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THE EFFECT OF VARIED SOLAR RADIATION UPON THE GROWTH, DEVELOPMENT AND NUTRIENT CONTENT OF WHITE PINE SEEDLINGS GROWN UNDER NURSERY CONDITIONS

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It is the usual practice in many forest nurseries to reduce by approximately 50% the light[1] received by coniferous seedlings during the entire initial growing season. In support of this practice it is pointed out how shading prevents excessive evaporation from the seed beds. It is also the belief of many nurserymen that increments of radiation above 50% of full sunlight, if not harmful, result in little or no increase in seedling yield. But evidence from carefully controlled sand and soil nutrient culture experiments (Mitchell, 1934; Gast, 1936) indicates that failure to respond to increased radiation is often due to limiting nutritional factors rather than to the inability of seedlings to utilize effectively the higher light intensities. All species studied made their best growth in full light when mineral nutrient supplies were favorable. However, the conclusions drawn from these experiments are not necessarily applicable to nursery practice because of the artificiality of the experimental method employed—pot cultures. The investigation reported here was designed to study, under actual nursery conditions, the relation of light to seedling growth and development. Since, as has been suggested (Mitchell, 1934), the chemical composition of seedlings may be a good index to soil quality—fertilizer needs—an attempt was made to determine the influence of varied solar radiation upon nutrient absorption.

About 400 white pine (*Pinus strobus* L.) seedlings were grown in a relatively poor nursery soil for 100 days (from the time seed coats were shed) in each of four radiation intensities: approximately 25, 50, 75 and 100% of full light. Variation in radiation was obtained by placing iron frames covered with brass wire cloth of different transmission factors over the seed beds. At the end of the growing season the seedlings were harvested, measured, dried, weighed, finely ground and analyzed for nitrogen, phosphorus and potassium. These data are summarized in Table 1, and a detailed description of the experimental methods follows.

DETAILS OF EXPERIMENT

Soil

The seed beds were prepared by thoroughly cultivating to a depth of one foot a relatively poor clay loam soil. No fertilizer had been added for several years other than the plowing under of an alfalfa crop a year previous to the experiment. A small amount of fine sand was worked into the upper layer to prevent excessive compacting of the soil.

Seeds

Seeds were obtained from a single tree growing on the Pack Demonstration Forest, Warrensburgh, New York. They were separated into 1 milligram classes on the basis of fresh weight. This permitted correction of plant weights at the time of harvesting for the original "capital" with which they started (see discussion, Mitchell, 1934, pp. 31-37). Only 2 weight classes were used in this experiment: class 00 (19.0—19.9 mg.) and class 0 (20.0—20.9 mg.). Seeds were sterilized for 1 minute in 0.1% bichloride of mercury, rinsed in sterile water, stratified in moist filter paper contained in sterile flasks, and stored for 6 weeks at a constant temperature of +5° C. On June 14, 1934, 400 seeds were planted in each of the 4 beds in rows 1.25″ x 1.25″. The beds were 31″ x 25″ and the 2 classes of seeds were separated in each by a blank row. The majority (about 90%) of the seeds had germinated and shed their seed coats by June 25. Although the soil was untreated, very little damping off was observed.

Radiation Control and Measurement

In this experiment the intensity of radiation was reduced by brass screens made of wires drawn to an exact dimension and accurately spaced. The many advantages of this material over the usual cheese cloth and wooden shades are discussed at some length by Gast (1936). Numerous tests have proved that the "open area" of brass screen (this value is stated in catalogs of accurately made screen) is an accurate measure of the transmission to be expected. Screens of the following specifications were used:

Mesh per inch	Wire diameter	Open area[1]
4x4	0.035	74.0
18x18	0.017	48.3
70x70	0.007	26.1

[1] Open area as percent of total area.

In each case a rectangular piece of screen 40″ x 38″ was shaped, with the aid of an iron frame, into a hemicylinder 40″ long with a radius of 12″. These frames were placed over the seed beds with long dimensions running north-south. An overhang was allowed on the north (beds only 31″ long), and the south ends were closed with semicircular pieces of screen tipped at an angle of about 45°. Seedlings in the 75% and full light beds were covered from the time of planting until July 8 with screens which reduced the radiation to about 50%. Experience has shown that white pine seedlings often do not survive high light intensities immediately following germination; also, the lowered radiation during germination prevented excessive evaporation.

Solar radiation was measured with Eppley Weather Bureau Type Pyrheliometers registering on a Leeds and Northrup two point recording potentiometer (Micromax, equipped with special integrating device). Values rep-

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

resenting the total solar radiation received by the various beds during the period (100 days from the time the seed coats were shed) are entered in Table 1, col. 1, and as percentages of "full light" in col. 2. The percentage values are not identical with the transmission factors of the screens used since the light received by seedlings in both the "open" and the "75%" beds was reduced to approximately 50% during the first few weeks of the experiment.

Care of Seedlings

The seedlings received no care other than weeding, and an occasional watering during dry periods.

Harvesting and Chemical Analysis

Trenches were dug around the beds and the soil washed away from the roots with the aid of a small stream of water from a garden hose. Very little breakage was noted. Seedlings were measured, 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.

Approximately 24 average seedlings from each group, selected on the basis of mean dry weight and root-shoot ratio, were finely ground and portions taken for chemical analysis. These results checked very well with analyses of average individuals, and samples obtained by grinding together all seedlings in each group; results are summarized in Table 1, columns 9-14.

DISCUSSION OF RESULTS

Yield

The total yield (root weight + shoot weight) of white pine seedlings was found to vary with the radiation intensity (Fig. 1, C; Table 1, col. 3). Increased light resulted in increased yield over the entire range studied, including full sunlight. Considered separately, root weights, and to a lesser extent shoot weights, showed similar correlations (Fig. 1, D and E; Table 1, cols. 4 and 5). It is quite evident that under the conditions of this experiment light variations had a relatively greater effect upon the development of the roots than upon the aerial portions of the seedlings. But the soil used was relatively infertile. This may account for the comparatively small shoot increment in response to increased radiation, for as will be brought out later in the discussion, mineral nutrition conditions the effect of radiation on seedling yield.

Under certain experimental conditions some tree species have been found to reach maximum growth at light intensities less than full sunlight. Shirley (1929) showed that the yield of loblolly pine seedlings increased but little when the light was raised from 50% to 100%, and that redwood seedlings reached maximum yield at approximately 47% of full sunlight. Others have reported similar results. On the basis of such experiments the conclusion has often been drawn that increments of radiation above 50% of full sunlight, if not harmful, result in little or no increase in the yield of tree seedlings. But, although such a conclusion may be true for a given species grown under certain environmental conditions, it should not be applied too broadly or without qualification. Evidence from recent experiments (Mitchell, 1934; Gast, 1936) indicates that soil fertility often governs to a large extent the response of seedlings to increases of solar radiation above 30% of full sunlight; and that plants otherwise capable of taking full advantage of high light intensities often fail to do so because of insufficient mineral nutrition.

A majority of the available information regarding the manner in which mineral nutrition conditions the re-

Table 1

The total weight, root weight, shoot weight, root-shoot ratio, shoot height, nitrogen, phosphorous and potassium content of white pine seedlings grown for 100 days in a nursery soil with varied solar radiation.

Cumulative Radiation for Growing Period (gram calories per cm ^{2})	Radiation as Percent of "Full Light"	Dry Wt. of Whole Plant in Mg.[1]	Dry Wt. of Roots[2] in Mg.	Dry Wt. of Shoots[2] in Mg.	$\frac{\text{Root}}{\text{Shoot}}$ Ratio[2]	Number of Seedlings Harvested[3]	Ht. of Shoots in Mm.	N%	N_D (3) × (9) = Mg.	P%	P_D (3) × (11) = Mg.	K%	K_D (3) × (13) = Mg.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
9,360	28.77	89.53±1.55[4]	30.83	59.26	0.520	271	43.05	1.618	1.448	0.160	0.143	0.461	0.413
17,322	53.24	107.14±1.21	42.21	58.87	0.717	338	39.87	1.538	1.648	0.153	0.164	0.374	0.401
24,075	74.00	114.18±1.46	48.90	64.16	0.762	324	38.09	1.533	1.750	0.142	0.162	0.363	0.414
32,533	100.00	123.65±1.95	52.25	67.24	0.777	114	31.50	1.623	2.007	0.135	0.167	0.333	0.412

[1] All weights corrected for seed size and expressed as of seed class 0 (See discussion, Mitchell, 1934, pp. 31-37). Reserve dry weight (See Gast, 1936) of seed class 0=12.66 mg.

[2] Root-shoot ratio for some unexplained reason varied somewhat with seed size. It was therefore inadvisable to apply the usual correction factors (for whole plants) to convert separate portions (root and shoot) of seedlings to weights equivalent to those of seedlings from a single seed size. Since portions of seedlings could not be reduced to a comparable basis, the results reported in cols. 4, 5 and 6 are of seedlings from only class 0 seeds, the class from which the majority of seedlings were grown.

[3] The relatively low survival (of the 400 seeds planted) in the 25% light bed is believed due chiefly to insufficient solar radiation. Trampling by dogs just previous to harvesting was responsible for the very poor survival in the full light bed.

[4] Standard error of mean.

sponse of tree seedlings to increased solar radiation has been obtained from sand nutrient culture experiments. In these, seedlings from seeds of known origin and weight were grown for approximately three months in sand contained in pots, and were supplied the essential nutrient elements as chemically pure salts in solution. Usually solar radiation and mineral nutrition were varied simultaneously. In one such experiment (Mitchell, 1934; see Fig. 3) it was found that only at relatively high nitrogen supplies were Scots pine yields proportional to radiation up to full insolation. At nitrogen supplies below 50 ppm, increasing the radiation from 50% to full light had no effect upon yield. Similar results with both Scots and white pine seedlings have been obtained by Gast (1936) in more elaborate subsequent investigations.

Using the data from the various sand nutrient culture experiments, Gast (1936, Fig. 14) shows that, "where neutral screens are used for the reduction of radiation intensities and under certain nutritional conditions," there is a linear relation between the yield of white pine seedlings and the logarithm "of the cumulative radiation received on a fixed horizontal surface during the period of growth." But it is quite evident that this relation is valid only when mineral nutrient supplies are favorable. With relatively low nitrogen (50 ppm), but excessively high potassium concentrations (200 ppm), the curves tended to break and become horizontal at the higher radiation values (Gast, *loc. cit.*, Fig. 14). Under favorable conditions, however, it appears that this arithmetic-logarithmic relation holds over a radiation range of from approximately 7 to 39 kg. calories per sq. cm. The higher value is the cumulative radiation received by seedlings grown in "full light" from July 6, to October 15, 1932 (see Mitchell, 1934, pp. 27-28, and Gast, 1936, Fig. 14).

The yields of seedlings from the present study (Table 1, col. 3) are also linearly related to the logarithm of the cumulative radiation. They are shown plotted in this way by Gast (*loc. cit.*, Fig. 15; compare with the sand nutrient culture data presented in Gast's Fig. 14). This similarity of response between seedlings grown in the "artificial" environment of the sand nutrient culture and those grown in a natural soil is interesting. But it is probably incorrect to assume from this that the yields of white pine seedlings grown in all natural soils would respond to radiation increments in exactly the same way, *i.e.*, according to the arithmetic-logarithmic relation true of sand-culture-grown seedlings. In fact there is some evidence that the yields of seedlings grown in natural soils of relatively high fertility increase with radiation increments at a greater rate. For example, Gast (*loc. cit.*, Fig. 5) found a direct arithmetic-arithmetic correlation between radiation and the yields of Scots pine seedlings grown in samples of "good raw humus" admixed with sand. The apparent dissimilarity of response to radiation increments of plants grown in sand cultures and in natural soils is probably due to differences in the "availability" of mineral nutrients in the two substrates.

In the sand nutrient cultures all nutrient elements are supplied in comparatively large quantities as free ions in solution. Under such conditions the external (solution) concentration governs the intake of these ions by the seedlings; and, other things being equal, it is the internal (seedling) nutrient content that controls the rate of dry weight increase (Mitchell, 1934, Figs. 3, 4 and 5 and unpublished data; Gast, 1936, Figs. 11 and 16). It should also be emphasized that, under these conditions, the internal (seedling) nutrient content, in milligrams, is relatively independent of seedling size. Large roots, therefore, do not always enable plants to secure more nutrients, which would in turn stimulate yield. For example, in a nutrient solution with a nitrogen concentration of 250 ppm, Scots pine seedlings grown in full light, although larger, were found to absorb only slightly more nitrogen than seedlings grown in 50% light (Mitchell, 1934, Fig. 3). But this is not characteristic of seedlings grown in natural soils or sand-humus mixtures. In these the plants must obtain their mineral nutrients from a complex in which there are usually few free ions, most being absorbed in organic or inorganic base exchange compounds. Often the supply of soluble ("available") nutrients is changing due to the activity of the microflora, with which the plants must compete for nutrients. In such a complex the greater absorbing area of large roots is a distinct advantage. They enable the seedlings to absorb more of the "bound" nutrients, and the increased nutrient intake stimulates dry weight increase. Gast (1936, Table 17) found that as plant size increased (with radiation), so did the quantity of nitrogen absorbed by Scots pine seedlings grown in identical sand-humus mixtures. This is not true of seedlings grown in sand nutrient cultures.

From the foregoing discussion it appears that the physical and chemical properties of the substrate in which seedlings are grown have a considerable influence upon the manner in which they will respond to increased radiation. If nutritional and other factors are favorable, the yields of both Scots and white pine seedlings increase with radiation, and the largest seedlings are those grown in full light; if not, the seedlings usually fail to take advantage of increments in radiation, especially the higher intensities. The arithmetic-logarithmic relation between yield and radiation apparently holds only where the absorption of mineral nutrients is not influenced to any great extent by increases in plant size. This is usually true of seedlings grown in sand nutrient cultures. But in the more complex substrates, such as natural soils and sand-humus mixtures, seedling size is often an important factor in nutrient absorption. Under such conditions the more favorable arithmetic-arithmetic correlation between yield and radiation is probably to be expected—provided that the soil is fertile and other factors are not limiting. It is suggested that such a response can be obtained from nursery-grown seedlings, without loss of root-shoot balance, if fertilizer applications are properly timed (see Gast, 1936, Fig. 17 and discussion; Mitchell, 1934, p. 23).

The yields of seedlings from the present experiment did not respond to increased radiation according to the linear arithmetic-arithmetic relation. The yields at the

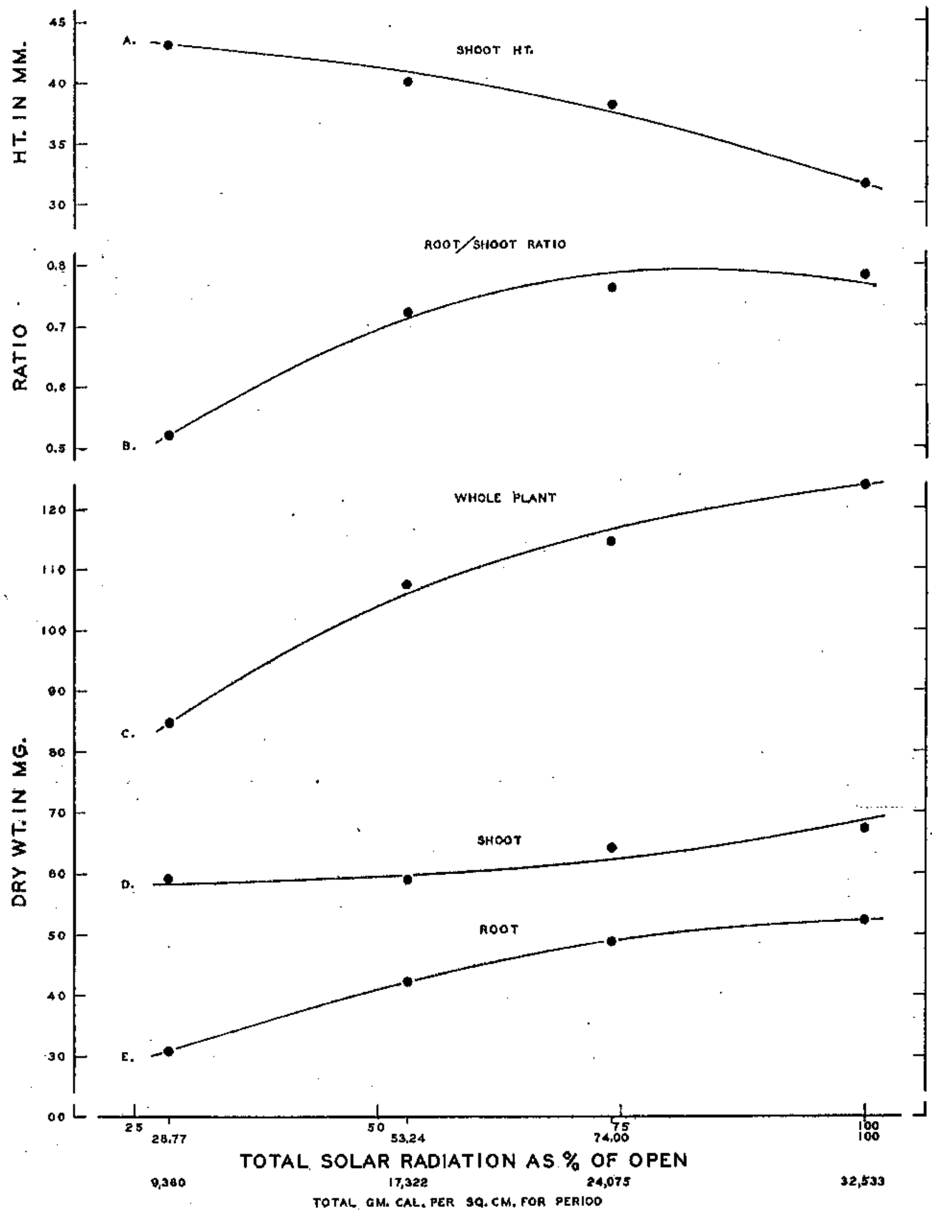

FIG. 1.—The effect of varied solar radiation on the shoot height, root-shoot ratio, total weight, shoot weight and root weight of white pine seedlings grown for 100 days in a nursery soil.

two higher light intensities were not sufficiently great to satisfy such a correlation. Therefore the curve (Fig. 1, C), tending to flatten at the higher radiation values, is perhaps the best "fit" with the data plotted in this way. Yields read from the curve will, of course, result in a straight line if plotted against the logarithm of the radiation (see Gast, 1936, Fig. 15). This relation, however, is characteristic of sand-culture-grown seedlings rather than of those grown in natural soils. In the latter, under certain conditions, seedlings size may effect nutrient intake and therefore yield. But, in the present case, the root extension of the seedlings grown in the higher intensities apparently was not sufficient to have much influence upon yield. The lack of greater response, especially to the higher light intensities, can probably be attributed to the poor quality of the soil used.

Although the soil was sufficiently fertile for the seedlings to make some response to increased light, the response was far below that of which the species is capable when properly nourished. For example, the average dry weight of those grown in the full light bed was only 123.6 mg (see Table 1, col. 3). But in samples of a fertile "cove" soil white pine seedlings weighing as much at 310 [2] mg. have been grown in approximately the same length of time (Mitchell, 1933 experiment, unpublished). Since other factors—solar radiation, seed size and source, soil temperature and soil moisture—were approximately equal, this suggests that mineral nutrient supplies were limiting. There remains another, and perhaps better, test of the fertility of the soil used, *i.e.*, the nitrogen, phosphorus and potassium content of the seedlings grown therein. These data are presented in Table 1, cols. 9-14, and are compared, in Table 2, with the N, P and K content of the 310 mg. seedlings produced by the cove soil referred to above.

The data in Table 2 show that the nutrient content of seedlings from the nursery soil was, as with yield, markedly less than that of seedlings grown in the more fertile cove soil. It is probably safe to conclude that the former failed to make a better response to increased radiation because of insufficient mineral nutrition.

Regardless of the exact form of the relation between solar radiation and seedling yield, which apparently varies with the chemical and physical properties of the substrate, the data presented show that where nutritional and other factors are favorable, the largest (total dry weight) one-year-old Scots and white pine seedlings are those grown in full light. This is true of temperate humid regions north of 40° latitude where the cumulative radiation received by seedlings during the growing season (June 1 to September 15) is about 40 kg. calories per sq. cm.; but this may not apply in regions where the mean daily intensity of radiation during the growing season is considerably greater. It should also be emphasized that seedlings of *Pinus,* particularly white pine, must be shaded (about 50%) during germination, after which the intensity of radiation should be gradually increased up to full light (over a period of 2-3 weeks) if best results are to be obtained.

[2] Correct for seed class 0; the yields in Table 1, col. 3, are expressed as from seeds of this size.

Root-Shoot Ratio

The ratio between root weight and shoot weight affords a good measure of the relative development or balance between the two portions of a seedling. In the present experiment root-shoot ratio was found to vary with solar radiation, reaching a maximum between 75% and full light (Fig. 1, B). Thus, seedlings grown in the higher light intensities are not only heavier in total weight and root weight, but have a more favorable balance between root and shoot. This is in agreement with the findings of Gast (1936, see Fig. 8) and other workers. High light intensities, like root pruning and low seed bed density, tend to produce stocky, hardy plants with well developed roots. Such plants are desirable since they have a much better chance of survival in the transplant bed or field than have the tall, spindling, underdeveloped seedlings produced in crowded, shaded beds.

Table 2

Comparison of the dry weights and nitrogen, phosphorus and potassium content (% dry matter basis) of white pine seedlings grown in two different natural soils.

Soil	Total Dry Weight in **Mg.**	Nitrogen	Phosphorus	Potassium
Nursery soil	123.6 [1]	1.623 [1]	0.135 [1]	0.333 [1]
Cove soil	310.0	2.230	0.209	1.190

[1] Data from seedlings grown in full light; see Table 1, cols. 3, 9, 11 and 13.

Height Growth

It has frequently been observed that shading, whether artificial or natural, tends to result in etiolated seedlings that are tall, spindly and succulent. This was true of seedlings from the present experiment. Height growth, as well as needle length and number, varied inversely as the radiation intensity. The height data are shown in Fig. 1, A. These data agree with those of Gast (1936) for both Scots and white pine seedlings. Burns (1914) and Nikolsky (see Zon) reported similar results with one-year-old pine and spruce seedlings. Additional supporting evidence is cited by Toumey (1916) and Shirley (1935).

The stimulating effect of low light intensities upon shoot elongation is as common to many other species of plants as to young coniferous seedlings. In fact most of the available information regarding etiolation has been obtained from experiments with field and garden species. Various explanations of the increased shoot increment of shade-grown plants have been offered. Brotherton and Bartlett (1918), who determined the size and number of epidermal cells in normal and etiolated plants of *Phaseolus multiflorus,* estimated that 34% of the increase in the length of etiolated stems was due to increased cell divisions, and that the other 66% was attributable to increases in the length of the constituent cells. The increased height increment of shade-grown *Helianthus* plants was found by Penfound (1931) to be due to an increase in the number of cells along the vertical axis, rather than to an increase in the length of the cells. Whatever the true explanation may be—and this may vary with species and environmental factors other than light—it is apparent that the rate of shoot elongation of young coniferous seedlings, as with many other species of plants, varies inversely as the radiation intensity. But, as has been shown (Fig. 1), the total assimilation of seedlings of *Pinus* is, under favorable conditions, directly correlated with solar radiation. Thus, although seedlings grown in low light intensities are *actually taller,* their *total assimilation,* as measured by dry weight, is usually *less* than those grown in higher light supplies. It is therefore evident that height increment is no index to dry weight increase, probably the best measure of the "growth" of young coniferous seedlings. But this is not true of older plants.

The total assimilation of older coniferous seedlings and saplings apparently is, as with 1 to 3-year-old plants, directly correlated with solar radiation. The former, however, unlike young seedlings, normally respond to increased light with height increments. A recent field study made by Duffield and Kraemer (unpublished manuscript [3]) is of interest in this connection. Dry weights were obtained, and height measurements made, of natural 7-year-old white pine reproduction from two cutting areas on the Harvard Forest, Petersham, Massachusetts: a 2-cut shelterwood that had received the first treatment, and a clear cut area (80-ft. north-south strips). Seedlings growing on the clear cut strips (unshaded) were found to be both taller (18.8″ as compared to 12.4″) and heavier (22.46 grams as compared to 6.97 grams, exclusive of roots) than those growing under the remaining canopy of the old stand. Since the diameter increment of 7-year-old white pine seedlings is negligible in comparison with the height increment, it appears that the greater portion of the total assimilate of the seedlings, which increased with the light intensity, was applied to height growth. This is believed to be typical of practically all tree species in the late seedling, sapling and pole stages. Gast (1930) found such a correlation between light and the leader growth of 11-year-old white pine seedlings. Shirley (1932) reported a similar relation between light and the mean annual height growth of white, Norway and jack pine saplings (up to 18-20 years of age) growing in a virgin Norway pine forest.

In view of the experimental evidence it appears that in the case of older seedlings and saplings, height growth, as well as dry weight increase, may be taken as a measure of total assimilation. But it is equally evident that the increased shoot elongation of young coniferous seedlings, in response to low light intensities, is not in the least correlated with total assimilation which, in such cases, is best measured as yield (dry weight). It is therefore impossible to use height increment as a basis for comparing the response, to varied solar radiation, of seedlings differing widely as to age. The height growth of a

[3] Manuscript on file at Harvard Forest Library.

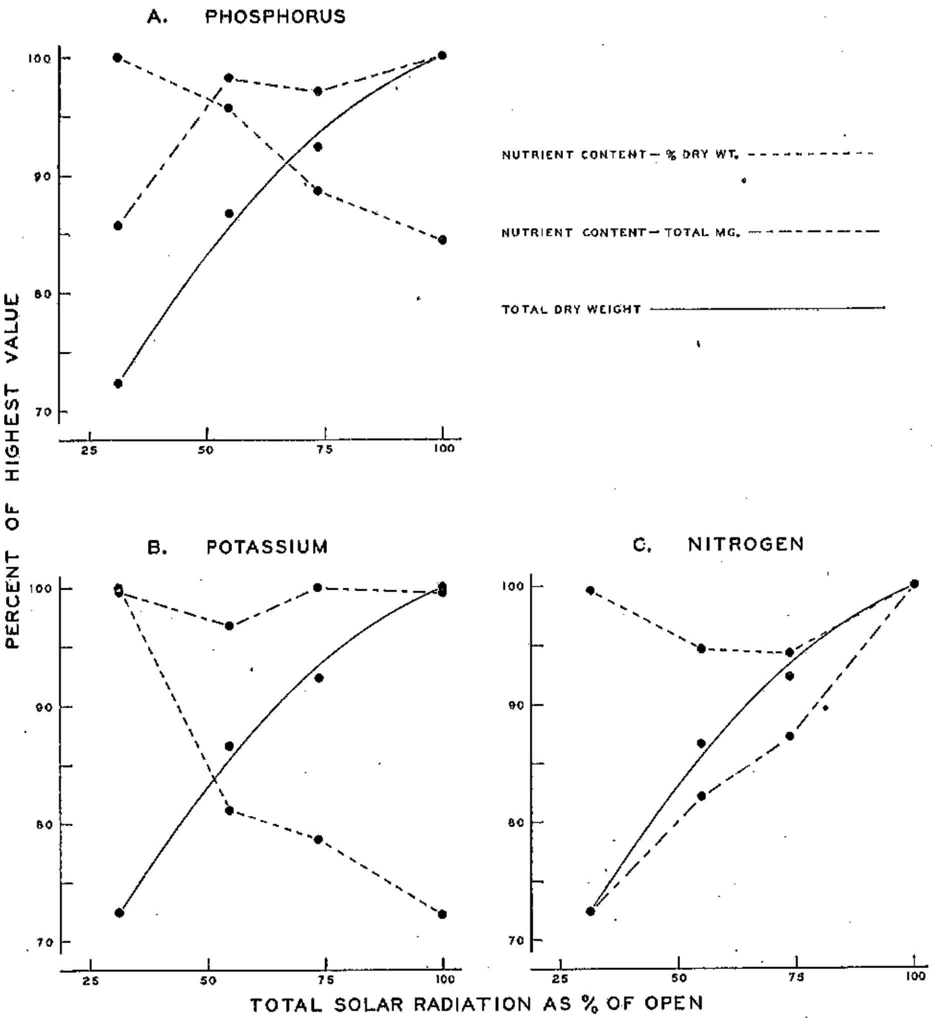

FIG. 2.—The effect of varied solar radiation upon relative trends in the nutrient content (as percent and total milligrams of N, P and K) and dry weight increase of white pine seedlings grown for 100 days in a nursery soil.

young, shaded seedling is only an expression of the degree of etiolation, and is neither related to, nor, consequently, a measure of the total assimilation.

Nutrient Absorption

It has been found that the quantities of nitrogen, phosphorus, potassium and calcium absorbed by coniferous seedlings are, as with many species of plants, proportional to the supplies of these elements available in the soil or nutrient media (Mitchell, 1934 and unpublished data; Gast, 1936). One obvious application of this information regarding proportional nutrient absorption is to nursery fertilization. Data are available to show that the results of chemical analyses provide reliable measures of the nutrient requirements—fertilizer needs—of coniferous seedlings. But if application is to be made of this procedure it is desirable to know the effect of varied solar radiation upon the nutrient intake of seedlings for, in practice, radiation conditions are not necessarily identical in all nurseries.

The nutrient content of a seedling may be expressed in two ways: (1) the absolute amount present, usually in milligrams, or (2) in terms of internal (seedling) concentration, as a percent of dry weight. The use of symbols will facilitate further discussion. Thus N_p, P_p and K_p represent, respectively, the total milligrams of nitrogen, phosphorus and potassium in a seedling (plant). For the same elements expressed in terms of seedling concentration, the subscript % is substituted for the p, *i.e.*, $N_{\%}$ $P_{\%}$ and $K_{\%}$.

Data from sand nutrient culture experiments (Mitchell, 1934) suggest that, under certain conditions, the total quantities of the various nutrient elements absorbed by Scots and white pine seedlings are relatively independent of light variations. But, in terms of concentration, the content values tend to vary inversely as the radiation. This is due to the "diluting" effect of increasing yield, with radiation, when the milligram content (of N, P, K and Ca) per plant is relatively constant. However, these relations do not always hold for seedlings grown in natural soils where, as has been shown, nutrient intake may be influenced by plant size. In the present experiment, with one exception, the greater root extension of seedlings grown in the higher light intensities had but little effect upon the intake, in milligrams, of soil phosphorus and potassium (Fig. 2; data from Table 1). Nitrogen absorption, though, apparently varied with increasing root size. In view of previous discussion this suggests that in the soil used, as in inorganic nutrient cultures, phosphorus and potassium were relatively free as ions in solution, but that at least part of the nitrogen may have been adsorbed in organic or inorganic base exchange compounds and, therefore, less readily available.

The interrelation of the several variables is shown in Fig. 2. As regards potassium, it is evident (Fig. 2) that K_p remains practically constant, but that seedling yield, as has already been shown, increases with the solar radiation. This results in an accumulation of K in the smaller seedlings. Thus $K_{\%}$ (an expression of concentration) is inversely proportional to light. Much the same is true of phosphorus, except that the total P content of seedlings grown in 25% light is considerably lower than might be expected. In this case the lack of greater phosphorus absorption can probably be attributed to root size. The concentration of nitrogen in the seedlings showed no consistent trends, but the total nitrogen intake, in milligrams, was proportional to the radiation intensity. Apparently, in this soil, nitrogen intake was affected by root extension, which varied with radiation. Neither phosphorus nor the potassium intake seemed to be influenced to any great degree by changes in root size.

No general conclusions can be drawn from these data regarding the effect of varied solar radiation upon the nutrient absorption of white pine seedlings. It appears that root size, which varies with radiation, may or may not influence nutrient intake, depending on the chemical and physical properties of the substrate. Thus, in another soil, the effect of varied radiation upon nutrient absorption may be entirely different than in the soil used in this experiment.

CONCLUSIONS

The experimental evidence presented indicates that regardless of the exact form of the relation between solar radiation and seedling yield, which apparently varies with the chemical and physical properties of the substrate, the largest (total dry weight) one-year-old Scots and white pine seedlings are those grown in full sunlight. But it should be emphasized that this is true only where nutritional and other factors are favorable. Since these conclusions are drawn from experiments conducted in temperate humid regions north of 40° latitude—where the cumulative radiation received during the growing season by seedlings exposed to "full light" is about 40 kg. calories per sq. cm. (received on a fixed horizontal surface)—they are not necessarily applicable in regions having a widely different climate.

It was found that young coniferous seedlings grown in low light intensities are actually taller, and have more numerous and longer needles than those exposed to higher intensities. But they are light, spindly, succulent and have poorly developed roots. High light intensities, like root pruning and low seed bed density, tend to produce heavier, stockier, hardier plants, with well developed roots and a more favorable balance between root and shoot weight.

In view of the experimental evidence it seems that, other factors being favorable, the most desirable seedlings are those exposed to full sunlight during the greater part of the growing season. Although some shading is necessary during, and for a short time following germination, there is little reason for continuing the practice for the entire growing season except in nurseries without adequate watering facilities, or those in very hot, arid climates. It is true, of course, that unshaded beds lose moisture quite rapidly, especially the lighter soils where some provision must be made to cut down evaporation. This has been accomplished in many nurseries by mulching with humus or other suitable material, thus eliminating mid-day watering which is apt to be harmful to young seedlings on very hot, dry days.

On the basis of experience at the Black Rock Forest Nursery, wire screens are recommended as the best material to use in shading seed beds during germination. The light transmitted by such screens is almost completely diffused, whereas seedlings shaded with the usual widely spaced wooden slats are alternately exposed to the direct rays of the sun and nearly complete shade. Metal screens absorb and conduct heat; they also permit a freer circulation of air currents than do some types of wooden, and all cloth shades. Adequate protection from birds and rodents is assured with wire screens.

Available data indicate that the chemical and physical properties of the soil govern, to a large extent, the effect that increased solar radiation will have upon the absorption of mineral nutrients by white pine seedlings. Therefore, results obtained with seedlings grown in other soils would not necessarily be the same as those reported here. In soils where a greater portion of the mineral nutrients are absorbed in inorganic and organic base exchange compounds, nutrient intake may vary with root size, which increases with solar radiation. But in soils and inorganic culture solutions where the majority of nutrient elements are free in solution, it appears that root size, which increases with light intensity, has little or no influence upon nutrient absorption.

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