identical external supply for the two species. But the increase in dry weight is smaller for sequential equal increments of available nitrogen. The law of diminishing return applies. It seems that this is also true of radiation under certain conditions—speaking with caution because there is some evidence of an interplay between temperature and radiation.

With the basic conditions thus adjusted tree seedlings reveal a mathematically exact response to environmental changes. For a science maturity is reached when it can pass from qualitative statement of cause and effect to quantitative prediction. Such is in prospect for tree seedling physiology. Whether or not this can be said more generally of plant physiology is an open question; it may well be that the physiological reactions of coniferous seedlings are more uniform than those of the annual crop plants. Or food reserves in coniferous seeds may be more uniform in composition than in seeds of annuals. Another contribution to the advantage in the use of conifers is that the seedlings are not influenced by a change to fruiting metabolism in their annual development. The prolonged vegetational period permits the more precise summation of the environmental effects.

From the accumulated data on many species, to which this paper makes an initial contribution, it will be possible to extract values for the efficiencies which characterize the use of radiation and nutrients by the various important tree seedlings. The same problem in older trees can be similarly approached, and the science of silvics will become the more precise.

By the discriminating use of information thus acquired the problem of forest site quality can be solved for its chemical aspects. In this paper such application has been made.

A method of detecting changes in the fertility of forest soil can well be more difficult than the measurement of the deficiencies of an agricultural soil. In the latter case approximate information will serve as a guide for the correction of nutrient defects. But in forest soils the method must reveal untoward changes or tendencies to improvement. The problem is complicated by the probable influence of mycorrhizal activities. Modification of weathering and base-exchange properties by the complex of biological activities is certain. For the integration of these influences nothing less than a biological response will be satisfactory for a standard.

The response of white pine seedlings as the "reactors" ("indicators") in this study indicates that irrespective of the other factors of site quality the soils of the Black Rock Forest are deficient in available phosphorus. Relative ratings of the availability of the nitrogen in soils from sample areas in four of the chief forest types indicate wide variation in the availability of nitrogen.

P. R. GAST.

APPENDICES

Appendix I

Tables 1 to 23

TABLE 1

NITROGEN SERIES NUTRIENT TREATMENT AND APPLICATION SCHEDULE
1932 SAND CULTURE EXPERIMENT

Basic Nutrient Solution Supplied to all Pots in Nitrogen Series

Source	*Milligrams of Source per Liter*	*Milligrams per Pot (3.5 Liters)*	*Concentration of Nutrient Elements in p.p.m. (Milligrams per Liter)*					
			P	K	Ca	S	Fe	Mg
KH_2PO_4	1112.0	3892.0	**253.4**	**319.4**	....	....	....	....
$MgSO_4 \cdot 7H_2O$	1780.0	6230.0	....	....	....	**231.5**	....	**175.6**
$CaCl_2 \cdot 2H_2O$	1335.0	4672.5	....	....	**363.8**	....	....	....
Ferric Citrate	20.0	70.0	....	....	....	....	**3.4**	....

Nitrogen Concentrations Used

Nitrogen Concentration p.p.m.	*Source*	*Milligrams of Source per Liter*	*Milligrams per Pot*[1] *(3.5 Liters)*
0	NH_4NO_3	0	0
12.94	"	36.97	129.39
88.27	"	252.20	882.70
219.39	"	626.84	2,193.94
425.90	"	1,216.88	4,259.08
838.88	"	2,396.84	8,388.94
1,238.98	"	3,540.01	12,390.03
1,664.88	"	4,756.89	16,649.11
2,077.87	"	5,936.89	20,779.11
2,490.85	"	7,116.85	24,908.97
2,903.87	"	8,296.94	29,039.29[1]

TABLE 1—*(Continued)*

Nitrogen Application Schedule[2]

Final Nitrogen Concentrations in p.p.m. to be Attained	0	**12.94**	**88.27**	**219.39**	**425.90**	**838.88**	**1238.98**	**1664.88**	**2077.87**	**2490.85**	**2903.87**[4]
Milligrams of NH_4NO_3 per Application											
Application No. 1[3]		77.96	77.96	77.96	77.96	77.96	77.96	77.96	77.96	77.96	77.96
No. 2			753.31	753.31	753.31	753.31	753.31	753.31	753.31	753.31	753.31
No. 3				1311.24	1311.24	1311.24	1311.24	1311.24	1311.24	1311.24	1311.24
No. 4					2065.14	2065.14	2065.14	2065.14	2065.14	2065.14	2065.14
No. 5						4129.86	4129.86	4129.86	4129.86	4129.86	4129.86
No. 6							4001.09	4001.09	4001.09	4001.09	4001.09
No. 7								4259.08	4259.08	4259.08	4259.08
No. 8									4130.00	4130.00	4130.00
No. 9										4129.86	4129.86
No. 10											4130.22
Total[1]											28987.86

[1] The totals of the columns in the application schedule + 51.43 should check with those values.

[2] Applications made at three day intervals.

[3] The sand used contained nitrogen equivalent to 51.43 mg. of NH_4NO_3 and this amount has been subtracted in each case from application No. 1. Acid bleached sand was used for the zero nitrogen treatment.

[4] Figures beyond those significant are retained in all tables for convenience in machine calculation.

TABLE 2

KEY TO SOIL CULTURE NUTRIENT TREATMENTS
1932 EXPERIMENT

Nutrient Treatment	*Source*	*Milligrams of Source*[1] *per Liter*	*Concentration of Nutrient Elements in p.p.m. (Milligrams per Liter)*						
			P	K	N	Ca	S	Fe	Mg
Basic Nutrient—N	KH_2PO_4	1112.0	253.4	319.4	....	....	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	$CaCl_2 \cdot 2H_2O$	1335.0	....	....	....	363.8	....	. .	....
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals[2]		253.4	319.4	×	363.8	231.5	3.4	175.6
Basic Nutrient—N-K	H_3PO_4	800.8	253.4	....	....	....	....	. .	....
	$Ca(OH)_2$	907.4	....	....	....	490.6	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals		253.4	×	×	490.6	231.5	3.4	175.6
Basic Nutrient—N-P	K_2CO_3	565.8	....	319.4	....	....	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	$CaCl_2 \cdot 2H_2O$	1335.0	....	....	....	363.8	....	. .	....
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals		×	319.4	×	363.8	231.5	3.4	175.6
Basic Nutrient—N-Ca	KH_2PO_4	1112.0	253.4	319.4	....	....	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals		253.4	319.4	×	×	231.5	3.4	175.6
Basic Nutrient	NH_4NO_3	276.5	....	....	96.8	....	....	. .	....
	KH_2PO_4	1112.0	253.4	319.4	....	....	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	$CaCl_2 \cdot 2H_2O$	1335.0	....	....	....	363.8	....	. .	....
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals		253.4	319.4	96.8	363.8	231.5	3.4	175.6
Basic Nutrient+N_1	NH_4NO_3	276.5	....	....	96.8	....	....	. .	....
	NH_4NO_3	276.5	....	....	96.8	....	....	. .	....
	KH_2PO_4	1112.0	253.4	319.4	....	....	....	. .	....
	$MgSO_4 \cdot 7H_2O$	1780.0	....	....	....	....	231.5	. .	175.6
	$CaCl_2 \cdot 2H_2O$	1335.0	....	....	....	363.8	....	. .	....
	Ferric Citrate	20.0	....	....	....	....	....	3.4	....
	Totals		253.4	319.4	193.6	363.8	231.5	3.4	175.6

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[1] Only one liter of solution used in Soil Culture.

[2] The total concentration of each nutrient element remains constant throughout the various treatments unless omitted or increased as stated under "Nutrient Treatment." One exception is the increased calcium concentration in treatment Basic Nutrient—N-K.

TABLE 3

PHOSPHORUS SERIES NUTRIENT TREATMENT 1933 SAND CULTURE EXPERIMENT

Phosphorus Concentration in p.p.m.	*Source*	*Milligrams of Source per Liter*[3]	*Milligrams of Source per Pot*[3] *(4.5 Liters)*	*Hydrogen Ion*[1] *Concentration of Sand Culture Solutions (pH)*	*Concentration of Nutrient Elements in p.p.m. (Milligrams per Liter)*[3]						
					P	K	N	Ca	S	Fe	Mg
0	KCl	609.00	2740.05	5.50	....	319.37	....	....	....	...	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals[2]	**X**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
50	KH_2PO_4	219.43	987.43	5.44	50.00	63.02	....	....	....	...	....
	KCl	488.83	2199.73		....	256.35	....	....	....	...	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**50.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
100	KH_2PO_4	438.87	1974.91	5.53	100.00	126.04	....	....	....	...	....
	KCl	368.66	1658.97		....	193.33	....	....	....	...	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**100.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
200	KH_2PO_4	877.77	3949.96	5.14	200.00	252.10	....	....	....	...	....
	KCl	128.27	577.21		....	67.27	....	....	....	...	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**200.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
300	KH_2PO_4	1111.98	5003.91	5.40	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	173.08	778.86		46.63	....	21.07	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	177.56	799.02		....	....	21.07	30.13	....	...	....
	NH_4NO_3	736.75	3315.37		....	....	257.86	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	1170.28	5266.26		....	....	....	214.09	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**300.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
400	KH_2PO_4	1111.98	5003.91	5.00	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	544.27	2449.21		146.63	....	66.26	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	558.41	2512.84		....	....	66.26	94.77	....	...	....
	NH_4NO_3	478.52	2153.34		....	....	167.48	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	816.94	3676.23		....	....	....	149.45	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**400.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
500	KH_2PO_4	1111.98	5003.91	5.21	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	915.46	4119.57		246.63	....	111.46	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	939.33	4226.98		....	....	111.46	159.43	....	...	....
	NH_4NO_3	220.23	991.03		....	....	77.08	....	....	...	....
	$CaCl_2 \cdot 6H_2O$	463.48	2085.66		....	....	....	84.79	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**500.00**	**319.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
600	KH_2PO_4	1111.98	5003.91	4.94	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	1286.65	5789.92		346.63	....	156.65	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	1320.17	5940.76		....	....	156.65	224.07	....	...	....
	$CaCl_2 \cdot 6H_2O$	110.14	495.63		....	....	....	20.15	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**600.00**	**319.37**	**313.30**	**244.22**	**231.50**	**3.40**	**175.60**
700	KH_2PO_4	1111.98	5003.91	4.49	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	1286.65	5789.92		346.63	....	156.65	....	....	...	....
	H_3PO_4	316.08	1422.36		100.00	....	....	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	1320.17	5940.76		....	....	156.65	224.07	....	...	....
	$CaCl_2 \cdot 6H_2O$	110.14	495.63		....	....	....	20.15	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**700.00**	**319.37**	**313.30**	**244.22**	**231.50**	**3.40**	**175.60**
800	KH_2PO_4	1111.98	5003.91	3.23	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	1286.65	5789.92		346.63	....	156.65	....	....	...	....
	H_3PO_4	632.16	2844.72		200.00	....	....	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	1320.17	5940.76		....	....	156.65	224.07	....	...	....
	$CaCl_2 \cdot 6H_2O$	110.14	495.63		....	....	....	20.15	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**800.00**	**319.37**	**313.30**	**244.22**	**231.50**	**3.40**	**175.60**
900	KH_2PO_4	1111.98	5003.91	3.08	253.37	319.37	....	....	....	...	....
	$NH_4H_2PO_4$	1286.65	5789.92		346.63	....	156.65	....	....	...	....
	H_3PO_4	948.24	4267.08		300.00	....	....	....	....	...	....
	$Ca(NO_3)_2 \cdot 4H_2O$	1320.17	5940.76		....	....	156.65	224.07	....	...	....
	$CaCl_2 \cdot 6H_2O$	110.14	495.63		....	....	....	20.15	....	...	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	...	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**900.00**	**319.37**	**313.30**	**244.22**	**231.50**	**3.40**	**175.60**

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[1] Average of check solutions.

[2] Except for a slight increase in nitrogen (starting at treatment 600 p.p.m. P) the total concentration of each nutrient element other than phosphorus, which is aried, remains constant throughout the series.

[3] Figures beyond those significant retained for convenience in machine calculation.

TABLE 4

Potassium Series Nutrient Treatment 1933 Sand Culture Experiment

Potassium Concentration in p.p.m.	Source	Milligrams of Source per Liter[3]	Milligrams of Source per Pot[3] (4.5 Liters)	Hydrogen Ion[1] Concentration of Sand Culture Solutions (pH)	Concentration of Nutrient Elements in p.p.m. (Milligrams per Liter)[3]						
					K	P	N	Ca	S	Fe	Mg
0	$NH_4H_2PO_4$	940.48	4232.16	5.20	....	253.37	114.50	....	....	....	....
	$Ca(NO_3)_2 \cdot 4H_2O$	964.95	4342.27		....	....	114.50	163.78	....	....	....
	NH_4NO_3	202.86	912.87		....	....	71.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	439.71	1978.69		....	....	....	80.44	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals[2]	**X**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
50	KCl	95.34	429.03	5.20	50.00	....	....	....	....	....	....
	$NH_4H_2PO_4$	940.48	4232.16		....	253.37	114.50	....	....	....	....
	$Ca(NO_3)_2 \cdot 4H_2O$	964.95	4342.27		....	....	114.50	163.78	....	....	....
	NH_4NO_3	202.86	912.87		....	....	71.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	439.71	1978.69		....	....	....	80.44	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**50.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
100	KCl	190.69	858.10	5.20	100.00	....	....	....	....	....	....
	$NH_4H_2PO_4$	940.48	4232.16		....	253.37	114.50	....	....	....	....
	$Ca(NO_3)_2 \cdot 4H_2O$	964.95	4342.27		....	....	114.50	163.78	....	....	....
	NH_4NO_3	202.86	912.87		....	....	71.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	439.71	1978.69		....	....	....	80.44	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**100.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
200	KCl	381.38	1716.21	5.33	200.00	....	....	....	....	....	....
	$NH_4H_2PO_4$	940.48	4232.16		....	253.37	114.50	....	....	....	....
	$Ca(NO_3)_2 \cdot 4H_2O$	964.95	4342.27		....	....	114.50	163.78	....	....	....
	NH_4NO_3	202.86	912.87		....	....	71.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	439.71	1978.69		....	....	....	80.44	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**200.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
319.37	KH_2PO_4	1111.98	5003.91	5.36	319.37	253.37	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**319.37**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
400	KH_2PO_4	1111.98	5003.91	5.23	319.37	253.37	....	....	....	....	....
	KCl	153.75	691.87		80.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**400.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
500	KH_2PO_4	1111.98	5003.91	5.38	319.37	253.37	....	....	....	....	....
	KCl	344.44	1549.98		180.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**500.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
600	KH_2PO_4	1111.98	5003.91	5.03	319.37	253.37	....	....	....	....	....
	KCl	535.13	2408.08		280.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**600.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
700	KH_2PO_4	1111.98	5003.91	5.47	319.37	253.37	....	....	....	....	....
	KCl	725.82	3266.19		380.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**700.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
800	KH_2PO_4	1111.98	5003.91	5.38	319.37	253.37	....	....	....	....	....
	KCl	916.51	4124.29		480.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**800.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**
900	KH_2PO_4	1111.98	5003.91	5.47	319.37	253.37	....	....	....	....	....
	KCl	1107.20	4982.40		580.63	....	....	....	....	....	....
	NH_4NO_3	857.16	3857.22		....	....	300.00	....	....	....	....
	$CaCl_2 \cdot 6H_2O$	1334.98	6007.41		....	....	....	244.22	....	....	....
	$MgSO_4 \cdot 7H_2O$	1780.00	8010.00		....	....	....	....	231.50	....	175.60
	Ferric Citrate	20.00	90.00		....	....	....	....	....	3.40	....
				Totals	**900.00**	**253.37**	**300.00**	**244.22**	**231.50**	**3.40**	**175.60**

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[1] Average of check solutions.

[2] The total concentration of each nutrient element except potassium, which is varied, remains constant throughout the series.

[3] Figures beyond those significant retained for convenience in machine calculation.

TABLE 5

Dry Weights and Nitrogen Contents of Scots Pine Seedlings from Sand Cultures with Varied Nitrogen Supplies

1931 Experiment

Nitrogen Concentration in p.p.m.	*Nitrogen Supply in Mg. per Seedling*	*Average Dry Weight of Seedlings*	*No.[1] of Seedlings*	*Seed Size Used*	*Dry Weights Corrected as of Seed Size 5*	*Nitrogen Content in % of Dry Weight (N %)*	*Nitrogen Content [4] in Total Milligrams (Np)*
			Full Light				
0	0	**41.6[2]±[5]0.5**	24	6	**37.3**	0.66±.02[5]	0.24
		37.6[3]± 0.6	22	5	37.6	0.64±.05	0.24
96.8	7.5	**213.7±10.4**	24	7	**173.5**	1.29±.03	2.24
		204.4± 9.6	24	7	165.9	1.09±.03	1.81
193.6	15.0	**299.4±15.2**	21	5	**299.4**	2.15±.03	6.44
		216.4±14.3	16	7	175.7	2.17±.07	3.81
387.2	30.0	**261.5±12.6**	18	4	**295.5**	3.75±.05	11.08
		190.4±17.6	24	5	190.4	2.76±.05	5.25
			Half Light				
0	0	**40.9± 0.5**	25	6	**36.6**	0.64±.03	0.23
		44.9± 0.8	26	7	36.4	0.54±.02	0.19
96.8	7.5	**206.6± 9.4**	23	7	**167.7**	1.49±.05	2.50
		186.5± 8.6	25	7	151.4	1.42±.02	2.15
193.6	15.0	**198.0± 3.5**	18	4	**223.7**	2.90±.02	6.48
		159.3± 5.0	21	6	142.7	2.09±.05	2.98
387.2	30.0	**263.4±10.1**	23		**236.0**	2.79±.13	6.58
		131.5±11.7	22	5	131.5	2.70±.17	3.55

[1] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.

[2] Continuously dilute solutions; these are the "**yield**" values used.

[3] Temporarily concentrated solutions.

[4] $N_p = \text{Mg. dry wt.} \times N_{\%}$.

[5] Standard error of mean.

TABLE 6

PHOSPHORUS APPLICATION SCHEDULE, PHOSPHORUS SERIES, 1933 SAND CULTURE EXPERIMENT[1]

Phosphorus Concentration p.p.m.	0	50	100	200	300	400	500	600	700	800	900	Source
Milligrams of Source per Application												
Application No. 1[2]		987.43[3]	987.43	987.43	987.43	987.43	987.43	987.43	987.43	987.43	987.43	KH_2PO_4
		No. 2	987.43	987.43	987.43	987.43	987.43	987.43	987.43	987.43	987.43	KH_2PO_4
			No. 3	1974.91	1974.91	1974.91	1974.91	1974.91	1974.91	1974.91	1974.91	KH_2PO_4
				No. 4	1053.95 778.86	1053.95 778.86	1053.95 778.86	1053.95 778.86	1053.95 778.86	1053.95 778.86	1053.95 778.86	KH_2PO_4 $NH_4H_2PO_4$
					No. 5	1670.36	1670.36	1670.36	1670.36	1670.36	1670.36	$NH_4H_2PO_4$
						No. 6	1670.36	1670.36	1670.36	1670.36	1670.36	$NH_4H_2PO_4$
							No. 7	1670.36	1670.36	1670.36	1670.36	$NH_4H_2PO_4$
								No. 8	1422.36	1422.36	1422.36	H_3PO_4
									No. 9	1422.36	1422.36	H_3PO_4
										No. 10	1422.36	H_3PO_4

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[1] The concentrations of all other nutrient elements were stepped up in a similar manner, corrections being made for the quantities of nitrogen and potassium taken care of in this schedule.

[2] Applications made at four day intervals.

[3] Figures beyond those significant are retained for convenience in machine calculation.

TABLE 7

DRY WEIGHTS, NITROGEN CONTENTS AND ROOT-SHOOT RATIO OF WHITE PINE SEEDLINGS FROM SOIL CULTURES WITH VARIED NUTRIENT TREATMENT

1932 EXPERIMENT

Ridge Soil

Nutrient Treatment	*Hydrogen Ion Concentration of Soil Solution (pH)*	*Average Dry Weight of Seedlings* [1]	*Root/Shoot Ratio*	*No. of Seedlings* [2]	*Seed Class Used*	*Dry Weights Corrected as of Seed Class 5*	*Dry Weights of Seedlings, Average of Duplicate Pots*	*Nitrogen Content of Seedlings as % of Dry Weight*	*% Nitrogen Average of Duplicate Pots*	*Nitrogen Content of Seedlings in Total Milligrams*	*Total Nitrogen Average of Duplicate Pots*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
Basic Nutrient—N	4.58	203.3±4.37[3] 218.9±8.74	0.712 0.890	22 21	4 4	211.0 227.3	219.1	1.091±0.049[3] 1.081±0.026	1.085	2.302 2.457	2.38
Basic Nutrient—N-K	5.37	219.9±6.75 199.4±5.19	0.860 0.924	25 23	4 4	228.3 207.0	217.6	1.090±0.025 1.072±0.037	1.081	2.488 2.218	2.35
Basic Nutrient—N-P	4.56	175.3±5.16 197.4±6.84	0.674 0.771	26 24	3 2	189.1 221.7	205.2	1.204±0.030 1.126±0.026	1.165	2.277 2.496	2.39
Basic Nutrient—N-Ca	...	218.8±3.83 225.1±7.56	0.878 0.847	26 26	2 2	245.7 252.8	249.3	1.210±0.025 1.111±0.042	1.160	2.973 2.808	2.89
Distilled Water Only	...	203.5±7.04 209.4±5.27	0.963 0.866	26 25	2 3	228.5 225.9	227.2	1.196±0.031 1.109±0.024	1.152	2.733 2.505	2.62
Basic Nutrient	...	214.6±5.23 220.9±7.14	0.773 0.666	20 23	3 3	231.5 238.4	234.9	1.410±0.060 1.411±0.026	1.410	3.264 3.362	3.31
Basic Nutrient+N_1	...	244.0±5.99 244.8±9.39	0.783 0.722	24 23	3 3	263.2 264.1	263.7	1.549±0.025 1.563±0.147	1.556	4.077 4.128	4.10

[1] All dry weights in milligrams.

[2] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.

[3] Standard error of mean.

TABLE 8

DRY WEIGHTS, NITROGEN CONTENTS AND ROOT-SHOOT RATIO OF WHITE PINE SEEDLINGS FROM SOIL CULTURES WITH VARIED NUTRIENT TREATMENT
1932 EXPERIMENT

Mid Slope (Poor) Soil

Nutrient Treatment	*Hydrogen Ion Concentration of Soil Solution (pH)*	*Average Dry Weight of Seedlings*[1]	*Root/Shoot Ratio*	*No. of Seedlings*[2]	*Seed Class Used*	*Dry Weights Corrected as of Seed Class 5*	*Dry Weights of Seedlings. Average of Duplicate Pots*	*Nitrogen Content of Seedlings as % of Dry Weight*	*% Nitrogen. Average of Duplicate Pots*	*Nitrogen Content of Seedlings in Total Milligrams*	*Total Nitrogen. Average of Duplicate Pots*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
Basic Nutrient—N	. . .	258.3±14.41[3] 260.9±9.53	0.880 0.804	26 25	4 4	268.1 270.8	**269.5**	1.257±0.055[3] 1.278±0.044	**1.267**	3.370 3.461	**3.41**
Basic Nutrient—N-K	. . .	249.2±6.12 259.7±6.48	0.689 0.811	23 23	4 4	258.6 269.5	**264.1**	1.453±0.032 1.343±0.061	**1.398**	3.757 3.619	**3.69**
Basic Nutrient—N-P	. . .	201.4±5.46 213.3±6.84	0.735 0.778	23 25	3 3	217.3 230.2	**223.7**	1.315±0.012 1.322±0.047	**1.318**	2.857 3.043	**2.95**
Basic Nutrient—N-Ca	. . .	252.6±9.75 239.3±8.47	0.872 0.876	24 23	3 2	272.6 268.7	**270.6**	1.262±0.035 1.145±0.061	**1.203**	3.440 3.076	**3.25**
Distilled Water Only	. . .	218.3±3.93 207.7±6.54	0.815 0.795	26 26	3 2	235.5 233.3	**234.4**	1.455±0.077 1.488±0.027	**1.471**	3.426 3.471	**3.45**
Basic Nutrient	. . .	223.0±4.77 269.2±8.55	0.691 0.822	19 19	3 2	240.6 302.3	**271.4**	1.714±0.070 1.722±0.016	**1.716**	4.124 5.205	**4.66**
Basic Nutrient+N_1	. . .	245.8±8.34 259.8±11.78	0.748 0.698	24 22	3 2	265.2 291.7	**278.5**	1.552±0.030 1.849±0.102	**1.700**	4.116 5.393	**4.73**

[1] All dry weights in milligrams.
[2] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.
[3] Standard error of mean.

TABLE 9

DRY WEIGHTS, NITROGEN CONTENTS AND ROOT-SHOOT RATIO OF WHITE PINE SEEDLINGS FROM SOIL CULTURES WITH VARIED NUTRIENT TREATMENT

1932 EXPERIMENT

Mid Slope (Good) Soil

Nutrient Treatment	*Hydrogen Ion Concentration of Soil Solution (pH)*	*Average Dry Weight of Seedlings* [1]	*Root/Shoot Ratio*	*No. of Seedlings* [2]	*Seed Class Used*	*Dry Weights Corrected as of Seed Class 5*	*Dry Weights of Seedlings. Average of Duplicate Pots*	*Nitrogen Content of Seedlings as % of Dry Weight*	*% Nitrogen. Average of Duplicate Pots*	*Nitrogen Content of Seedlings in Total Milligrams*	*Total Nitrogen. Average of Duplicate Pots*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
Basic Nutrient—N	5.30	.... 260.9±8.00[3]	.... 0.940	.. 20	.. 4	.... 270.8	270.8	.... 1.216±0.020[3]	.... 1.216	.... 3.293	3.29
Basic Nutrient—N-K	6.38	240.1±7.16 255.6±9.31	0.872 0.978	21 19	4 4	249.2 265.3	257.3	1.301±0.022 1.203±0.036	1.252	3.242 3.198	3.22
Basic Nutrient—N-P	5.15	212.4±3.63 208.1±5.36	0.827 0.828	21 24	4 3	220.5 224.5	222.5	1.322±0.032 1.337±0.018	1.329	2.915 3.001	2.96
Basic Nutrient—N-Ca	...	244.6±8.24 238.6±10.69	0.929 0.916	22 26	4 3	253.9 257.5	255.7	1.077±0.017 1.079±0.032	1.078	2.734 2.778	2.76
Distilled Water Only	5.49	218.1±3.39 212.5±1.19	0.865 0.845	22 19	4 3	226.4 229.3	227.8	1.226±0.041 1.289±0.042	1.257	2.775 2.955	2.86
Basic Nutrient	5.24	245.3±7.54 270.8±11.29	0.750 0.781	18 21	3 3	264.7 292.2	278.4	1.791±0.039 1.673±0.065	1.732	4.741 4.888	4.82
Basic Nutrient+N_1	...	270.8±9.42 273.6±7.71	0.765 0.891	26 25	2 2	304.2 307.2	305.7	1.782±0.056 1.827±0.033	1.804	5.421 5.612	5.51

[1] All dry weights in milligrams.

[2] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.

[3] Standard error of mean.

TABLE 10

DRY WEIGHTS, NITROGEN CONTENTS AND ROOT-SHOOT RATIO OF WHITE PINE SEEDLINGS FROM SOIL CULTURES WITH VARIED NUTRIENT TREATMENT

1932 EXPERIMENT

Cove Soil

Nutrient Treatment (1)	*Hydrogen Ion Concentration of Soil Solution (pH)* (2)	*Average Dry Weight of Seedlings*[1] (3)	$\frac{\textit{Root}}{\textit{Shoot}}$ *Ratio* (4)	*No. of Seedlings*[2] (5)	*Seed Class Used* (6)	*Dry Weights Corrected as of Seed Class 5* (7)	*Dry Weights of Seedlings. Average of Duplicate Pots* (8)	*Nitrogen Content of Seedlings as % of Dry Weight* (9)	*% Nitrogen. Average of Duplicate Pots* (10)	*Nitrogen Content of Seedlings in Total Milligrams* (11)	*Total Nitrogen. Average of Duplicate Pots* (12)
Basic Nutrient—N	4.97	258.7±10.14[3] 261.3±9.83	0.722 0.828	19 25	4 4	268.5 271.3	**269.9**	1.673±0.014[3] 1.476±0.071	**1.574**	4.492 4.004	**4.25**
Basic Nutrient—N-K	5.07	275.9±9.46 266.1±10.29	0.746 0.838	21 19	4 4	286.4 276.2	**281.3**	1.614±0.065 1.769±0.040	**1.691**	4.622 4.886	**4.76**
Basic Nutrient—N-P	5.04	184.9±4.02 186.6±4.40	0.700 0.666	23 25	2 3	207.7 201.4	**204.5**	1.808±0.045 1.829±0.030	**1.818**	3.755 3.683	**3.72**
Basic Nutrient—N-Ca	...	.... 264.7±9.32	.... 0.975	.. 22	.. 3	.... 285.6	**285.6**	.... 1.379±0.011	**1.379**	.... 3.938	**3.94**
Distilled Water Only	...	215.0±5.02 210.7±3.82	0.849 0.745	26 17	2 3	241.5 227.3	**234.4**	1.648±0.026 1.697±0.045	**1.672**	3.979 3.857	**3.92**
Basic Nutrient	...	243.6±15.18 260.6±10.43	0.703 0.792	19 21	2 3	273.6 281.2	**277.4**	1.845±0.048 1.900±0.026	**1.872**	5.048 5.343	**5.19**
Basic Nutrient+N_1	...	266.2±17.44 262.7±9.39	0.727 0.777	20 21	2 3	298.9 283.5	**292.2**	2.111±0.018 2.055±0.024	**2.083**	6.309 5.823	**6.08**

[1] All dry weights in milligrams.
[2] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.
[3] Standard error of mean.

TABLE 11

Hydrogen-ion Concentration Variations
1933 Sand Culture Nitrogen Series

Nitrogen Concentration of Sand Nutrient Solution in p.p.m. N.	*Hydrogen-ion Concentration of Solutions (pH).*
0	5.28
25	5.45
50	5.50
75	5.57
100	5.52
200	5.33
250	5.59
300	5.59
400	5.45

TABLE 12

Radiation Available to Plants, Recorded by an Eppley Weather Bureau Thermoelectric Pyrheliometer (Plane Type) from July 25 to October 15, 1931

	Control in open	*Full Light Pit*	*Half Light Pit*
		gram calories per cm²	
Total for 83 days	30,204.5	25,605.3	14,407.2
Average per day	363.9	308.4	173.5
Maximum per day	719.1	594.2	359.5
Minimum per day	43.8	23.4	13.1
Standard deviation	141.2	136.6	81.2
Percent of open for 83 days		84.7	47.7
Percent of full for 83 days			56.2

TABLE 13

Total Radiation in Gram Calories per Square Centimeter by Months

	June	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*
1932[1]	14,549	17,613	14,584	11,339	6,720	4,967
1933[1]	15,766	14,637	11,535	9,418	8,248	4,502
Average[2] for past 8 years.	12,672	12,801	10,536	9,003	6,540	3,799

[1] The comparative records for 1932 and 1933 are from the summaries published by the New York Weather Bureau Observatory in Central Park.

[2] The 8 year average (1925 to 1932 inclusive) was obtained through the courtesy of Dr. Arthur of the Boyce Thompson Institute, Yonkers, N. Y.

TABLE 14

DRY WEIGHTS, NITROGEN CONTENTS AND ROOT-SHOOT RATIO OF WHITE PINE SEEDLINGS FROM SAND CULTURES WITH VARIED NITROGEN CONCENTRATIONS

1932 EXPERIMENT

Nitrogen Concentration p.p.m. (N)	*Average Dry Weight of Seedlings in[1] Milligrams*	$\frac{Root}{Shoot}$ *Ratio*	*No. of Seedlings[2]*	*Seed Class Used*	*Nitrogen Content of Seedlings[4]*	
					% Dry Weight ($N_\%$)	*Total Milligrams* (N_p)[3]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0	115.2 ±[5] 3.62	0.784	25	5	0.72 ± 0.012[5]	0.83
12.94	147.8 ± 3.59	0.810	27	5	0.81 ± 0.013	1.20
88.27	299.6 ± 13.01 276.8 ± 18.13	0.780 0.739	18 17	5 5	1.77 ± 0.093 1.87 ± 0.020	5.30 5.18
219.39	379.9 ± 12.08	0.640	24	5	2.71 ± 0.035	10.29
425.90	363.7 ± 14.41 351.9 ± 19.98	0.415 0.453	18 17	5 5	3.69 ± 0.026 3.63 ± 0.070	13.42 12.77
838.88	308.2 ± 15.44 273.3 ± 9.37	0.309 0.336	22 22	5 5	4.53 ± 0.190 4.42 ± 0.219	13.96 12.08
1238.98	234.4 ± 6.51	0.277	18	5	4.49 ± 0.047	10.52
1664.88	215.8 ± 18.96 231.3 ± 12.73	0.283 0.286	11 18	5 5	4.51 ± 0.067 4.19 ± 0.036	9.73 9.69
2077.87	174.8 ± 9.96	0.248	19	5	4.50 ± 0.075	7.86
2490.85	134.2 ± 12.23	0.221	12	5	4.87 ± 0.100	6.53

[1] No correction for seed size necessary. All from size 5 seeds (column 5).

[2] Number of harvested seedlings after discarding those whose weights deviated from the mean by more than 3 × stand. dev.

[3] Mg. dry wt. × $N_\%$ = N_p.

[4] Based on individual analysis of from 4 to 12 seedlings from each pot.

[5] Standard error of mean.

TABLE 15

Check on Accuracy of the Method for Nitrogen Determination

Sample Number	*Dry Weight of Sample in Milligrams*	*Milligrams of Nitrogen*	*Per Cent of Dry Weight*
1	28.5	0.19	0.65
2	31.6	0.22	0.68
3	31.8	0.22	0.67
4	38.7	0.26	0.66
5	38.9	0.25	0.64
6	46.9	0.31	0.65
7	47.8	0.31	0.64
8	76.3	0.49	0.64

Mean = 0.654
Standard Dev. = ±0.016

TABLE 16

Nitrogen Content of the Four Soils by Chemical Analysis

Milligrams of Nitrogen per Kilogram of Soil (Air dry basis)

Nitrogen as:	*Cove Soil*	*Mid-Slope (good) Soil*	*Mid-Slope (poor) Soil*	*Ridge Soil*
Ammonia	210	50	156	113
Organic Nitrogen	3,311	1,170	1,612	1,707
Nitrates and Nitrites	274	315	206	195
Total Nitrogen	3,795	1,535	1,974	2,015
The Various Forms of Nitrogen as Percent of Total Nitrogen				
Ammonia	5.53	3.26	7.90	5.61
Organic Nitrogen	87.25	76.22	81.66	84.71
Nitrates and Nitrites	7.22	20.52	10.44	9.68
Total Nitrogen	100.00	100.00	100.00	100.00

TABLE 17

THE AVERAGE DRY WEIGHT OF SEEDS, SEED COATS AND FOOD MATERIAL IN SEEDS FROM THE VARIOUS FRESH WEIGHT CLASSES, AND OF SEEDLINGS FROM SEEDS OF VARYING FOOD CONTENT

1932 EXPERIMENT

Seed Class	*Ave. Fresh Wt. of Class in Mg.*	*Ave. Dry Wt. of Seed Coats in Mg.*		*Ratio*	*Ave. Dry Wt. of Seeds in Mg.*		*Ave. Dry Wt. of Food Material in Seeds* [2] (7)—(4)=	*Ave. Dry Wt. of Seedlings in Mg.* [3]		*Correction* [5] *Factors*
		Determined by Experiment	*Estimated from Regression Equation*	$\frac{(4)}{(7)}\times 100$	*Determined by Experiment*	*Estimated from Regression Equation*		*Determined by Experiment*	*Estimated from Regression Equation* [4]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
0	20.5	6.75±0.028[1]	6.62	34.7	18.88±0.058[1]	19.05	12.43	....	66.07	1.22
1	21.5	7.06±0.038	6.95	34.9	19.78±0.046	19.89	12.94	....	69.03	1.17
2	22.5	7.20±0.021	7.29	35.2	20.90±0.047	20.73	13.44	71.83±0.53[1]	71.93	1.12
3	23.5	7.40±0.030	7.62	35.3	21.74±0.069	21.57	13.95	75.62±0.93	74.89	1.08
4	24.5	7.68±0.043	7.96	35.5	22.60±0.023	22.42	14.46	78.67±0.84	77.85	1.04
5	25.5	8.55±0.037	8.29	35.6	23.52±0.110	23.26	14.97	79.82±1.03	80.81	1.00
6	26.5	8.83±0.050	8.63	35.8	24.07±0.090	24.10	15.47	....	83.71	0.96
7	27.5	8.71±0.080	8.96	35.9	24.77±0.110	24.94	15.98	....	86.67	0.93
8	28.5	9.44±0.102	9.30	36.1	25.71±0.210	25.78	16.48	....	89.57	0.90

[1] Standard error of mean.

[2] Dry weight of seed less dry weight of seed coat is taken as a measure of the quantity of food in the seed.

[3] Grown for 51 days in washed sand receiving no nutrients.

[4] The average relation between the dry weight of the food material in the seed and the dry weight of the resulting seedling.

[5] Factors for converting the weights of seedlings from seeds of various size to a weight equivalent to seedlings from seed class 5.

TABLE 18

CALCULATED COMPARED WITH EXPERIMENTALLY DETERMINED YIELDS AND NITROGEN CONTENTS OF SCOTS PINE SEEDLINGS FROM SAND CULTURES WITH VARIED NITROGEN CONCENTRATIONS

1931 EXPERIMENT

Full Light

	Dry Weight of Seedlings in Mg.		*Nitrogen Content of Seedlings*			
			Per Cent of Dry Weight (N%)		*Total Milligrams (Np)*	
Nitrogen Concentration p.p.m.[1] *(N)*	*Experimentally Determined*	*Calculated*[2]	*Experimentally Determined*	*Calculated*	*Experimentally Determined*	*Calculated*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
0	37.5	37.5	0.65	0.56	0.24	0.27
50.0	....	115.4	....	0.97	....	1.12
96.8	173.5	177.7	1.29	1.35	2.24	2.44
150.0	....	233.8	....	1.79	....	4.29
193.6	299.4	268.3	2.15	2.15	6.44	6.04[3]
250.0	....	296.1	....	2.61	....	....
300.0	....	307.2	....	3.02	....	....
350.0	....	306.7	....	3.43	....	....
378.4	295.5	299.0	3.75	3.74	11.08	....

Half Light

0	36.5	36.5	0.59	0.49	0.21	0.27
50.0	....	116.3	....	1.09	....	1.27
96.8	167.7	166.6	1.49	1.64	2.50	2.65
150.0	....	203.6	....	2.29	....	4.50
193.6	223.7	222.6	2.90	2.81[3]	6.48	6.19[3]
250.0	....	236.6	....	....	....	....
300.0	....	241.7	....	....	....	....
350.0	....	242.0	....	....	....	....
378.4	236.0	239.0	2.79	....	6.58	....

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[1] The equations expressing the Scots pine relations require N in terms of milligrams nitrogen per seedling. N (p.p.m.) × 0.07748 = N (mg. per seedling '31).

[2] Mitscherlich formula; constants in App. II.

[3] Data too meagre to justify calculation beyond this point. Probable shape of curves shown in Fig. 3.

TABLE 19

CALCULATED COMPARED WITH EXPERIMENTALLY DETERMINED YIELDS AND NITROGEN CONTENTS OF WHITE PINE SEEDLINGS FROM SAND CULTURES WITH VARIED NITROGEN CONCENTRATIONS

1932 EXPERIMENT

			Nitrogen Content of Seedlings			
	Dry Weight of Seedlings in Mg.		*Per Cent of Dry Weight (N%)*		*Total Milligrams (Np)*	
Nitrogen Concentration p.p.m. (N)	*Experimentally Determined*	*Calculated*[1]	*Experimentally Determined*	*Calculated*[2]	*Experimentally Determined*	*Calculated*[3]
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
0	115.2	114.9	0.72	0.70	0.83	0.87
12.94	147.8	150.8	0.81	0.87	1.20	1.63
50.00	....	233.1	....	1.33	....	3.65
88.27	299.6 276.8	291.6 291.6	1.77 1.87	1.74 1.74	5.30 5.18	5.49 5.49
100.00	....	305.6	....	1.85	....	6.01
150.00	....	348.1	....	2.30	....	7.91
219.39	379.9	376.3	2.71	2.80	10.29	10.01
250.00	....	380.6	....	2.99	....	10.74
300.00	....	381.5	....	3.26	....	11.73
350.00	....	375.8	....	3.49	....	12.49
400.00	....	366.2	....	3.68	....	13.05
425.90	363.7 351.9	360.0 360.0	3.69 3.63	3.76 3.76	13.42 12.77	13.26 13.26
450.00	....	353.4	....	3.84	....	13.41
500.00	....	342.7	....	3.97	....	13.62
550.00	....	335.1	....	4.09	....	13.70
600.00	....	326.4	....	4.18	....	13.66
650.00	....	316.9	....	4.27	....	13.52
700.00	....	306.4	....	4.33	....	13.28
838.88	308.2 273.3	285.0 285.0	4.53 4.42	4.47 4.47	13.96 12.08	12.74 12.74
900.00	....	276.9	....	4.52	....	12.51
1238.98	234.4	245.7	4.49	4.52	10.52	11.10
1664.88	215.8 231.3	211.4 211.4	4.51 4.19	4.52 4.52	9.73 9.69	9.55 9.55
2077.87	174.8	176.2	4.50	4.52	7.86	7.96
2490.85	134.2	140.8	4.87	4.52	6.53	6.36

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[1] Calculated with Mitscherlich formula up to 450 p.p.m.N, and $\frac{Np}{N\%} \times 100 = y$ the rest of the range. See App. II for constants.

[2] Calculated with Mitscherlich formula up to 900 p.p.m.N; the remainder is a straight line parallel to the abscissa. See App. II for constants.

[3] Calculated with Mitscherlich formula up to 650 p.p.m.N; the remainder is a linear decrease. See App. II for constants.

TABLE 20

COMPARISON OF THE CALCULATED YIELDS AND NITROGEN CONTENTS OF SCOTS AND WHITE PINE SEEDLINGS FROM SAND CULTURES WITH VARIED NITROGEN CONCENTRATIONS

1931 AND 1932 EXPERIMENTS

Nitrogen Concentration p.p.m.	*Nitrogen Supply. Milligrams per Seedling '31*	*Dry Weight of Seedlings*[1] *in Mg.*		*Nitrogen Content of Seedlings*			
				Per Cent of Dry Weight		*Total Milligrams*	
		White pine	*Scots pine*	*White pine*	*Scots pine*	*White pine*	*Scots pine*
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
0	0	114.9	37.5	0.70	0.56	0.87	0.27
50	3.87	233.1	115.4	1.33	0.97	3.65	1.12
100	7.75	305.6	181.7	1.85	1.38	6.01	2.54
150	11.62	348.1	233.8	2.30	1.79	7.91	4.29
200	15.49	370.3	272.1	2.68	2.20	9.48	6.31[2]
250	19.37	380.6	296.1	2.99	2.61	10.74	
300	23.24	381.5	307.2	3.26	3.02	11.73	
350	27.12	375.8	306.7	3.49	3.43	12.49	
400	30.99	366.2	296.1	3.68	3.84	13.05	

[1] Calculated with the Mitscherlich formula, constants App. II.

[2] Data too meagre to justify calculation beyond this point. Probable shape of curve is shown in Fig. 3, B.

TABLE 21

CALCULATED COMPARED WITH EXPERIMENTALLY DETERMINED YIELDS OF SCOTS PINE SEEDLINGS GROWN IN HALF AND IN FULL LIGHT

Nitrogen Concentration p.p.m.	*Nitrogen Supply in mg. per Seedling*	*Yield in Milligrams Dry Weight*						
		Full Light				*Half Light*		
		Mitscherlich Formula	*Compound Interest Formula*	$\frac{N_p}{N\%} \times 100 = y$	*Found*	*Mitscherlich Formula*	$\frac{N_p}{N\%} \times 100 = y$	*Found*
0	0	37.5	53.5	42.8	37.5	36.5	33.3	36.5
19.3	1.5	69.1	68.7	68.0	....	71.2	94.3	....
38.7	3.0	99.2	105.4	97.9	....	100.9	127.6	....
77.4	6	153.5	161.4	154.6	....	148.2	163.8	....
96.8	7.5	177.7	185.2	180.7	173.5	166.6	175.6	167.7
116.1	9	200.0	207.2	203.3	....	182.3	186.0	....
154.9	12	239.0	247.4	244.8	....	206.1	199.1	....
193.6	15	268.3	283.8 [1]	280.9 [2]	299.4	222.6	207.4 [3]	223.7
232.3	18	289.0	....	....	....	233.1	....	....
271.0	21	302.2	....	....	....	239.2	....	....
309.7	24	307.5	....	....	....	242.1	....	....
348.4	27	306.2	....	....	....	241.0	....	....
387.2	30	299.0	....	....	295.5	239.0	....	236.0

[1] This formula derived from first three points only. No depression constant used.

[2] Np not calculated beyond this point.

[3] Neither Np nor N% calculated beyond this point at half light.

TABLE 22

TENTATIVE GROUPING OF YOUNG TREES AS TO THEIR RESPONSE TO RADIATION BASED ON PRESENT INFORMATION

Group 1		*Group 2*		*Group 3*	
Larch	(Cieslar, 1909)	Spruce	(Cieslar, 1909)	Redwood	(Shirley, 1929)
White Fir	" "	Black Fir	" "		
White Pine	(Shirley, 1932)	Loblolly Pine	(Shirley, 1929)		
Norway Pine	" "				
Jack Pine	" "				
Bur Oak	(Holch, 1931)				
Red Oak	" "				
Hickory	" "				
Linden	" "				
Walnut	" "				
White Pine	(Gast, 1930)				

TABLE 23

PERCENT NITROGEN CONTENTS OF NEEDLES COMPARED WITH PERCENT NITROGEN CONTENTS OF WHOLE PLANTS

Seedling Number	*Nitrogen % of Needles*	*Nitrogen % of Whole Seedling*		*Difference*	*Difference as % of Found*
		Predicted	*Found*		
1	1.41	1.24	1.33	0.09	0.67
2	1.54	1.30	1.37	0.07	0.41
3	1.59	1.32	1.17	0.15	12.82
4	1.66	1.36	1.26	0.10	7.93
5	1.80	1.43	1.46	0.03	0.20
6	1.83	1.44	1.35	0.09	0.66
7	1.84	1.44	1.31	0.13	9.92
8	1.94	1.49	1.53	0.04	0.26
9	2.05	1.54	1.48	0.06	0.40
10	2.11	1.57	1.57	0.00	0.00
11	2.13	1.58	1.60	0.02	0.12
12	2.30	1.66	1.60	0.06	0.37
13	2.31	1.67	2.11	0.44	20.85
14	2.35	1.68	1.83	0.15	8.19
15	2.47	1.74	1.91	0.17	8.90
16	2.55	1.78	1.66	0.12	7.22
17	2.80	1.90	1.93	0.03	0.15
18	2.85	1.92	1.63	0.29	17.79
				Mean	5.38

APPENDIX II

Statistical Treatment

Yield

THE Mitscherlich formula has been used to express the relation between nitrogen supply (N) and yield (y). The normal equation is

$$y = A \cdot (1 - 10^{-c[x+b]}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{I}$$

in which y=the yield, x=a growth factor (in this case N), A=the maximum theoretical yield that may be obtained with an infinite amount of x, c=the "efficiency" constant for the added growth factor, and b= the "x" equivalent in the seed, soil, or both. To express the depression effect of high nitrogen concentrations, a constant, k (depression constant), is added to the normal equation which becomes

$$y = A \cdot (1 - 10^{-c[x+b]}) \cdot 10^{-kx^2} \quad \ldots\ldots\ldots\ldots\ldots \text{II}$$

This equation was used to calculate the yields of white and Scots pine grown in full light, and Scots pine grown in half light. The necessary constants are:

	A	b	c	k
White pine (full light)	438.26	33.290	0.003969	0.000000434
Scots pine (full light)	780.30	1.694	0.012620	0.000216700
Scots pine (half light)	285.30	1.365	0.043540	0.000062040

Constants were calculated according to Willcox (1930) and Mitscherlich (1928). The constant b, as used here, represents the nitrogen supplied by the seed. The independent variable x (in this case N), has been expressed in two ways: milligrams of nitrogen supply per seedling (for Scots pine), and as nitrogen concentration in p.p.m. (white pine). A conversion factor is necessary if yields of the two species are to be compared: 12.9058 × N, as mg. per seedling = N, as p.p.m. In use, since nitrogen was the only growth factor varied, N is substituted for x in equations I and II.

The Mitscherlich equation does not accurately express white pine yields over the entire N range (see text). Above nitrogen concentration 450 p.p.m., it was necessary to use the formula

$$\frac{N_p}{N_{\%}} \times 100 = y.$$

Several alternative methods were discussed in the text.

The Mitscherlich calculated yield curves were tested statistically. Two measures of accomplishment were derived: SE (standard error; a measure of curve accuracy), and CI (correlation index; a measure of the degree of association between two variables). They are summarized as follows:

Yield curve	SE_y[1]	CI_{yN}[2]
White pine (0-450 p.p.m. N)	7.41	.9943
White pine (entire range, two formulæ)	10.63	.9918
Scots pine (full light, entire range)	14.12	.9926
Scots pine (half light, entire range)	1.27	.9998

Percent Nitrogen

The average relation between nitrogen supply and the percent nitrogen content of white pine seedlings may also be expressed by an equation of the Mitscherlich type. Since the formula is to be solved for nitrogen percent, $N_{\%}$ is substituted for y in equation I, but x again $=$N, the independent variable (as p.p.m.). A becomes the maximum theoretical $N_{\%}$ that may be obtained with an infinite amount of N, $c =$ the "efficiency" constant for N, and $b =$ the N equivalent in the seed. The equation is

$$N_{\%} = A \cdot (1 - 10^{-c[N+b]}) \quad \ldots\ldots \text{III}$$

and the numerical values of the essential constants are:

A	b	c	N
4.704	47.357	0.001477	as p.p.m.

No depression constant is necessary. The relation is linear and parallel to the abscissa from 900 p.p.m. N to the highest concentration used. The statistical measures are:

	$SE_{N\%}$	$CI_{N\%\,N}$
From 0 to 425.9 p.p.m. N	0.0859	.9971
Entire range	0.1440	.9948

If equation III is solved for N ($N_{\%}$ becomes the independent variable as in Fig. 7, B), the statistical measures are:

	SE_N	$CI_{N\,N\%}$
$N_{\%}$ range: 0.72 to 3.69	18.0	.9943

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[1] The subscript y, refers to the dependent variable (yield).

[2] The first subscript refers to the dependent variable, the second to the independent (nitrogen supply). The distinction is essential in a curvilinear relation, for CI would not necessarily be the same with N dependent as with y dependent (for example, see Text Fig. 7).

The linear relations between nitrogen supply and the percent nitrogen content of Scots pine seedlings grown in half and full light are expressed by the following equations:

$$\text{Full light } N_{\%} = 0.1060 \cdot N + 0.56 \quad \ldots\ldots\ldots\ldots \text{IV}$$

$$\text{Half light } N_{\%} = 0.1554 \cdot N + 0.48 \quad \ldots\ldots\ldots\ldots \text{V}$$

and the statistical measures are:

	$SE_{N\%}$	CC[1]
Full light	0.054	.9989
Half light	0.116	.9925

In equations IV and V, N is in terms of milligrams nitrogen per seedling. Equation V is applicable only to 15 mg. nitrogen per seedling; probable shape of curve for remainder of range is shown in Fig. 3, C.

Total Milligrams Nitrogen

The relation between nitrogen supply and the total milligrams nitrogen content of white pine seedlings is expressed by the equation

$$N_p = A \cdot (1 - 10^{-c[N+b]}) \cdot 10^{-kN^2} \quad \ldots\ldots\ldots\ldots \text{VI}$$

This is a formula of the Mitscherlich type, but again used to calculate a variable other than yield. The depression constant (k) is necessary since the curve reaches a maximum and then descends. The constants are:

A	b	c	k
18.83	14.03	0.001464	0.00000022432

and the statistical indexes:

Nitrogen range	SE_{Np}	$CI_{Np\,N}$
0 to 650 p.p.m. N	0.307	9980

Above 650 p.p.m. N, the relation becomes a linear decrease which is expressed by the formula

$$N_p = -0.003862 \cdot N + 15.983 \quad \ldots\ldots\ldots\ldots \text{VII}$$

For the entire range (two formulæ): $SE_{Np} = 0.335$, and $CI_{NpN} = .9966$. To determine the quantity of nitrogen absorbed (N_a) from the nutrient solution, the nitrogen of the seed ($N_s = 0.87$ mg. for size 5 white pine seed) must be subtracted from the total nitrogen content ($N_a = N_p - N_s$).

The quantities of nitrogen absorbed (N_a) by Scots pine seedlings grown in half and full light may be calculated with the following formulæ:

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[1] Correlation "coefficient" when the relation is linear and "index" when curvilinear. Subscripts are not necessary in the case of linear correlations.

Full light $\text{Log } N_a = 1.4119 \log N - 0.89951$ VIII
Half light $\text{Log } N_a = 1.3142 \log N - 0.77294$ IX

and the statistical measures are:

	SE_{Na}	$CI_{Na\ N}$
Full light (0 to 15 mg.)	0.259	.9933
Half light (0 to 15 mg.)	0.192	.9973

In these two equations N is in terms of mg. nitrogen per seedling. Neither equation VIII nor IX accurately express N_a at nitrogen supplies higher than 15 mg. N per seedling; the probable shapes of curves at higher supplies are shown in Fig. 3, B. To obtain N_p, 0.27 mg. (N_s of size 5 Scots pine seeds) is added to the N_a values.

Statistical measures were calculated according to methods outlined by Mills (1931), Wallace and Snedecor (1931), and Bruce and Reineke (1931). Since there is no universally accepted system of statistical symbols, the system of Bruce and Reineke has been used: initial letters serve as symbols. They are more convenient to use and are more easily remembered than the system of Greek letters. For a complete discussion of the Mitscherlich formula the reader is referred to Mitscherlich (1928), and Willcox (1930).

SYMBOLS

The following are the more important symbols employed in the preceding pages.

y = Total yield (root + shoot) as milligrams dry weight.
SE = Standard Error.
CI = Correlation Index.
CC = Correlation Coefficient.
N = Nitrogen concentration of sand or soil culture solution—external concentration. Usually expressed as p.p.m. (parts per million $\bumpeq$ milligrams per liter). All formulæ expressing the Scots pine relations require N in terms of milligrams of nitrogen per seedling (29 per pot). But for purposes of comparison the equivalents in terms of p.p.m. are given in all tables.
$N_{\%}$ = Nitrogen content of the seedling expressed as a percent of dry weight—internal concentration.
N_s = The quantity of nitrogen (total milligrams) supplied by the seed.
N_a = The quantity of nitrogen (total milligrams) absorbed by a seedling from the nutrient media.
N_p = Total milligrams of nitrogen contained by a plant ($N_s + N_a = N_p$).

APPENDIX III

Description of Forest Types from which Soil Samples were Taken

Cove Hardwoods.—This mixture of species—the Cove Hardwood type—is usually found skirting the high ground around the edges of ponds; also in the moist bottoms of the numerous V-shaped valleys through which streams flow except in unusually dry seasons.

Of the more valuable commercial species, Red and White Oak,[1] White Ash, Yellow Birch, Basswood and Yellow Poplar are in the majority. Of the lesser species Red Maple, Chestnut Oak, Black Birch, Beech, Ironwood, Dogwood and Hop Hornbeam are present in varying amounts.

The reproduction is chiefly Red Oak, White Oak, Red and Hard Maple, White Ash and an occasional Yellow Poplar. The underbrush is largely *Viburnum* (sp.) with some Witch Hazel. Ferns are the principal ground cover. The leaf litter averages rather shallow, only about one year's fall being ordinarily present. Likewise the duff and humus zones, except in pockets, are relatively thin. Apparently decomposition is fairly rapid. Beneath the organic horizons the mineral soil, of the brown earth type, has a loose granular structure—often a crumb mull 1—4 inches in depth. On many areas the mineral soil, except for a few twigs and leaves, is entirely exposed.

Mid-Slope (good) Hardwoods.—This type is representative of a large proportion of the total Forest acreage. It occupies some relatively level land formed by rock out-crops as well as the steeper slopes.

Red Oak of good form and condition is most numerous, with Chestnut and White Oak, Hard and Red Maple and an occasional Hemlock, White Ash, Yellow Poplar or Hickory making up the balance. There is frequently present a distinct understory of Dogwood, Ironwood and Hop Hornbeam.

The reproduction is Hard and Red Maple, Red and Chestnut Oak, White Ash and Dogwood. The underbrush is apt to be scanty *Viburnum*. Ferns, shrubs and some *Vaccinium* make up the ground cover.

Decomposition of the organic soil horizons is slightly more rapid than in the Coves. Probably because the local climate of the latter is more cool and moist. The mineral soil of the dark brown horizon is of a loose granular structure often approaching a crumb mull. Although it has been shown to be of about the same fertility (available mineral nutrients) as that of the Coves, it is not so deep.

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[1] Scientific equivalents of common names are given in Table I, p. 18, Black Rock Forest Bull. 1.

Mid-Slope (poor) Hardwoods.—Not infrequently the Mid-Slope Hardwood type suddenly breaks down from the thrifty, well-conditioned stand found on the good slopes, and, for some reason, becomes a slow-growing community of ragged, short-bodied trees, rarely of good form and having a markedly low potential yield.

The mixture of species is largely Chestnut Oak and Red Maple with some Red Oak. An understory of Dogwood is frequently present. The reproduction includes Red Maple, Chestnut and Red Oak, Hickory and Dogwood; the underbrush is chiefly *Viburnum* and Dogwood while the ground cover is often mostly *Vaccinium.*

The physical appearance of the soil, except for a slightly greater accumulation of litter and duff, is approximately the same as that of the better slopes. Also moisture conditions are fairly comparable—not enough different to account for the poor tree growth. Since the present study has shown that the "poor" slope soils are capable of supplying slightly more available nitrogen than the "good" ones, the difference of tree growth can not be attributed to nitrogen supply. Possibly it is the result of a difference in the supply of some other nutrient element. Therefore the soils of both types are being checked for available P, K and Ca.

Ridge Hardwoods.—Beginning around 1000 feet elevation are found stands of gnarled and twisted trees, frequently with perceptibly flattened crowns. The number of stems per acre is seldom high; the growth rate is slow; and small grassy areas and thick patches of *Vaccinium* are usually present. Chestnut Oak with some Red Oak forms by far the bulk of the stand.

Here again the accumulation of litter is small. Probably, because of the exposure of the site, a good bit of the material that ordinarily composes the litter is carried away by the wind. The soil, except in the early spring or after a heavy rain, is very dry. A thick felted mat of duff containing many intertwining roots covers the mineral soil with only a thin zone of humus distinguishable between. The mineral soil is lighter in color and of poorer texture—finer and more compact—than that of the lower slopes. Because of the thick matted duff erosion is much less than might be expected. The mantle of soil on and near the ridges is, compared to the lower slopes, relatively thin.

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