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The differential effect of solar radiation on seedling establishment under a forest stand was studied to develop a basis for controlling species composition in the regenerating stand. The study was carried out on the Oregon Coast where current silvicultural practice is to clearcut mature stands and establish Sitka spruce (*Picea sitchensis* (Bong.) Carr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings in full sunlight. While generally favorable for conifer seedlings, the clearcut environment also favors growth of competing red alder (*Alnus rubra* Bong.) which often overtops and suppresses the conifers.

An exploratory study in a Sitka spruce, western hemlock, and Douglas-fir stand on gentle topography indicated the mechanics of manipulating canopy density could be handled without difficulty but removal of the overstory after seedling establishment needed to be

done with care to avoid damage to seedlings. Logging slash was readily disposed of by piling and burning and the mature stand suffered only light storm damage even though a very severe windstorm occurred during the study period. Many Sitka spruce and western hemlock, some Douglas-fir, and no red alder seedlings became established under the forest canopy, but species differences were influenced by differences in seed supply. Competing vegetation increased following thinning of the forest canopy but generally did not prevent establishment of conifer seedlings.

In the main study scarified plots were established under a 118-year-old stand thinned to provide a range in canopy density and, therefore, in solar radiation reaching the forest floor. Establishment and growth of seedlings originating from natural seedfall and artificial seeding were measured and related to solar radiation by regression analysis.

Sitka spruce, western hemlock, and Douglas-fir seedlings all became established more readily on mineral soil under the forest canopy than red alder. The ratio of viable seeds sown in the spring to established seedlings in the fall was 5.8 for the conifers compared to 46.7 for alder. The intensity of solar radiation had surprisingly little effect on seedling establishment even though intensities ranged from less than ten to almost 70 percent of radiation in the open.

Radiation played a more important role in first-season growth.

Spruce and hemlock growth increased with radiation up to an average daily radiation of about 150 Langleys or 50 percent of radiation in the open, then decreased at higher radiation levels. Red alder's response was similar with the optimum at about 39 percent of full sunlight. Growth of Douglas-fir continued upward at higher radiation levels, exhibiting a growth response significantly different from the other species.

Red alder, generally recognized as an intolerant tree, appeared to be very tolerant of shade during its first and probably its second growing season. Starting from a smaller seed, it outgrew spruce and hemlock at low radiation levels indicating a basic photosynthetic efficiency surpassing these conifers.

The downtrend in growth of spruce, hemlock, and alder at the higher radiation levels apparently was caused by high soil moisture tension and did not occur in a supplemental study where seedlings were watered. Even in the moist coastal climate soil moisture is apparently an important environmental factor limiting first-season seedling growth.

# Differential Effect of Solar Radiation on Seedling Establishment Under a Forest Stand

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# Differential Effect of Solar Radiation on Seedling Establishment Under a Forest Stand

## INTRODUCTION

The density of the forest canopy is of paramount importance for silviculture. From the first closure of the forest canopy to final harvest of mature trees the number and size of trees and consequent thickness and compactness of the canopy influence the forest environment. A dense canopy reduces radiation reaching the forest floor, decreases temperature extremes in the air and in the soil, increases humidity, and restricts wind movement. Canopy density is also important because it is one of the most readily controlled variables in the forest and is the silviculturist's major technique for controlling forest environment. He avoids the loss in productivity that results from such wide spacing between trees that the site is not fully utilized. He avoids overcrowding of the trees and the stagnation of growth that results. Between these extremes he thins periodically to distribute growth to the best trees and to control tree size and growth rate. And near the end of the rotation he manipulates density again to create an environment favorable to establishment of the new crop.

The latter objective is the subject of this thesis--the manipulation of overstory density to favor establishment of desirable tree seedlings in the understory. The standard silvicultural term for this is shelterwood cutting. The study was carried out on the Oregon Coast where standard silvicultural practice is to clearcut mature stands and establish Sitka spruce (Picea sitchensis (Bong.) Carr.), western hemlock (Tsuga heterophylla (Raf.) Sarg.) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings in full sunlight. While generally favorable for conifer seedlings, the coastal clearcut environment also favors establishment and growth of competing red alder (Alnus rubra Bong.), as well as several brush and herbaceous species. Alder seedlings with their high initial growth rate frequently overtop and suppress slow-starting conifers. Yet conifers are usually the preferred species because wood production over a normal rotation far surpasses that of alder. Since Sitka spruce and western hemlock are considered more shade-tolerant than red alder, it should be possible to control alder silviculturally by leaving part of the forest canopy to provide shade during the regeneration period. Compared to clearcutting, the shelterwood system has at least four advantages:

1. Selected crop trees retained during the regeneration period should result in better utilization of site productivity.
2. There is an important aesthetic advantage in avoiding clearcutting in scenic coastal areas.
3. Application of herbicides to control alder may be avoided.

4. Broadcast burning of slash and resulting air pollution may be avoided.

General observations confirm that there is indeed a species differential in natural reproduction under forest canopies compared to that in the open. An understory of spruce and hemlock is common under moderately dense stands while alder is scarce or entirely absent, and under very dense stands there appears to be a differential effect favoring hemlock over spruce. Douglas-fir, generally considered intermediate in tolerance, is not common in the understory of coastal forests.

The first step in this research was an exploratory study to determine the general feasibility of the shelterwood system for regenerating a Sitka spruce--western hemlock stand. During this study several problems became apparent, the most important being determination of the optimum level of overstory density for seedling germination and establishment. This became the basic objective of the main study--to determine the differential effects of the density of forest canopy on regeneration of spruce and hemlock seedlings in the understory. It appeared that solar radiation was the most significant factor in establishment of regeneration, and this received major emphasis, but other factors were measured as well. The approach was to thin a mature stand to various levels of overstory density and seek correlations of seedling establishment with solar radiation.

Douglas-fir was included in the study because of its importance in the coastal forest complex.

As there are little microclimate data available for Sitka spruce--western hemlock stands, the information reported here, besides its use in the present study, should be useful to others studying ecology of coastal forests. Environmental conditions are described in terms of measured variables whenever possible to facilitate comparisons with other areas.

# LITERATURE REVIEW

Many studies relating to germination, establishment, and growth of tree seedlings beneath forest canopies have been reported in the literature. For example, Shirley (1945) lists 57 references, Reifsnyder and Lull (1964) list 185, and Anderson (1964) lists 321, and most references listed cite other articles on the general subject. Many articles, however, give only minor emphasis to the specific question at hand, so it was necessary to be selective in choosing references for intensive review. Literature cited includes articles considered most pertinent to the subject and at the same time representative of the large body of literature available.

## Overstory Density and Forest Regeneration

In order to germinate, tree seeds require suitable temperature and adequate water and oxygen. Some require exposure to light (U.S.D.A., 1948; Kramer and Kozlowski, 1960). After germination, growth depends on light, carbon dioxide, and water for photosynthesis; suitable temperatures for metabolic processes; water for mineral uptake and translocation; and availability of mineral nutrients. Overstory density is related to all these environmental factors, and through them, to seed germination and seedling growth; so more precise knowledge of the relationships involved will help the silviculturist in manipulating overstory density to favor germination and growth of selected tree species.

A physiological process may be affected by several interacting factors although one may be recognized as the most significant at a given time (Kramer and Kozlowski, 1960). Among the several physical and biological factors that may limit germination and growth of tree seedlings beneath a forest canopy, radiation and root competition have probably received the most attention and various authors have argued that one or the other is the more significant factor. Root competition by understory plants can be eliminated by weeding them from plots, but this modifies the aboveground competition as well. Competition above ground is mainly for radiation and crown space. Radiation can be measured in the forest and, by artificially shading tree seedlings, can be varied independently of root competition and evaluated more precisely (Shirley, 1945). Solar radiation is the basic energy source of photosynthesis and, therefore, for seedling growth under a forest canopy. It is probably the most common limiting factor in the moist, warm climate of the Oregon Coast and should be measured to help explain seedling establishment and growth.

Several research workers, recognizing the importance of radiation for establishment of understory forest regeneration, have attempted to relate intensity of radiation to a more easily measured variable such as stand age, crown closure, or basal area per acre. Light intensity is related to stand age, but the relationship is complicated by variations in stand density and presence of more than one tree species (Geiger, 1965; Shirley, 1945).

Several attempts have been made to find a satisfactory relationship between transmission of radiation through the forest canopy and crown closure, and according to Anderson (1964), almost all have been unsuccessful. One approach assumes the canopy to be a thin plane with openings, something like a lath house, for which the relationship should be linear. Later attempts sought a curvilinear relationship which recognizes that the canopy has the third dimension of crown depth or thickness. These attempts also met with little success (Miller, 1955).

Wellner (1946, 1948) related radiation intensity under the canopy to stand density expressed as the sum of diameters breast high per acre and as basal area per acre. He concluded that either of these parameters could be used to estimate radiation with ten percent accuracy. As young stands develop a closed canopy, basal area increases while transmission decreases. As the trees grow older, basal area continues upward, but transmission reverses its downward trend and slowly increases as foliage volume declines due to competition of damaging agents (Kittredge, 1936; Miller, 1959; Mitscherlich as cited by Geiger, 1965). Miller (1955, 1959), using nine different series of measurements from American and German sources including Wellner's, plotted regressions of transmission of radiation on summation of diameters. A fairly satisfactory relationship was found. He concluded that sum of diameters may be used as a measure of the transmission of radiation through the canopy and that this is a better parameter than basal area per acre.

## Partitioning of Solar Radiation by the Forest

Solar energy available for germination and growth of tree seedlings on the forest floor is highly variable in intensity and not constant in spectral composition. The solar constant[1] of 1.98 g cal $cm^{-2} min^{-1}$ (International Council of Scientific Unions, 1957-58) is depleted and modified by changing atmospheric conditions. It varies with season and time of day and is further depleted and modified by the forest canopy. Little can be done to change atmospheric conditions or seasonal or diurnal variations; so this leaves modification of the forest canopy as the silviculturist's most promising approach for controlling radiation at the forest floor level. To the extent that this radiation is related to seedling response, he may thus control seedling establishment and growth.

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[1] Solar radiation falling on a unit area normal to the solar beam outside the atmosphere at the earth's mean distance from the sun.

A general view of effects of a forest stand on incident radiation is needed as a basis for understanding changes resulting from manipulation of the canopy and as a background for selecting efficient measurement techniques. Radiation incident to the top of a forest canopy logically may be partitioned into three parts--that reflected, absorbed, and transmitted.

## The Reflecting Forest

Miller (1955), assuming a flux of solar radiation about equally divided between visible and infrared radiation, computed an average reflectivity or albedo of 0.12 for conifer needles. He points out that much of the radiation reflected by one needle is absorbed by another. Albedo of the forest canopy should be lower than that of individual needles and, for crowns of ordinary closure and depth, an average albedo of 0.08 may be used. Geiger (1965) and Budyko (1956) report somewhat higher values stating that a dense coniferous forest may have an albedo of 0.10 to 0.15. This is a little less reflection than from a meadow or grain field and about the same as dark or moist soil. Albedo is greater in the morning and evening than at midday because the sun's rays do not penetrate as deeply into the forest.

Krinov (as cited by Reifsnyder and Lull, 1965) measured reflectivities of a conifer forest in summer and found considerable variation with wavelength:

| Wavelength (nanometers) | Color Spectrum | Reflectivity |
|---|---|---|
| 400 | Violet | 0.04 |
| 450 | Blue | 0.05 |
| 550 | Green | 0.08 |
| 630 | Orange | 0.07 |
| 700 | Red | 0.07 |
| 800 | Infra-red | 0.28 |

Considering still longer wavelengths, Engle (as cited by Miller, 1955) reports that albedo rises rapidly to 0.50 at wavelengths between 800 and 1100 nanometers after which it declines to about 0.10 at 2400 nanometers. At longer wavelengths values are still lower.

## The Absorbing Forest

The second partition of radiation incident to the top of the forest canopy is radiation absorbed by leaves, limbs, and trunks of the trees. Reviewing data reported by several authors and considering various spectral regions, Miller (1955) concluded that absorptivity for individual leaves averaged about 0.25. This is much less than values reported for the forest because radiation reflected from one leaf may be absorbed by another or by a nearby limb or tree trunk.

A forest normally absorbs 60 to 90 percent of incident radiation, the exact amount depending primarily on its density and the development of its foliage (Reifsnyder and Lull, 1965). Forest absorptivity coefficients of 0.60 to 0.90 are similar to those of dry, plowed ground and approach that of a water surface (Brooks, 1959). Baumgartner and Trapp (as cited by Geiger, 1965) and Richards (1952) all measured light at various levels within a stand and found that absorption causes a sharp decrease in light intensity near the top of the canopy, then a more gradual decrease through the lower crown and trunk area.

Absorption of radiation by evergreen canopies varies with season much like deciduous canopies but to a lesser degree. The conifers apparently carry a greater weight of leaf during the summer period after new leaves develop and before old leaves fall so that a definite light regime can be recognized with increased absorption during the summer months. For a western hemlock plantation in England, light under the canopy ranged from 1.0 to 2.5 percent of that in the open during August and September, but 2.0 to 2.5 in April before new needle growth (Ovington and Madgwick, 1955). Most absorbed radiation is converted into sensible heat. About half is used in evapotranspiration. Almost another half goes to heating the leaves and other plant parts. This heat can be taken up by the surrounding air thereby raising the temperature of the enviornment. Only about one percent of absorbed energy is used in photosynthesis (Waggoner and Shaw, 1952; Miller, 1955; Geiger, 1965, Vézina, 1965).

## The Transmitting Forest

The final partition of incoming solar radiation is that portion which is transmitted through the forest canopy and reaches the forest floor. This is the portion that directly effects establishment of understory seedlings, and, therefore, is of major concern for the present research. Its magnitude can be as low as one percent but can be increased to any desired level by thinning, shelterwood cutting or clearcutting (Evans, 1956; Geiger, 1965, Vézina, 1961, 1965). Transmitted radiation may also be partitioned into three components; shade light transmitted through the leaves and reflected from foliage, limbs and stems; skylight coming through holes in the forest canopy; and sunflecks which on clear days are superimposed on the first two.

On clear days small openings in even a dense forest canopy permit direct insolation to reach the forest floor in a shifting pattern of sunflecks. They vary in position from minute to minute and in intensity from full sunlight to shade light. Sunflecks can contribute 50 to 70 percent of the total radiation reaching the forest floor (Evans, 1956; Whitmore and Wong, 1959). Yet many investigators have biased their work by avoiding them and confining observations to days with heavy overcast sky when the relation of transmission to canopy density may be different than on clear days. Observations should be integrated over an entire day (Miller, 1955).

Clouds greatly reduce solar radiation incident to the top of the forest canopy, and therefore, radiation reaching the forest floor. Also on overcast days the spectral character of the diffuse radiation is different from that of the direct plus diffuse radiation received under clear sky conditions. Solar energy in the infrared end of the spectrum is greatly reduced and terminates at about 1500 nanometers because of strong absorption by water vapor. Ultraviolet radiation terminates at about 340 nanometers because of scattering. It follows that plants growing in a persistently cloudy environment not only receive much less total radiation, but also receive proportionately less ultraviolet and infrared radiation than those growing in a sunny environment (Gates, 1965). But within the photosynthetically active wave band of 400 to 700 nanometers the spectral distribution of radiation is about the same irresprctive of sky condition (Taylor and Kerr, 1941).

A proportionately greater amount of incident radiation may be transmitted through the forest canopy during cloudy weather because, in effect, insolation is coming from a plane rather than a point source and can enter the canopy from all angles (Miller, 1959; Vézina, 1961). For example, the forest canopy of a 43-year-old red pine (<u>Pinus resinosa</u> Ait.) plantation transmitted only 14 percent of the incident solar radiation on a clear day compared to 27 percent on a cloudy day. This cloud effect, however, occurs mostly in the crown and trunk areas. Differences at ground level under a dense red beech forest were less than five percent (Molga, 1958; Trapp as cited by Geiger, 1965).

Radiation transmitted through a hardwood forest canopy is substantially depleted in wavelengths absorbed by green leaves and has a high intensity of infrared relative to full sunlight (Evans, 1939, 1956). A conifer canopy, on the other hand, has little effect on spectral composition of transmitted radiation (Molga, 1958; Vézina and Boulter, 1966; Knuchel as cited by Anderson, 1964). The main effect of a conifer forest canopy, therefore, is its effect in reducing the intensity of solar radiation.

## Effect of Aspect and Slope

Different aspects and slopes receive different amounts of radiation, but for gentle slopes the differences are not great. For example, the annual potential direct beam solar radiation at latitude 44 degrees north is (Frank and Lee, 1966):

| Slope Percent | Aspect | Annual Direct Beam Radiation Langleys |
|---|---|---|
| Level | | 240,588 |
| 10 | South | 258,813 |
| 10 | North | 220,380 |

| Slope Percent | Aspect | Annual Direct Beam Radiation Langleys |
|---|---|---|
| 20 | South | 274,472 |
| 20 | North | 199,035 |

Since diffuse sky radiation received at the forest floor varies with slope but not with aspect, radiation differences during cloudy weather are reduced to slope effects alone (Geiger, 1965). That these are still important for forest regeneration is illustrated by Garman (1955). He studied germination of Sitka spruce, western hemlock and Douglas-fir on three aspects of a five-year-old burn at Lois Lake, British Columbia. All seedbeds had a 40 percent crown coverage of bracken fern (*Pteridium aquilinium*). All species germinated best on a 25 percent north aspect and poorest on 25 percent south aspect.

## Radiation Requirements for Seedling Establishment

Light intensities needed to induce germination of tree seed are generally low, and when seed of some species are chilled under moist conditions, light is no longer required. In the case of Douglas-fir, germination can be speeded by exposure to continuous light or to 16-hour days. Fifty percent germination occurred in about 16 days in the light, but required 30 days in the dark (Jones, 1961).

One of the most comprehensive reports on effects of radiation on seedling germination and growth was by Shirley (1945) in which he related response of seedlings to radiation in the open, under timber stands and under shade frames in a nursery. Only the nursery seedlings received periodic watering. In all areas subject to surface drying, germination was improved by shading, but where the soil surface remained moist, shading caused little improvement. Early survival was also improved by shading, mainly through reducing desiccation and concurrent heating of the surface soil. Losses in low radiation intensities were attributed to insufficient photosynthetic activity to balance day and night respiration, to build up a reserve to supply the roots, to maintain health over winter, and to replace tissues lost through senescence or other means. Losses in high radiation intensities were attributed to drying and overheating of the soil surface.

Only a few reports of radiation requirements are available for coastal species of the Pacific Northwest. Baker (1950) prepared a tolerance table listing important tree species in the order of their ability to endure shade under average field conditions. Western hemlock is shown as most shade-enduring of the species studied here and is classified as very tolerant. Sitka spruce is classified as tolerant and Douglas-fir and red alder as intermediate.

Douglas-fir generally is considered a light-demanding, aggressive tree that forms pure even-aged stands after fire or logging but normally does not reproduce in its own shade. In undisturbed stands natural succession is from Douglas-fir to western hemlock and other shade-tolerant species (Munger, 1940; Worthington and Staebler, 1961). However, abundant Douglas-fir reproduction is sometimes found following partial cutting (Wick, 1965). Worthington and Heebner (1964) observed Douglas-fir regeneration under thinned and unthinned stands on the McCleary Experimental Forest and found more seedlings on thinned plots. Hemlock seedlings also were more numerous on thinned plots, and ground cover was much more dense. They noted differences in age of seedlings and concluded that thinning apparently stimulated Douglas-fir germination but not survival, presumably due to increased competition from ground vegetation on thinned plots. In a study at Lois Lake, British Columbia, Garman (1955) measured germination on seedbeds in the open and shaded by cedar lath to give 25, 30, and 75 percent shade. Douglas-fir germinated best in 25 percent, western hemlock and Sitka spruce in 75 percent shade, with all three species germinating most poorly in the open.

Wick (1965) found that alder encroachment under a Douglas-fir shelterwood canopy was most pronounced on plots with exposed mineral soil and where the canopy had been at least partially opened up. All the plots with alder seedlings also had Douglas-fir seedlings.

## Temperature and Seedling Establishment

Solar radiation is the basic source of heat available for germination and growth of tree seedlings under a forest canopy, but it may reach the seed or seedling in several ways. It may be in the form of short wave radiation direct from the sun or sky or radiation reflected by or transmitted through tree foliage. It may be long wave radiation absorbed and reradiated downward from leaves, branches, and stems. It may be heat brought in by precipitation or advective heat brought in by wind. Whatever the source or wave-length of the radiation, the end result must be a temperature regime suitable for seed germination and seedling growth.

The main effect of the forest on air temperatures within the stand is a reduction in temperature extremes, the reduction depending on the density of the forest canopy. The trees intercept incoming radiation by day, outgoing radiation by night, and retard advective heating and cooling. The result is fewer lethally high temperatures on one hand and killing frosts on the other. In contrast to the extremes, the effect on average temperatures is much less. Increasing canopy density does cause a consistent but minor decrease in average temperature. Soil climate is largely determined by atmospheric climate above the ground, so the effect of the forest on soil temperature is similar to its effect on air temperature. The soil temperature in turn modifies the root environment for plants and this effects plant growth (Crabb and Smith, 1953; Geiger, 1965; Shirley, 1945).

The importance of shade in prevention of temperature extremes that may be lethal to tree seedlings has been emphasized by several authors. The shade can come from a forest canopy (Geiger, 1965; Isaac, 1938) or from a small particle on the south side of a seedling stem (Silen, 1960). Lethal temperatures normally occur in a tissue-thin layer at or just above the soil surface as evidenced by heat lesions on stems of dead seedlings. They apparently drop off rapidly immediately above and below the surface (Geiger, 1965). Silen (1960) studied lethal temperatures for Douglas-fir and found a temperature of 59 degrees centigrade to be well correlated with seedling mortality under field conditions. Hoffman (1924), in an earlier study, reported that a surface temperature of 62 degrees centigrade caused seedling mortality by killing the cambium and girdling the seedlings. The maximum temperature reached depended on the intensity and duration of the radiation. Lethal temperatures did not occur if the soil surface was wet. In fact, Maguire (1955) found that rainfall lowered the surface temperature by as much as 28 degrees and extreme temperatures did not occur again until the surface dried out.

## Soil Moisture and Seedling Establishment

There is ample evidence that shading by a forest canopy reduces moisture loss from the soil surface. This causes the surface to remain moist and generally helps prevent soil moisture becoming a limiting factor in germination of tree seed and establishment of seedlings. For example, Shirley (1945) established seedspots under various densities of aspen (*Populus tremuloides* Michx.) and jack pine (*Pinus banksiana* Lamb.) stands, under shade frames in a nursery, and in the open and found that in all areas subject to surface drying germination of conifer seeds improved with increased shading. Germination was generally improved by sowing the seed in mineral-soil and covering it about one-eighth inch. Seedling survival during the first few weeks was also improved by shading, the main advantages being protection of seedlings from drying and overheating of the surface soil.

## Measurement of Solar Radiation

There are several problems associated with measurement of solar radiation. The apparent path of the sun varies with season and crosses different parts of the canopy; there are wide variations in radiation intensity as sunflecks move across a given point on the forest floor; understory plants may receive the major part of their solar radiation during only a small part of the day; and weather conditions often vary from hour to hour. Of several investigators who have reported on these problems, most have concluded that measurements are best made with instrumentation that integrates radiation over time (Miller, 1959).

Neither the common photoelectric cell nor the more expensive luxmeter are suitable for integrating radiation over time, and conversion of readings to absolute units is almost insurmountable (Fairbairn, 1958; Reifsnyder and Lull, 1965; International Council of Scientific Unions, 1957-1958; Anderson, 1964). The solarimeter or pyranometer measures short-wave radiation from approximately 300 to 3000 nanometers. Radiation can be integrated over time by recording a trace on a recorder chart and calculating the area under the curve (Reifsnyder and Lull, 1965). These instruments and recorders are expensive and it is impractical to take large numbers of observations simultaneously for comparative purposes.

Photosensitive solutions have been recommended from time to time and have been used by several investigators. Photolysis of uranyl oxalate was carefully investigated by Leighton and Forbes (1930) but they recommended that solutions be stirred during exposure, an impractical requirement for field use. Conner (1958) found the solution too sensitive for measuring light over an appreciable period of time. Heinicke (1963) found it sound and reliable for measuring microclimate around fruit trees but his methods were questioned by Anderson (1964).

A recent method of measuring radiation proposed by Dore (1958) is based on the property of anthracene in benzene solution to polymerize to insoluble dianthracene on exposure to radiation. After exposure, the reduced concentration of anthracene, measured spectrophotometrically, is proportional to the amount of radiation received.

The anthracene technique has two important advantages. First, a large number of vials can be placed in the field simultaneously, so all study plots can be measured under the same weather conditions. Secondly, radiation effects can be accumulated over time so that much time-dependent variability is averaged out. Anthracene has the disadvantage that maximum absorption of radiation is in wavelengths just outside the visible spectrum in the ultraviolet while wavelengths most effective for photosynthesis are within the visible spectrum. This is not serious, however, because ultraviolet radiation is generally proportional to visible and to total solar radiation. Conifer needles do not show distinct selectivity as to wavelength (Molga, 1958), so variation in overstory density should not have an important differential effect on wavelength distribution of radiation measured in the understory.

Since glass can be an effective ultraviolet absorber, care must be taken in selecting vials to hold the light-sensitive solution and the same type of glass should be used throughout an experiment. Borosilicate glass is a better ultraviolet transmitter than the flint glass commonly used as vial material (Rediske, Nicholson, and Staebler, 1963).

# SEEDLING ESTABLISHMENT UNDER A FOREST STAND--AN EXPLORATORY STUDY

## Introduction

This study was an exploratory test of the shelterwood system in a coastal Sitka spruce-western hemlock stand. Objectives were to see if reproduction would become established, if it was practicable to harvest the timber by this system, if logging slash would obstruct seedling establishment, if excessive blowdown would occur, and if competing vegetation would overtop conifer seedlings. Also, it was hoped that the experience would aid in identifying research needs that might be prerequisite to intensive application of shelterwood cutting.

The shelterwood method consists of,

> Removal of the mature timber in a series of cuttings, which extend over a relatively short portion of the rotation, by means of which the establishment of essentially even-aged reproduction under the partial shelter of seed trees is encouraged (Smith, 1962, p. 354).

The cuttings normally are classified as preparatory cuttings, which prepare for reproduction; seed cuttings, which assist in the establishment of reproduction; and removal cuttings, which free established seedlings.

The study area was a 12-acre tract in the Neskowin Creek drainage 5.5 miles inland from the Pacific Ocean. Topography was gentle with slopes averaging about 12 percent and aspect varied from northwest to southwest. The tract is on the Cascade Head Experimental Forest maintained by the Pacific Northwest Forest and Range Experiment Station, Forest Service, U. S. Department of Agriculture.

## Methods

The timber stand was 113 years old at the initiation of the study in 1956. An improvement thinning had been made in 1947 removing 20 percent of the net volume, or about 19,000 board feet, Scribner log rule, per acre. Timber removed included all merchantable dead material plus dying, defective, and poorly formed trees and many slow growing trees in the suppressed and intermediate crown classes. The residual stand contained an estimated 76,000 board feet per acre. Canopy density after thinning was estimated at 80 percent, but it had increased considerably above this figure by 1956. Sitka spruce and western hemlock reproduction was established under much of the thinned stand, but growth of the seedlings seemed to have slowed and the spruce appeared to be dying out.

A shelterwood cutting of 27,000 board feet per acre was made in May 1956 taking the suppressed, intermediate, and many of the codominant trees and leaving large, vigorous trees to provide seed and shelter for the new stand. Canopy closure of the residual stand was estimated at 60 percent. Yarding was by small crawler tractor and tractor operators were instructed to protect established regeneration as much as practicable. Where brush concentrations were encountered, they were asked to yard logs through the brush to destroy it and expose the mineral soil. Logging slash did not constitute a serious fire hazard in the wet coastal climate, and no slash disposal measures were undertaken. The emphasis was on providing increased solar radiation, preparing the seedbed, and providing seed for establishment of regeneration. The cutting, therefore, was classified as a seed cut. It did release some established regeneration and to this extent was also a removal cut.

Prior to removal cuts planned for June 1963 the study was divided into two six-acre units. On the north unit, the entire timber stand of 89,000 board feet per acre was removed, but on the south unit only 56,000 board feet, or about 63 percent of the stand was removed. Logging slash on both units was hand piled and burned in the fall of 1964.

A grid of 124 milacre plots was established in the study area in 1956 using 25- by 66-foot plot spacing and with a buffer strip around the perimeter. Plots were referenced to nails driven in the base of nearby trees to facilitate relocation after logging disturbance. They were examined in April 1956 before shelterwood cutting, March 1957 after cutting, March 1960, November 1961, May 1963, and in

September 1964 to March 1965 after removal cutting. They were classified as stocked or nonstocked with tree seedlings, with stocking recorded by species during the last two examinations. A base map showing stocked milacres was taken to the field and, using the milacre plots as reference points, the area stocked with conifer seedlings was sketched on the map.

Two seed traps, each with 11.4 square feet of effective area, were maintained under the shelterwood canopy from the fall of 1957 until the spring of 1960. The top screens were 3-mesh hardware cloth and the bottom screens were 24-mesh window screen. Seeds were removed periodically during the seed year, identified, counted, and treated for soundness by the cutting test (U.S.D.A., 1948).

Estimates were made of percent of each milacre plot covered by herbs, brush, trees, mineral soil, duff and litter, logging slash, and wood and rotten wood. Definitions for each of these classifications are given in Appendix A.

## Results

### Seedling Establishment

The 1956 seed cut was effective in providing adequate seed for natural regeneration. The Sitka spruce and western hemlock trees in the shelterwood overstory produced sufficient seed during the three-year measurement period, but the few Douglas-firs produced only a light crop in the 1959-60 seed year. No alder trees were present in the canopy but a few seeds did drift in during the 1959-60 seed year, probably from young alder established on a clearcut area to the northeast (table 1).

Table 1. Seedfall of sound seeds under the shelterwood canopy by species and seed year

| Species | Seed year | | |
|---|---|---|---|
| | 1957-58 | 1958-59 | 1959-60 |
| | (thousands of seeds per acre) | | |
| Sitka spruce | 1,055 | 274 | 1,532 |
| Western hemlock | 378 | 53 | 6,167 |
| Douglas-fir | -- | -- | 87 |
| Red alder | -- | -- | 4 |
| Total | 1,433 | 327 | 7,790 |

The seed cut also produced environmental conditions favorable for seed germination and seedling establishment. Before logging, 51 percent of the milacre plots had one or more established conifer seedlings. This converts to an estimated 11,000 seedlings per acre (Bever, 1961). The logging operation reduced stocking to 35 percent; then it increased to 60 percent during the next three growing seasons and on up to 90 during the next two. The examination after the sixth season, one season prior to the removal cuts, indicated an average stocking of 82 percent. All these stocking levels were adequate, even the 35 percent stocking after the seed cut represented about 3,500 established seedlings per acre.

Complete removal of the overstory on the north unit reduced stocking from 94 to 55 percent. Sixty-three percent removal on the south unit reduced stocking from 73 to 67 percent. In general, the portion of the 12-acre study area sketched in as stocked with conifer seedlings followed the percent of milacre plots stocked with seedlings (figure 1).

By far the greatest number of milacre plots were stocked with western hemlock, with Sitka spruce second, and Douglas-fir a poor third (table 2). However, Douglas-fir demonstrated an ability to establish under a shelterwood canopy, and considering the limited seed source, did surprisingly well.

Table 2. Milacre plots stocked with tree seedlings by species, area and year

| Species | Stocked milacre plots | | | |
|---|---|---|---|---|
| | North unit | | South unit | |
| | 1963 | 1964-65 | 1963 | 1964-65 |
| | Percent | | | |
| Sitka spruce | 75 | 30 | 56 | 51 |
| Western hemlock | 92 | 55 | 69 | 60 |
| Douglas-fir | 15 | 4 | 13 | 6 |
| Any species | 94 | 55 | 73 | 67 |

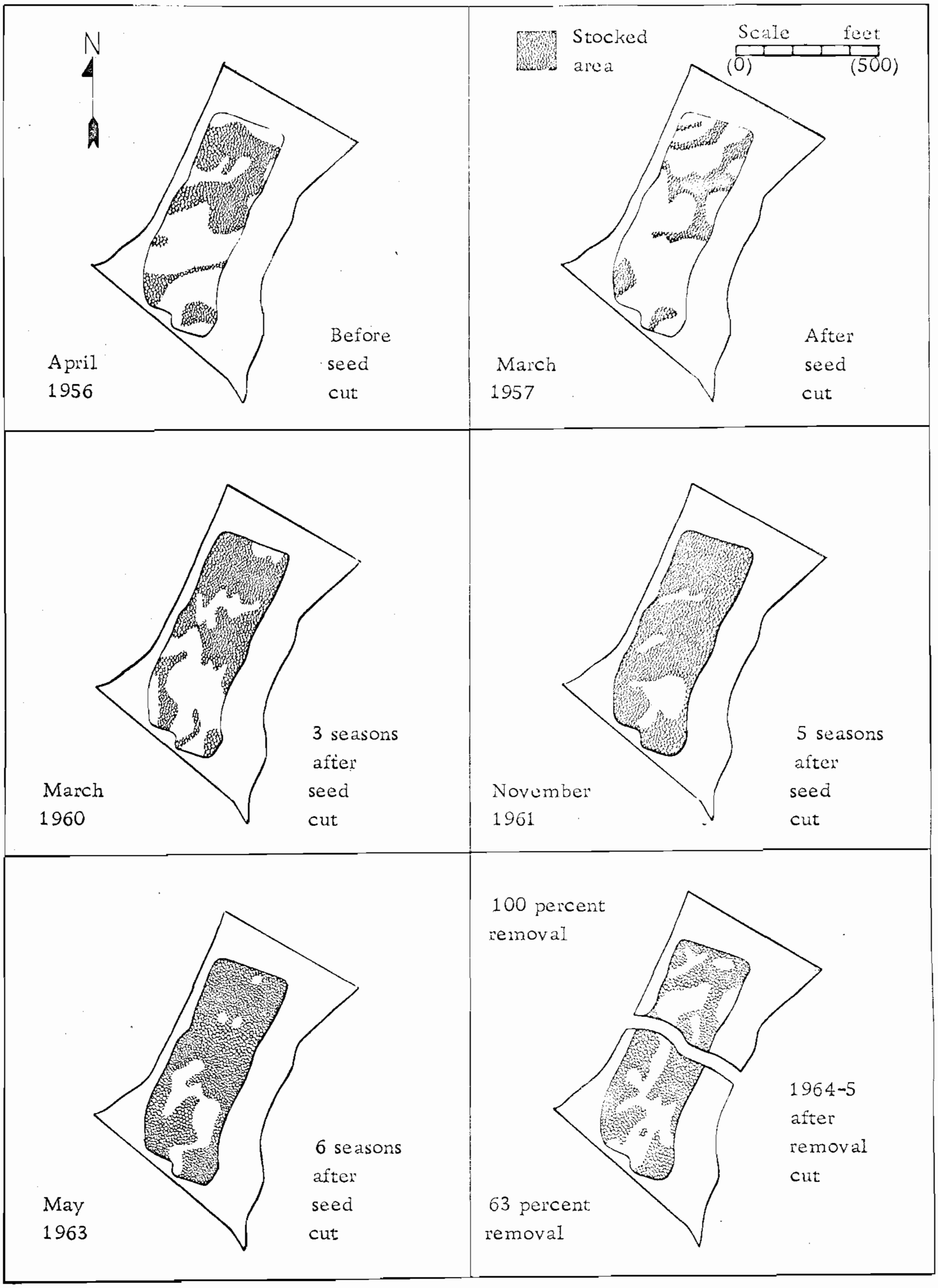


Figure 1. Maps of shelterwood study area by treatment and year showing area stocked with tree seedlings.

## The Harvesting Operations

Harvesting timber marked for the 1956 seed cut presented no serious harvesting problems and tagged trees were removed without serious damage to the shelterwood stand. The area was readily accessible from rocked logging roads, yarding distances were short, and logging costs were normal. The 63 percent removal cut on the south unit also caused little damage to the remaining overstory timber even though 56,000 board feet of logs were harvested. Crown coverage by understory conifer seedlings was reduced from 16.8 to 12.7 percent and milacre stocking from 73 to 67 percent. Logging costs were probably below those for the seed cut because of larger log sizes and the greater volume removed per acre.

The 100 percent removal cut caused considerable damage to established seedlings. Crown coverage by conifer seedlings was reduced from 16.8 to 6.8 percent and milacre stocking from 94 to 55 percent (figure 2). Logging costs were probably well below normal because of the high timber volume per acre, uniformly large trees, and an apparent lack of special measures to protect the conifer seedlings.

## Slash Accumulation

Logging slash left from the 1947 thinning covered 8.1 percent of

Figure 2. Complete removal of shelterwood overstory destroyed many conifer seedlings, north unit.

the plot area in the spring of 1956. New slash from the 1956 seed cut increased coverage to 27.0 percent; then coverage decreased gradually to a low of 2.4 percent, only to increase above previous levels after removal cuts in 1963. The north unit was fully exposed to the sun and a decision was made to reduce fire hazard on both the north and south units by slash piling and burning. When last measured in 1964 slash coverage was only 8.0 percent on the north and 2.6 on the south unit. Slash piles covered only a small percentage of the area and were located mainly in tractor roads so slash disposal played only a small role in reduction of stocking.

## Storm Damage

A total of 31 trees were killed by storm winds between the seed cut in 1956 and the removal cuts in 1963. About half were uprooted and half broken off. Sitka spruce and western hemlock suffered about equal damage.

| Species | Uprooted | Broken |
|---|---|---|
| | Number of trees | |
| Sitka spruce | 8 | 7 |
| Western hemlock | 6 | 7 |
| Douglas-fir | 2 | 1 |
| Total | 16 | 15 |

Direction of fall was variable, but with most trees falling in a northwesterly direction. The storm damage observation period included the October 12, 1962 storm which blew down several billion board feet of timber in the Pacific Northwest. The majority of storm damage in the shelterwood area occurred during this particular storm (figure 3).

Competing Vegetation

Although the understory was well stocked with conifers, their canopies dominated only a fraction of the ground surface. The seed cut reduced coverage by conifer seedlings from 19.7 to 4.0 percent. It increased to 16.8 percent, only to be reduced again by the removal cuts. The remainder of the ground surface was dominated largely by herbaceous plants, although there were temporary increases in area dominated by mineral soil, slash, and wood and rotten wood following logging. Brush coverage, like conifer seedlings, tended to increase with time after the seed cut (figure 4). Percent coverage by cover class, examination date and treatment is given in Appendix B.

## Discussion

Results of this exploratory study supported earlier general observations that the shelterwood system of harvest cutting is an entirely feasible technique for establishment of regeneration under

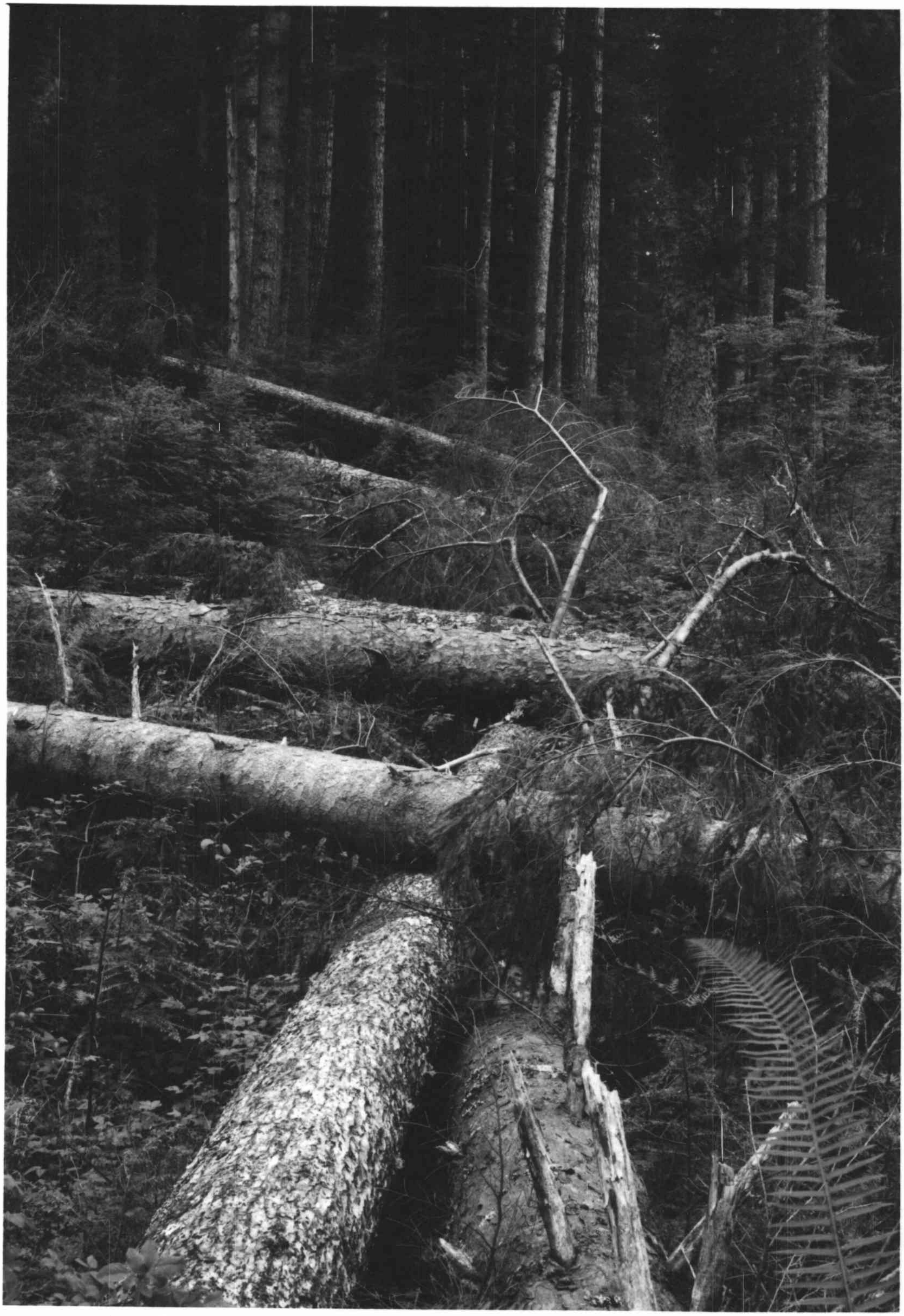

Figure 3. Storm damage resulting from October 12, 1962 windstorm, shelterwood area.

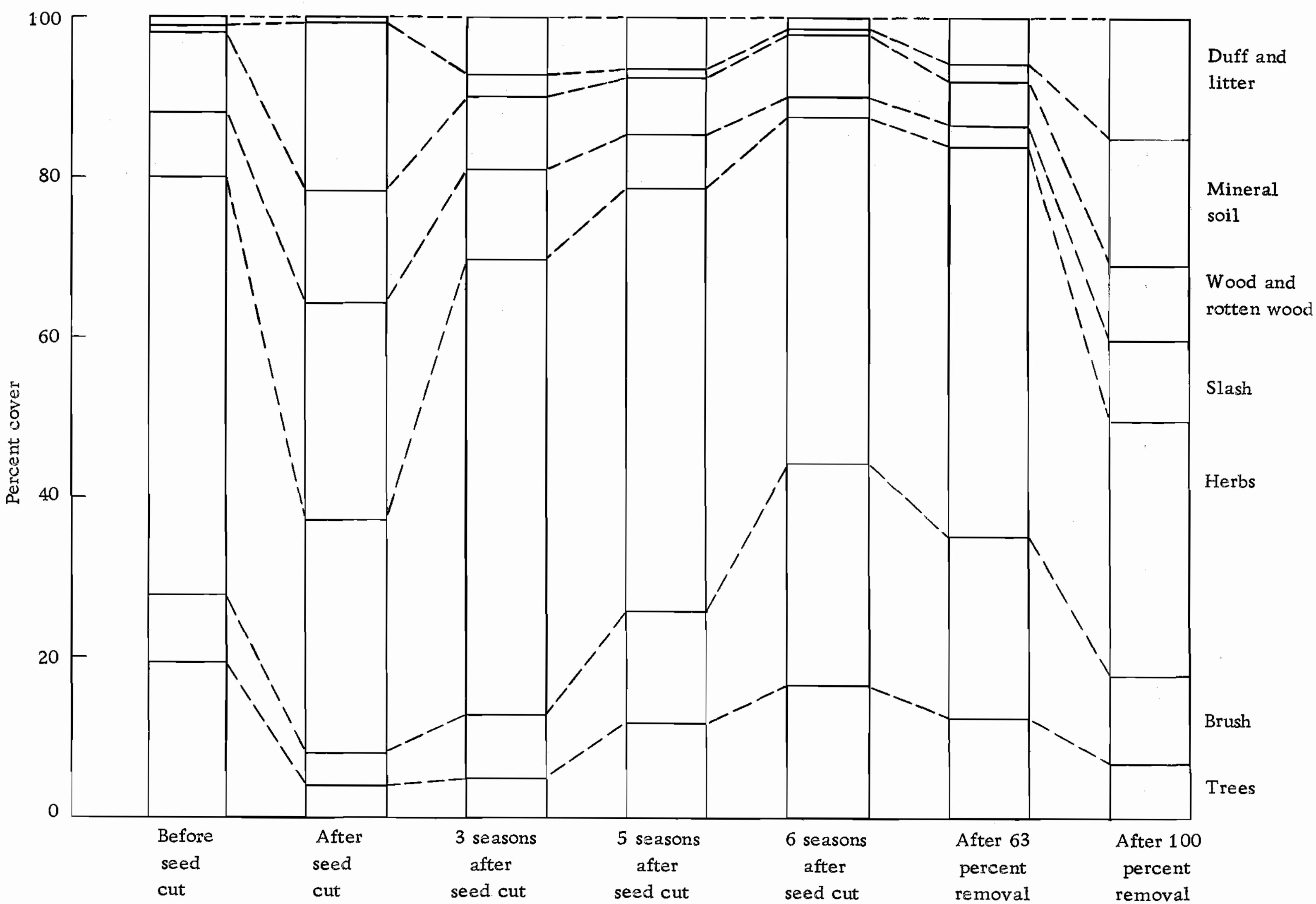


Figure 4. Ground cover trends on milacre plots by cover class and treatment, shelterwood area.

a coastal spruce-hemlock timber stand. In fact, finding 51 percent of the milacre plots stocked, an estimated 11,000 seedlings per acre, eight years after an improvement thinning indicates that thinning regimes contemplated as part of intensive management may in themselves result in regeneration establishment. This may be the case especially if the thinning regime calls for less than the 76,000 board feet per acre of growing stock left on the study area after thinning. The increased solar radiation would presumably stimulate additional seedling establishment. The important problem seems to be one of species composition and seedling growth more than regeneration establishment per se.

The only serious harvesting problem was one of damage to established seedlings during complete overstory removal on the north unit. Some damage was inevitable because of the high timber volume, and some was needed as a means of thinning dense patches of reproduction that would require costly pre-commercial thinning at a later date. But many of the best seedlings were destroyed and seedling distribution was poor. Research on overstory removal techniques is needed. The north unit appeared somewhat bare of vegetation and rather hot and dry the first summer after the removal cut--not very different from a typical clearcut area. It certainly had little of the aesthetic advantage claimed for the shelterwood system. Compared to the south unit, released seedlings had poor vigor, a yellow appearance, and apparently were suffering some shock from the abrupt exposure to full solar radiation. Completing removal of the overstory on the south unit should provide additional information. At present, the more gradual overstory removal on the south unit seems the better of the two cutting schedules. The gentle topography, easy accessibility, and short yarding distances greatly facilitated harvesting operations. Additional harvesting problems can be expected on steeper and less accessible areas.

Storm damage is a major problem in coastal forests (Ruth, 1965) and opening up a dense stand with a shelterwood seed or removal cutting probably increases blowdown hazard until the trees can develop additional windfirmness. That the study area sustained only light storm damage even during a very severe storm was certainly an encouraging result. As a minimum, the blowdown problem does not rule out further tests of the shelterwood system. And perhaps proper shelterwood cutting schedules and overstory densities will not seriously increase the hazard. Looking to the future, intensive management of young stands through periodic thinnings should increase windfirmness and make shleterwood cutting less of a blowdown hazard than when it is initiated as a harvest cutting procedure in an unmanaged stand.

An important point about the increases in competing vegetation following the seed cut was that percent of stocking and percent of plot area dominated by tree seedlings increased concurrently. In general, the tree seedlings seemed to hold their own against the competition. Of course, there were specific areas clearly dominated by brush or thick mats of herbaceous plants, and without special treatment they will probably end up as openings in the new timber stand. An unfortunate thing about the study was the very limited red alder seedfall which precluded an evaluation of this species as a competitor under a shelterwood overstory.

Seed production was more than adequate and it seems unlikely that a spruce-hemlock shelterwood overstory would be made light enough for seed production to be limiting. However, manipulation of a forest canopy to control species composition of seedfall and, therefore, of reproduction is an integral part of the shelterwood system (Smith, 1962). From this viewpoint, more information is needed on the relationship of overstory density of a particular species to seed production by that species.

Seedling establishment of spruce and hemlock was satisfactory following both the improvement thinning and the seed cutting. But lacking careful measurement of overstory density, solar radiation, and seedling response, little can be said about exact relationships. The limits, if any, and the optima need to be determined. How dense and how light can the overstory be and what is optimum for establishment of each species? Another research need, perhaps more important and little touched upon in this exploratory study, is determination of optimum growing conditions following seedling establishment. All this information is needed for associated Douglas-fir and alder as well as for spruce and hemlock.

The next step in this research was to investigate some of these problems.

# SOLAR RADIATION AND SEEDLING ESTABLISHMENT

## Introduction

The main objective of this study was to measure relationships between solar radiation and seedling establishment, and if significant relationships could be found, to determine optimum radiation intensities for the species. Secondary objectives were to briefly explore related effects of soil temperature and soil moisture.

## Methods

The study was conducted in a mature 118-year-old timber stand located in the Oregon coastal strip 6.0 miles from the Pacific Ocean and 3.5 miles northeast of Otis, Oregon. Elevation ranges from 750 to 1,000 feet above sea level. Stand composition on the 104-acre study area was approximately 33 percent Sitka spruce, 63 percent western hemlock, and 4 percent Douglas-fir. Average diameter breast high was about 25 inches and height about 165 feet. No alder trees were noted in the area, but a peripheral seed source was present to the north, south, and east. This study area is also on the Cascade Head Experimental Forest.

Topography is gentle, north-facing, and dissected by several small streams and intervening ridges. Slopes range from level to moderate with occasional steep pitches. Average slope is about ten percent. Soils are unclassified and unmapped, but closely resemble the Astoria series silty clay or clay loam. They belong to the reddish-brown latosol suborder of the great soil groups. Soil depth ranges from two to six feet with clay content increasing with depth. Small stones are scattered thinly throughout the profile (Madison, 1957). The marine climate is greatly influenced by westerly winds off the Pacific Ocean and is characterized by equable temperatures, much cloudiness, frequent rains, and summer fog (Ruth, 1954). Annual precipitation at the experimental forest headquarters 2.0 miles to the south averages about 90 inches.

Sixty-four acres of the study area were thinned in 1955 and 1956 by removal of 13,500 board feet per acre, Scribner log rule, mostly from the lower crown classes. The remaining 40 acres were left unthinned. Estimated net stand volumes per acre in 1962 were:

| Species | Thinned | Unthinned |
|---|---|---|
| | ---- Board Feet | ------- |
| Sitka spruce | 32,000 | 36,000 |
| Western hemlock | 62,000 | 67,000 |
| Douglas-fir | 3,000 | 5,000 |
| Total | 97,000 | 108,000 |

Understory conditions of the unthinned stand were typical of young-growth spruce--hemlock stands with duff, litter, and moss seedbeds most common. There were areas of scattered hemlock regeneration up to 1.5 meters tall and an intermittent cover of shrub and herbaceous vegetation. Conditions under the thinned stand were essentially the same but here there were numerous hemlock and spruce seedlings up to 7.5 centimeters tall, presumably a result of increased solar radiation following thinning.

A 22-acre clearcut adjacent to the west of the shelterwood area was logged in 1961 and 1962. This provided a convenient open area for measuring radiation and temperature simultaneously with measurements under the timber.

## Establishment of Clinal Plots

Four lines of plots were established in the shelterwood area and the timber was thinned along each line to provide a gradual decrease in overstory density. The objective was to establish lines of plots on the forest floor that received gradually increasing solar radiation progressively along the line from plot to plot. This design is an adaptation of that proposed by Dawkins (1960). Hopefully, optimum conditions for establishment of regeneration would occur along the lines and could be identified by relating radiation to seedling response through regression analysis. Lines were oriented on an azimuth of 24 degrees with lines one and two in the stand thinned in 1956 and lines three and four in the unthinned stand. Lines ranged from 1,650 to 2,375 feet long. They were at least 330 feet apart and each had a buffer strip at least 115 feet wide on each side. Trees in the buffer strips were tagged for removal and harvested in the same manner as trees along the lines themselves.

Direction of the first cline in each area was determined by drawing a random number, the second cline being assigned the opposite direction. Thus, timber at the north end of lines one and three was thinned heavily with thinning intensity decreasing to the south. Thinning intensity on lines two and four decreased from south to north.

The main advantage of this plot layout lies in the large number of treatments, each differing only slightly from its neighbor. Edge effect from adjacent plots along a line is minimal and the normal type of buffer strip between plots can be dispensed with. It is further argued that having a greater thinning intensity on one side of a plot and a lower one on the other compensates for any edge effect that may be present. Having two lines of plots adjacent to each other with the clines running in opposite directions should minimize effects of any site differences present in the study area. With this arrangement, the experimental area is greatly reduced and brought within the realm of practicality (Dawkins, 1960). On the other hand, Scott (1962) argued that plot treatments within a line, in this case thinning intensities, have been assigned serially rather than randomly, thus confounding results with any site trend that may exist along that line. For this study it was assumed there were not appreciable site differences or fertility trends along the lines. In fact, any differences present would more likely be localized in smaller units associated with minor topographic variation. Also, with radiation increasing toward the north on two lines and toward the south on the other two tends to compensate for any environmental trends along lines.

Felling and bucking of the timber began in the clearcut in July and in the shelterwood in August 1961. Harvesting was completed in August 1962 except for later yarding of some logs from outside the buffer strips. Subsequently, on October 12, 1962, a severe windstorm blew down an estimated 5,000 board feet of timber per acre in the shelterwood area. Distribution of the blowdown did not change the general gradation in overstory density along the lines, but did increase variability in canopy density, and as a result, there were numerous plots that received more radiation than their position along a line would indicate. Salvage of the blowdown was completed September 10, 1963. Additional blowdown averaging about 600 board feet per acre occurred January 24 to February 6, 1964 and added more variability in crown density over the plots. It was salvaged during the summer of 1964 taking special care to avoid disturbance of established plots. It seemed safe to assume that blowdown, which apparently occurred at random in the mature stand, would not effect any relationship between radiation and seedling establishment. In fact, blowdown had a beneficial effect of adding randomization to the plot layout.

The logging operation was typical of commercial thinnings in the Pacific Northwest (figure 5). Trees were designated for cutting by applying a spot of spray paint to two sides of each tree above stump height and a spot near the base below stump height. An initial marking designated only about two-thirds of the trees planned for removal. After these had been felled and yarded, a follow-up marking designated the remaining trees to be harvested. The second marking afforded a better view of the forest canopy and resulted in more uniform gradation in canopy density along the strips than would have been possible had all trees been marked at once. It had the added advantage that trees damaged in removing the first marking could be designated for removal during the second, although in the plot areas maintenance of desired canopy density was given first priority. Felling and bucking was by power saw with the trees bucked into logs up to 40 feet long. Yarding was by crawler tractors equipped with bulldozer blades, winches and logging arches. Tractor size was restricted to "D-4" or equivalent. Tractor operators were required to keep tractors on main skid roads as much as possible, using the bull lines to yard logs to the roads. This reduced damage to established seedlings and residual trees. Slash

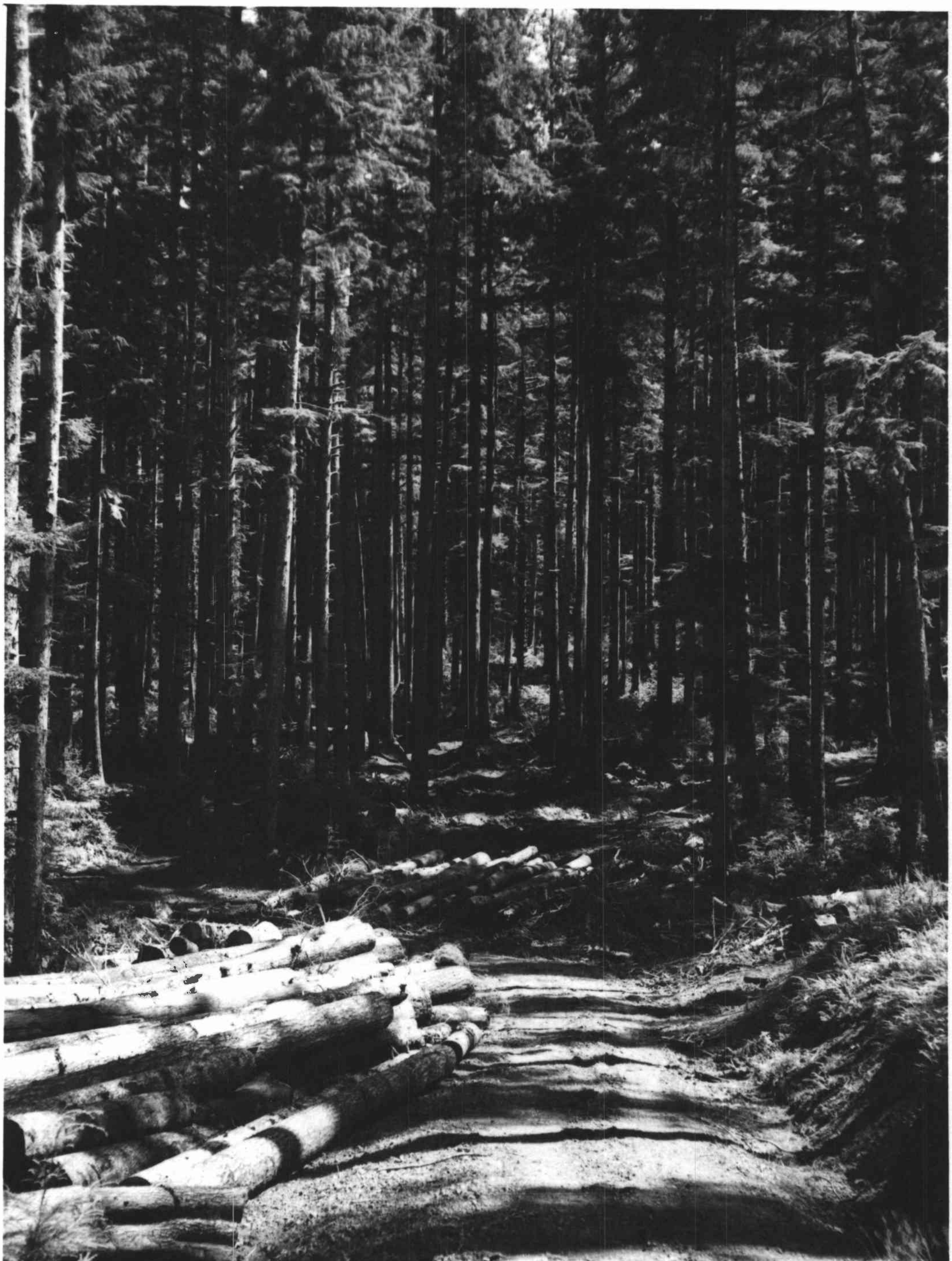

Figure 5. Logs decked along truck road under moderate timber overstory, north end of line 1. Dense overstory at north end of line 2 is in the background.

disposal was by piling and burning which was completed on the clear-cut in September 1963 and in the shelterwood later that fall.

## Establishment of Scarified Plots

Locations for scarified milacre plots were staked at approximately 90-foot intervals along lines one through four under the shelterwood overstory. Plots that fell on slopes over 30 percent, in creek bottoms, or on roads were rejected. Established vegetation was removed from the plots September 11 and 12, 1963 by scraping with a bulldozer blade mounted on a tractor. The scarification work was carefully done with the objective of removing the vegetation, yet leaving all possible topsoil. A hand rake was used to smooth out irregularities in the soil surface left by the bulldozer blade and to extend any plots that were not a full circular milacre in size. Roots encountered near the soil surface were cut and removed. Eighty-nine plots were established in the shelterwood area. Each plot center was marked by a small stake whose top protruded six inches or less to minimize any shading effect. The north tangent of each plot was designated by a numbered stake. All plots had been scarified and carefully levelled by September 27 which was well in advance of the beginning of seedfall (figure 6).

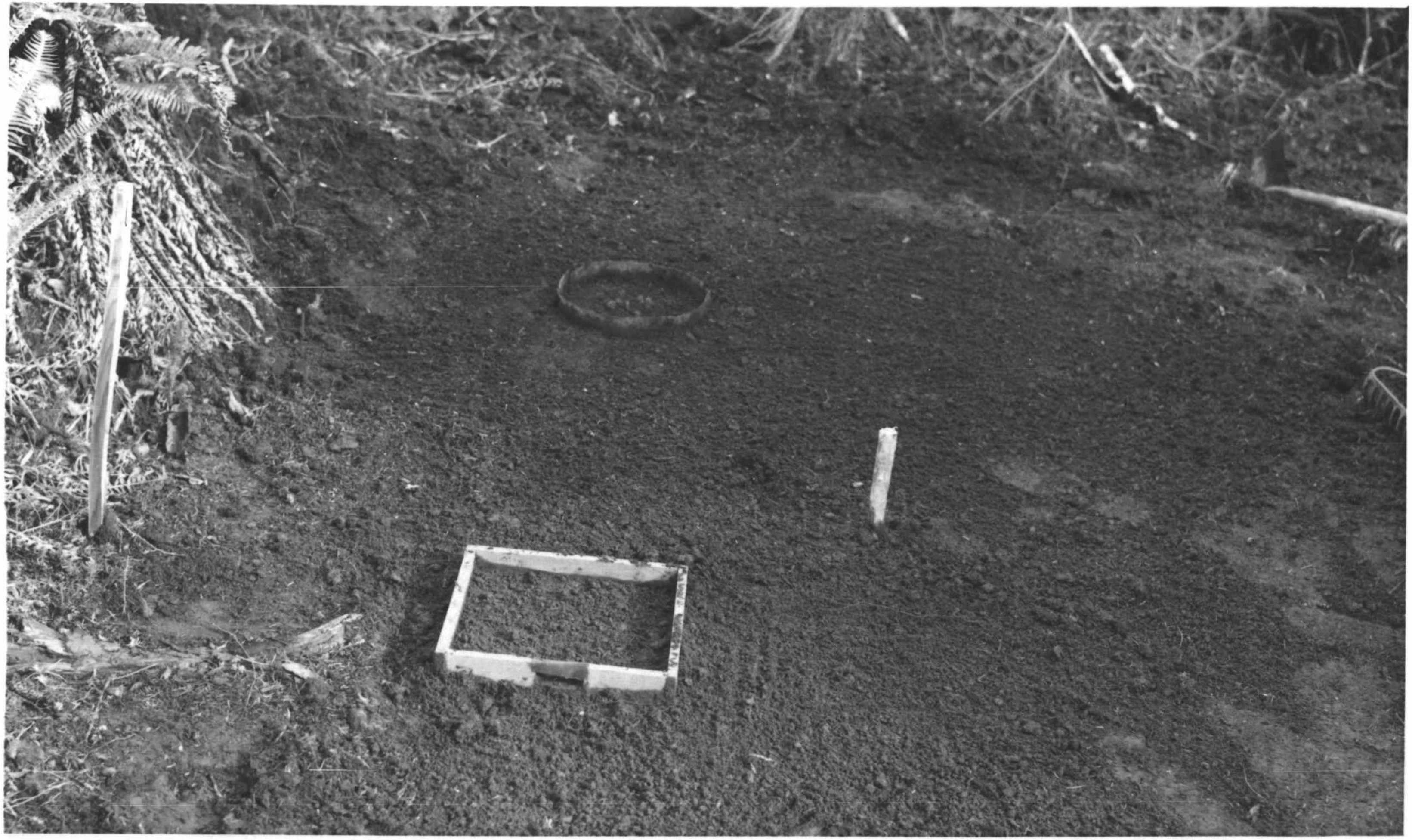

Figure 6. Scarified milacre plot used to measure seedling response to radiation in shelterwood area.

## Measurement of Seedfall

Ten seed traps were set out along line one and ten along line two on September 28, 1962 and maintained for three seed years until May 31, 1965. The traps were rectangular, two feet by three feet, with an effective trap area of 5. 7 square feet. Seed was collected monthly from November 1 to June 1, identified, counted and soundness determined by the cutting test (U. S. D. A., 1948). When there were over 36 seeds of one species per trap, soundness percentages were determined by sampling. Seedfall data were tabulated by species, trap, line, month, year, and soundness. One-quarter-acre plots with each seed trap location as the plot center were identified in the field, all standing trees within the plot measured at 4.5 feet above the average ground level, and basal areas per acre calculated by species. Least squares regressions were calculated in an I. B. M. 7040 computer to seek relationships between seed trees in terms of basal area per acre, and seedfall. Seedfall for a species was related to basal area of that species only. Eighteen regressions were run in all, testing for linearity and curvilinearity.

## Rodent Control

Poison bait was distributed in the shelterwood and clearcut area to protect seed to be sown on scarified milacre plots and also protect natural seedfall. Rodents to be controlled were the white-footed deer mouse (Peromyscus maniculatus rubidus Osgood), several shrews (Sorex spp.), and the Townsend chipmunk (Eutamias T. townsendii Backman). Baiting with sodium monofluoroacetate, "1080", on wheat February 25 to March 11 and on rolled oats March 25, 1964 did not provide adequate control. A follow-up baiting with thallium sulfate on mixed grain--one-half wheat, one-fourth cracked corn, and one-fourth milo on July 6, 1964 finally controlled the rodents. Initial baiting for the 1965 season with thallium sulfate on wheat on April 7 was ineffective, but a second baiting with thallium sulfate on mixed grain provided excellent control.

## Open Seedspot Study

The 1963-64 seed crop was essentially a failure. This left the scarified plots virtually bare of seed for spring germination and subsequent measurement; so a decision was made to seed artificially. Direct seeding had a definite advantage because the number of seed could be controlled and Douglas-fir and red alder could be included. The natural seed source for fir and alder was inadequate at best, so there was no hope for an even distribution of seed of these species on the scarified plots.

Sitka spruce cones had been collected from one of the few cone-bearing trees in the shelterwood area in the fall of 1963 and hemlock cones from several trees in the fall of 1962. Red alder strobili were collected about five miles southwest of the study area in February 1964. Seed was extracted by drying the cones and strobili in a drying oven and tumbling them in a homemade tumbler. Douglas-fir seed was obtained from a 1961 collection from zero to 500 feet elevations near the coast at Waldport, Oregon. All seed was stored in a cold room at -18 degrees C. Seed preparation consisted of dewinging the seeds by hand and cleaning them with at least two runs through a laboratory seed separator. A germination test was conducted in a growth chamber programmed to simulate coastal conditions. The photoperiod was 16 hours and the thermoperiod a ten-hour day temperature of 20 degrees C., a six-hour night temperature of ten degrees C., and two transition periods of four hours each. Three seed lots, each consisting of 20 unstratified seed of each species, were placed in covered petri dishes on moist soil. Water was added as needed. Results after 60 days were:

| Species | Germination (Percent) |
|---|---|
| Sitka spruce | 73 |
| Western hemlock | 80 |
| Douglas-fir | 56 |
| Red alder | 93 |

The final step in seed preparation was to count 80 seeds, 20 of each species, into 100 small paper cups which were nested together, wrapped in clean, moist cloth, and placed in a cold room at about two degrees centigrade. This stratification treatment began March 13, 1964.

General observations of the scarified plots during the winter indicated considerable soil movement during rainstorms, apparently due to large raindrops that dripped from the shelterwood canopy. Where there was a slope of the soil surface, considerable sheet erosion had occurred. The process was continuing and would make it difficult to keep track of seed. Hand tools were used to level the northwest quadrant of each milacre plot before seedspotting. The soil was thoroughly mixed to kill any underlying roots near the surface. As a further precaution and to provide for easy identification of the plots, wood plot frames with a 30 cm square inside diameter were constructed of 1.1 cm thick Douglas-fir lumber and set in the soil in each plot with about 1 cm of the edge protruding above the soil level. Soil was firmed in and around the frames by foot pressure. Preliminary tests of this arrangement during the next storm revealed a tendency for frames to fill with water and seed to float over the edge. This problem was solved by cutting a six cm-wide notch in each frame down to soil level and covering the notch with window screen (figure 6).

Twenty stratified seed of each species were broadcast in the seedspots March 26-27, 1964. To minimize side shade, no seed was sown within four cm of the wood frame, and seeds that fell touching each other were separated. Broadcasting all four species together minimized any problem of difference in microenvironment between species, and separating seed that fell touching each other reduced problems of competition for light, moisture, and nutrients.

Some of the seedspots were examined April 9, 1964 and it was difficult to find the seed because of soil disturbance by spring rains. Also, empty seedcoats were found, indicating rodent activity. An examination of parts of lines one and two and the clearcut on April 28, about one month after sowing, revealed no conifer seedlings, even though some germination was expected by this time. Numerous Douglas-fir seedcoats again were found, and the conclusion was that even with two baiting treatments rodent control had been inadequate. A decision was made to put out additional seedspots and screen them for rodents. Observation of the uncovered seedspots was continued, however, and they were examined June 25-26, July 16, and November 5, 1964. Observations also were continued into 1965, both for the seedlings that were then in their second season and for new seedlings originating from the 1964-65 winter seedfall. Examination dates were April 9-12, April 28-29, May 19-21, June 8-9, June 30, August 11-12, and September 22.

Seedlings germinating within four cm of the plot frame were recorded separately and discarded during analysis as they may have been effected by side shade not related to overstory density. In November the two-year-old seedlings were cut off below ground level and brought into the laboratory. Here the root crown was identified by inspection of the stem, root parts clipped off, and tops measured for height.

The first data analysis was of number of 1965 seedlings originating from natural seedfall. Seedlings per plot were converted to an acre basis and regressions of seedlings per acre on examination date, by species, provided an over-all view of magnitude and timing of germination and survival. The largest number of seedlings found on a plot, which were taken as a measure of initial seedling establishment, was converted to seedlings per-acre and regressions calculated of maximum seedlings per acre on radiation. Next, the number of seedlings surviving at the end of the season was related to radiation; then covariance was used to test for a significant reduction in seedlings as related to radiation. These computations were all for individual species. Height data for the two-year-old seedlings were combined with data from other plots and the analysis procedure will be described later.

Screened Seedspots, 1964

The same seedlots were used as for the open seedspot study. Seedspots were prepared by cutting bronze window screen into strips 5 cm wide by 90 cm long, bending them into a circle about 28 cm in diameter, and setting the circles 2.5 cm deep into prepared and levelled soil in the northeast quadrant of each scarified milacre plot. The circular screen provided a fence around the seedspot that would let water out and keep seed in. Ten unstratified seed each of Sitka spruce, western hemlock, Douglas-fir and red alder were sown in the seedspots May 14, 1964. Seeds were kept away from the side screen to avoid shading and separated from each other to avoid crowding. Seedspots were covered with four-mesh hardware cloth held down with a bent wire at two corners (figure 7). A total of 53 seedspots were established on lines three and four and in the clearcut. Seedspots were examined for germinated seedlings on June 26, July 16 when the top screens were removed, and on November 5, 1964. The 1965 examinations were on April 9 to 12, April 29 to May 3, May 19 to 24, June 8, June 30, August 12, September 22, and a final examination in November including height measurements of the two-year-old seedlings. The 1965 germination and survival data, like that from the uncovered seed-spots, were a measure of seedling establishment resulting from the

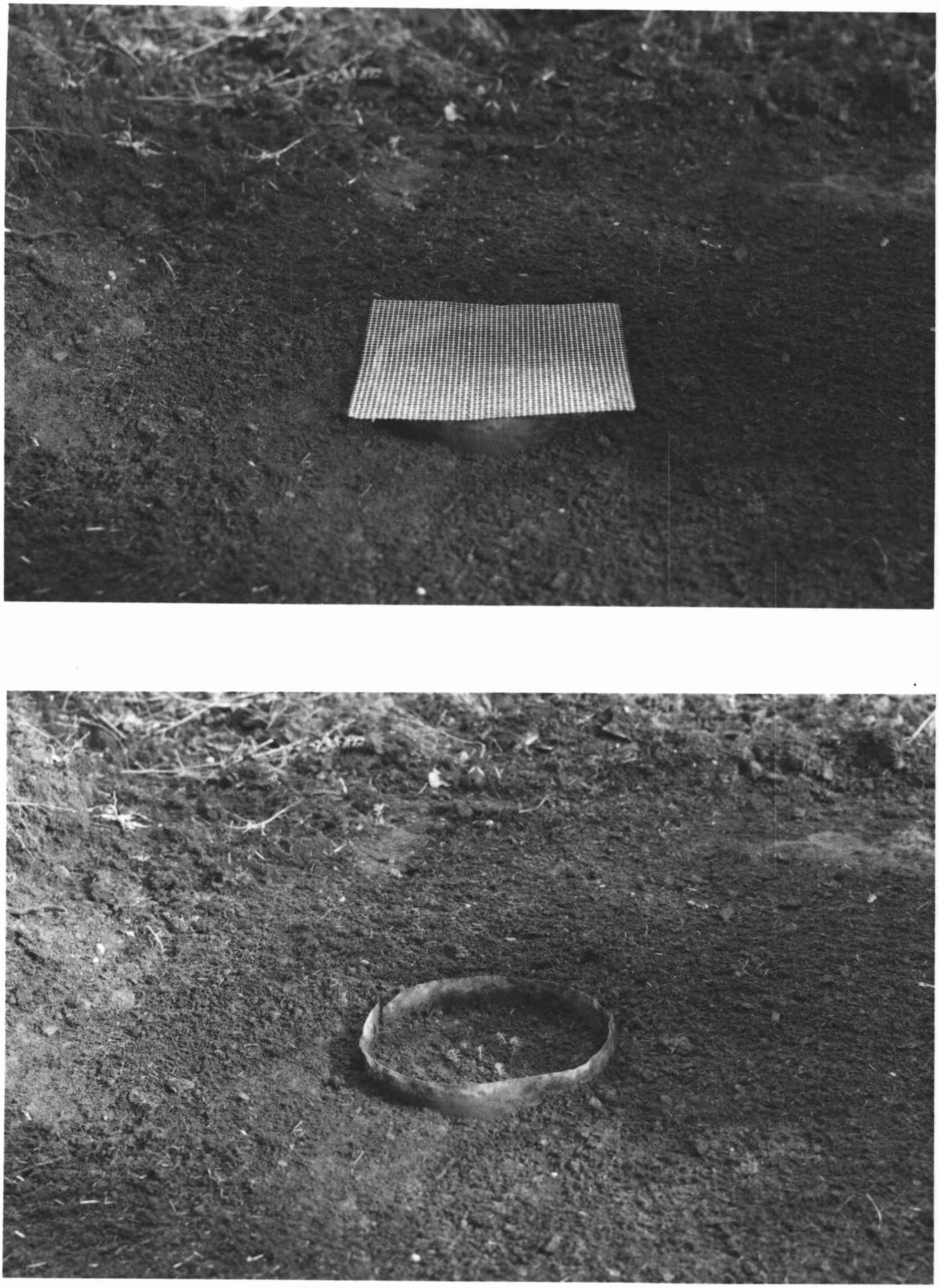

Figure 7. Screened seedspots. A. Hardware-cloth cover kept out rodents. B. Cover removed after germination.

1964-65 winter seedfall. Data analysis procedures for the 1965 germinants were the same as for the uncovered seedspots.

## Screened Seedspots, 1965

Additional screened seedspots were established in 1965 to (1) insure availability of seedlings to measure in case rodents had eaten the natural seed crop, and (2) include Douglas-fir and red alder in the experiment. It was apparent from measurements of 1964-65 natural seedfall that few fir and alder seeds had fallen in the study area. Cone collections of Sitka spruce, western hemlock, and Douglas-fir had been made the previous fall in the shelterwood area, and red alder strobili were collected about five miles to the southwest. Seeds were extracted and stored in a cold room at -18 degrees C.

The number of seeds to be sown was varied, depending on percent of soundness, so that each seedspot received 20 sound seeds of each species. Numbers sown were Sitka spruce 21, western hemlock 21, Douglas-fir 22, and red alder 24. Douglas-fir seeds, because they germinate slowly without previous stratification, were soaked overnight, drained, and placed in a refrigerator at three degrees C on April 7. Seeds of the other species were treated similarly and placed in the refrigerator April 14. Seedspots were prepared as for the 1964 screened seedspots and seeds were sown between April 15 and 21. This time the seeds were covered with about three mm of fine mineral soil.

Also, on April 21 a laboratory viability test was started by placing 20 unstratified seeds of each species in each of three petri dishes and placing the dishes in a growth chamber at 25 degrees C day and 17 degrees night temperature. Photoperiod was 16 hours. Results after 31 days were:

| Species | Days to 50 percent germination | Viability percent |
|---|---|---|
| Sitka spruce | 10 | 95 |
| Western hemlock | 16 | 92 |
| Douglas-fir | 17 | 74 |
| Red alder | 13 | 58 |

Applying the viability percentages to number of seeds sown in the field provided an estimate of the number of viable seeds sown. These were: Sitka spruce 20, western hemlock 19, Douglas-fir 16, and red alder 14.

Cover screens were removed on May 19 and seedling counts made May 20-24, June 8-9, June 30-July 2, August 8-11, and September 22. In November all seedlings were carefully lifted, soil washed from roots, and top height and root length measured. They were dried in a drying oven and tops and roots weighed to the nearest 0.1 milligram. Leaves were present on alder seedlings at time of lifting and were included in the weights.

As before, the first step in data analysis was to get an over-all view of germination and survival by relating numbers of seedlings to examination date. This time the analyses were on a seedling-per-plot rather than a seedling-per-acre basis because seeds were sown artificially. With this exception, other analyses based on seedling counts followed the procedure described for the open seedspots. For analysis of seedling growth, a preliminary step was to calculate regressions of total seedling weight over radiation, separately by species and lines, then use covariance analyses to test for significant differences among lines. These analyses were all done on an I. B. M. 7040 computer. They revealed no consistent differences among the lines. It was concluded, therefore, that the relationship between seedling weight and radiation was not affected by lines and that for subsequent analyses data from the four lines could be pooled. Regressions were calculated of each measured seedling response (top height, root length, total length, top weight, root weight, top-root ratio, and total weight) over weighted average radiation per plot, by species, using the plot count as a weight for each observation. Covariance analyses were then used to test for significant differences among species.

Height Growth Study, Mineral Soil Seedbeds

This study supplemented the seedspot studies by providing additional data on Douglas-fir and red alder. Two-year-old seedlings were included to see if growth responses at the end of the second season were similar to those after the first. Plots were located in the shelterwood area by walking secondary tractor roads and locating undamaged Douglas-fir and red alder seedlings growing on mineral soil. Sitka spruce and western hemlock were almost always available for comparison. An attempt was made to select plots over a wide range of radiation classes. Seedlings to be measured were usually within 25 cm of each other and were not accepted if outside a circular plot one square meter in area. No attempt was made to control aspect and slope and both varied considerably from plot to plot.

After radiation measurement, seedlings on each plot were clipped just below ground level, placed in a plastic bag with a numbered plot tag, and brought into the laboratory where they were identified by species, examined for age, and measured for 1965 height growth and top height. Regressions were calculated to test the relationships between height growth and radiation. Covariance analyses were made to test for significant differences among species.

## Two-Year-Old Seedling Analysis

This supplemental analysis was made to obtain additional information on second-year response of Douglas-fir and red alder by combining data from four sources:

1. Open seedspots
2. Screened seedspots, 1964
3. Height growth study, mineral soil
4. Potted seedlings

Methodology for the first three sources has already been described. For the fourth, seed was planted in mineral soil in six-centimeter-square paper pots May 22 to June 1, 1964. Five seeds each of Sitka spruce, western hemlock, Douglas-fir, and red alder were planted three millimeters deep in each pot. The pots were placed near the windows in a field laboratory and given supplemental light from incandescent and photoflood lamps. Watering was by subirrigation. If more than one seed of a species germinated, the extras were weeded out. If none germinated, seedlings germinated concurrently on covered germination plates were planted in the pots. On July 15, 1964, two pots were set flush with the mineral soil surface in each scarified plot on line four. Eight additional pots were set out on each of the same plots on August 13, 1964. Twenty-one additional pots were set out on plot 89, a plot with very low radiation intensity, on September 3, 1964. Seedlings on some plots were apparently clipped by rodents or birds and these were abandoned. Originally, the potted seedlings were grown as a hedge against rodent problems. After rodent control was obtained the screened seedspots provided a better sample, and the potted seedlings were used only to supplement the two-year-old seedling analysis.

Radiation for data sources one, two, and four were converted to percent of radiation received in the open on September 8-10, 1965, so they would be comparable with data from source three, the height growth study. Regressions of total height on radiation were calculated for each species.

## Natural Regeneration Survey

A survey of natural regeneration on the various seedbeds in the shelterwood area supplemented earlier studies which were limited to bare mineral soil. A cluster of four circular milacre plots was established around each of the original scarified plots by measuring out three meters in each cardinal direction from the center of the scarified plot. All seedbed types were included in the survey except that plots were adjusted back toward the main plot center if they included a standing tree or a stump or cull log left from the harvesting operation. Plots falling on truck roads or in creeks were also adjusted. Survey results, therefore, apply to the seedbed area normally available for seedling establishment with roads, creek, trees, and fresh stumps and logs excluded. Only seedlings that germinated in 1964 and 1965 were counted, and they were grouped together in the counting process because the large number of age determinations would have been impracticable. Older seedlings present might have been affected by overstory density before the shelterwood treatment, and 1966 seedlings were still becoming established when the survey was made from June 16 to July 14, 1966. Also, only seedlings not overtopped by competing vegetation were included. Seedlings on the four plots were added together, by species, and seedlings per cluster converted to seedlings per acre.

Height measurements were made on enough seedlings on each plot to obtain a reliable average height for each species and plot. Heights were measured to the top of the 1965 growth, excluding 1966 leader growth which was in progress during the measurement period. Weighted average height for each cluster was calculated using the number of seedlings per plot for the weight.

Multiple regression analyses were calculated relating dependent variables of average number and height of seedlings to independent variables of average daily radiation and basal area per acre and sum of diameters per acre of the overstory stand.

## Measurements of the Physical Environment

Radiation. Only a continuous record of every wavelength of solar radiation reaching the forest floor during the growing season would completely characterize the radiant energy available for seedling establishment. This was clearly impractical because of the instrumentation required; so the radiation measurements had to be a compromise between complete accuracy and practicality. The challenge was to make this compromise yet still measure the really important elements of the radiant flux.

The approach used for radiation measurements was:

1. Measure all plots simultaneously.
2. Integrate radiation over at least a full day.
3. Measure on a clear, partly cloudy, and cloudy day during the growing season and weight the results by proportion of each type of day.
4. Limit measurements to a single wavelength band because of equipment limitations.

Radiation was measured chemically using a solution of anthracene, $C_6H_4CH{:}C_6H_4{:}CH$, in benzene, $C_6H_6$.

A solution of 100 milligrams per liter was prepared by dissolving chromatographic grade anthracene in spectrophotometric grade benzene. The solution was poured in 13 × 100 millimeter borosilicate glass vials with a capacity of about nine milliliters. Screw tops for the vials were Teflon-lined to prevent deterioration by the benzene. A small air space was left in each vial to allow for expansion of the solution when exposed to the sun.

For open or light overstory conditions a starting concentration of 100 milligrams per liter was used. This concentration was such that after exposure for a full day during clear weather the resulting concentration was within the range for easy measurement on the spectrophotometer, that is, 40 milligrams per liter or less. Maximum absorption of anthracene was measured and found to be at a wavelength of 350 nanometers and this wavelength was used for all measurements. For moderate overstory conditions a starting concentration of 50 milligrams per liter was used and for dense overstory conditions 30 milligrams per liter. During cloudy weather the same starting concentrations were used but vials were left out for a longer period of time. The cap of each vial was numbered for identification and a special light-proof box constructed for storing and transporting the vials.

Anthracene vials were placed on scarified field plots directly on the bare mineral soil with the caps facing north. For the height growth study they were placed at the plot center suspended approximately ten cm above the soil by a single wire wrapped once around the vial in the groove between the cap and the shoulder of the glass.

They were suspended about horizontally with the cap facing north. On clear or partly cloudy days they were put out during, or shortly after, morning twilight when radiation was at a low level. Vials were always collected in the same order put out to avoid any bias among plots.

Simultaneously with exposure of vials on study plots, calibration vials containing all three starting concentrations were exposed in the open adjacent to a Moll Gorczynski solarimeter sensitive to wavelengths from 280 to 3, 000 nanometers. The sensing element is a thermophile of manganin and constantan wires and the instrument has been widely used in meteorological networks in Europe (Anderson, 1964). The calibration procedure permitted expression of results in absolute terms so that comparisons could be made with other experiments. Calibration vials were collected periodically during the day to provide a range of exposure periods. The solarimeter was mounted on a board to facilitate keeping it level throughout the exposure period. The radiation recorder was a Rustrak model 117 temperature recorder converted for radiation use by removing the compensation device and replacing it with a low-range resistor. With the input terminals shorted, the pointer was adjusted to zero.

Following each exposure period anthracene vials were stored in the light-proof box until they could be brought to the laboratory for analysis. Laboratory procedure was to remove a sample of the solution from each vial with a syringe, place it in a silica glass cuvette and measure its percent of transmittance in a Beckman model DB spectrophotometer set at medium slit width and a wavelength of 350 nanometers. The syringe and cuvette were carefully rinsed after each measurement with a small amount of the next solution to be measured.

Radiation values corresponding to each exposure period of the calibration vials were determined from the strip chart of the recorder by calculating the area under the radiation curve.

Transmittance data from the calibration vials were related to actual radiation received on the solarimeter by calculation of regression equations of radiation on transmittance using an I. B. M. 7040 computer. Curves of regression were plotted for each exposure period and concentration, using second degree equations when they were significant at the five percent level or more. Radiation for each anthracene exposure on a field plot was determined by referring to the proper curve and reading off the radiation corresponding to the transmittance resulting from that exposure period.

Vials containing anthracene solution were exposed August 5, 1965 which was a clear day, August 26, 1965 which was partly cloudy, and September 8 to 10, 1965 during cloudy weather. This distribution of type of day differed from a ten-year average for the May to September season taken at the experimental forest headquarters 2.5 miles south of the study area (Ruth, 1954), so radiation data were weighted to correspond to average conditions which were:

| Type of Day | Percent |
|---|---|
| Clear | 46.4 |
| Partly cloudy | 22.2 |
| Cloudy | 31.4 |
| Total | 100.0 |

The above methodology using anthracene solutions permitted simultaneous measurements on all plots, integrated radiation over time to minimize effects of sunspots, and sampled different kinds of weather conditions. Measurements were calibrated against a solarimeter sensitive to all solar wavelengths to permit expression of results in absolute units.

Additional radiation measurements were made October 13-18, 1965 adjacent to seedlings to be measured for the height growth study. Skies were overcast during this entire period. Calibration and computation procedures were the same as already described. Anthracene vials were also exposed in the adjacent clearcut area simultaneously with all measurements under the shelterwood stand. This permitted expression of radiation on the shelterwood plots as a percent of radiation in the open. On this basis, results on the milacre plots could be compared and combined with those for the height growth study.

Soil Temperature. Continuous records of soil temperature at two depths under a level soil surface were taken at three locations in the study area. One temperature station was established under dense timber at the north end of line two. The surrounding timber had a basal area of 278.6 square feet per acre and the nearest scarified plot, number 45, distance 70 feet, received solar radiation averaging 23.1 Langleys (calories per square centimeter) per day during the growing season. This was 7.4 percent of radiation in the open. A second station was located under a moderate timber stand with 237.5 square feet basal area per acre. The nearest scarified plot, number one, distance 20 feet, received solar radiation averaging 136.8 Langleys per day or 44.0 percent of radiation in the open. This station and the nearby scarified plot received considerable side light which was not picked up in the basal area data but was included in the radiation measurement. The third station was located in the adjacent clearcut area and received full solar radiation.

An exploratory study of rooting depth of one- and two-year-old Sitka spruce and western hemlock was made to determine optimum sampling depths for measuring soil temperature in the rooting area. Results were:

| Species | Average root length in centimeters | |
|---|---|---|
| | Light canopy | Dense canopy |
| Sitka spruce | 4.2 | 2.1 |
| Western hemlock | 4.8 | 3.6 |

Based on these results the two temperature probes available at each station were placed at 2.5 and 5 cm in mineral soil. The thermographs were Foxboro filled-system type, clock driven, with disc-type charts (figure 8). The thermographs were calibrated initially in the laboratory, then periodically in the field against a mercury-in-glass thermometer placed in the soil adjacent to each probe. Soil depths over the probes were also checked and new soil added whenever erosion had occurred. Charts were replaced weekly.

Soil moisture. Available soil moisture is a common limiting factor in plant survival and growth, but coastal rain forests are often considered a special case where soil moisture is available to plants throughout the year. Exploratory measurements were taken to determine if soil moisture was, in fact, fully available during the growing season and to evaluate the need for intensive study. The measurements were made in 1962 beginning with observations in June in the clearcut area, then extended to the shelterwood area in July and August, the two months of the year with lowest annual precipitation. Three plots were selected to represent average conditions in the clearcut and three in the shelterwood area. A soil sample was taken

Figure 8. Thermograph recording soil temperature in clearcut area. Temperature probes set at 2.5 and 5.0 centimeter depths are connected to recorder by flexible cable.

at each plot by compositing five subsamples, each taken with a "T" tube sampler at a random azimuth and distance from the plot center. Separate samples were taken from the 0 to 15 and 15 to 30 centimeter soil levels. Moisture determinations were made by the gravimetric method. A separate set of samples was taken in the same way and sent to the Soils Testing Laboratory, Oregon State University for determination of percent soil moisture when soil tension was 15 atmospheres.

None of the soil moisture percentages fell below the percentage at 15 atmospheres (table 3) indicating that water was continuously available to plants during the 1962 season. It was concluded that soil moisture should be monitored throughout the study, but for climatic conditions similar to 1962, need not be studied in detail.

Overcast days and intermittent rainfall during the 1965 growing season kept soil moisture at high levels (figure 9), although there were occasional periods of drying close to the soil surface.

It was not until late July that general observations of soil moisture indicated enough drying to warrant measurement of moisture as a possible limiting factor in seedling survival. Composite soil samples were taken of mineral soil in the scarified plots on line one and in the clearcut on July 29, 1965. Sampling was to 7.5 cm depth with a T-tube soil sampler to fill a pint soil can. Moisture determinations were by the gravimetric method and soil moisture

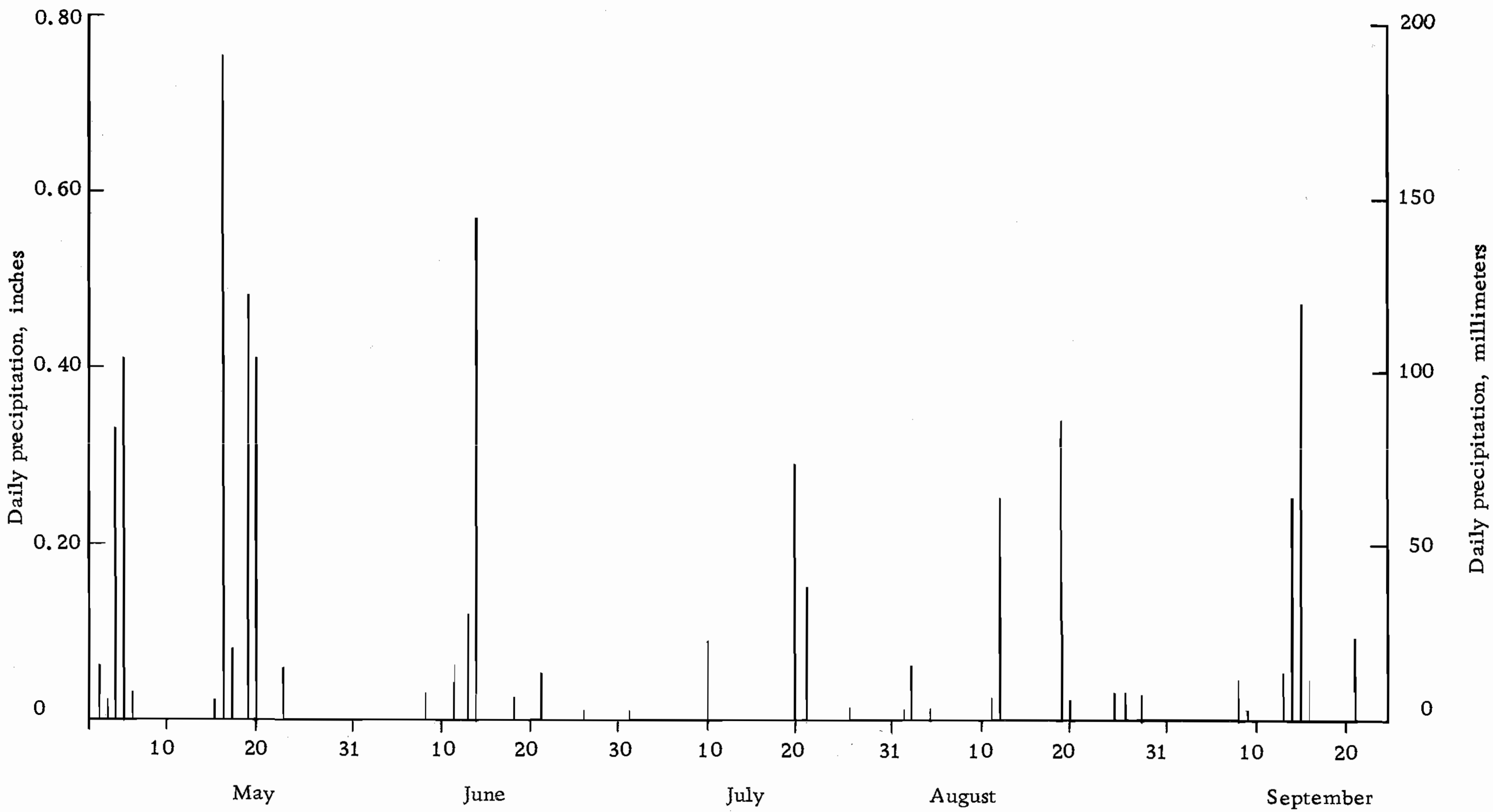


Figure 9. Daily precipitation at experimental forest headquarters, 1965 growing season.

percent was related to solar radiation by regression analysis.

Table 3. Average soil moisture percent by treatment, date, and depth class, and soil moisture at 15 atmospheres tension

| | Depth class | |
|---|---|---|
| | 0-15 centimeters | 15-30 centimeters |
| | ---------- Percent --------- | |
| <u>Clearcut</u> | | |
| June 26, 1962 | 99 | 95 |
| July 12, 1962 | 85 | 80 |
| August 2, 1962 | 102 | 82 |
| August 9, 1962 | 111 | 102 |
| At 15 atmospheres | 30 | 25 |
| <u>Shelterwood</u> | | |
| July 12, 1962 | 49 | 43 |
| August 2, 1962 | 96 | 81 |
| August 9, 1962 | 112 | 86 |
| At 15 atmospheres | 36 | 32 |

With intermittent summer rainfall the rate of drying near the surface becomes very important for seedling establishment. Precipitation totalling 0.36 inch fell on August 19, 1965 and this was followed by a slow drying out of surface soil. Samples were collected on September 9, 1965 at four depths along line one and in the clearcut. Plot size was 25 centimeters square and sampling depths were zero to two centimeters, by half-centimeter increments. The sample from each layer was enough to fill an eight-ounce soil can. Twenty plots were sampled using a specially made scoop with a guide wire indicating the half-centimeter thickness to be sampled. Soil moisture percent was related to radiation by regression analysis with covariance analysis used to test for significant differences among depth classes. A composite soil sample from the same plots was analyzed in the laboratory to determine moisture percent at 15 atmospheres soil moisture tension.

Basal Area and Sum of Diameters. Tree diameters, by species, were measured on 0.25-acre circular plots with the center of each scarified milacre plot taken as the plot center. Measurements were taken at breast height using a Biltmore stick with frequent checks by diameter tape. Diameters were converted to basal area, added to get basal area per plot, and converted to basal area per acre. The sum of diameters per plot also was determined and converted to an acre basis.

Multiple regression analyses were computed using basal area per acre, sum of diameters per acre, and average daily radiation as the independent variables. Dependent variables used were total seedling weights from the 1965 screened seedspots. Separate step-wise regressions were calculated for Sitka spruce, western hemlock, and Douglas-fir.

# Results

## The Physical Environment

Study years 1964 and 1965 had near-normal temperature and precipitation in the coastal area. Using long-term averages at Newport, Oregon to the south and Seaside to the north as a base, departures from normal at these stations for the May to September growing seasons were quite moderate (table 4). Assuming no unusual variation between these stations, 1964 and 1965 were near-normal years at the study area.

Table 4. Temperature and precipitation departures from normal, Newport and Seaside, Oregon by years

| Year | Average Departure from Normal | | | |
|---|---|---|---|---|
| | Temperature | | Precipitation | |
| | Newport | Seaside | Newport | Seaside |
| | Degrees C | | Millimeters | |
| 1964 | -0.8 | -0.6 | 50 | 80 |
| 1965 | -0.8 | 0.3 | -180 | -280 |

Air Temperature. Average monthly air temperatures at the experimental forest headquarters, 2.5 miles southwest, provide a general characterization of the temperature environment at the study area. The long-term average for the study period was 10.2 degrees C. The highest monthly average was 16.3 in August 1965 and the lowest 4.7 degrees C in December 1964. Temperature extremes were moderate with the average monthly maximum only going up to 21.6 and average monthly minimum only going down to 2.1 degrees C (table 5).

Table 5. Average air temperature by month and year, experimental forest headquarters

| Year | Month | Air temperature | | |
|---|---|---|---|---|
| | | Maximum | Minimum | Average of maximum and minimum |
| | | Degrees C | | |
| 1963 | November | 11.7 | 6.0 | 8.9 |
| | December | 10.0 | 3.2 | 6.6 |
| 1964 | January | 8.9 | 3.5 | 6.2 |
| | February | 10.7 | 1.1 | 5.9 |
| | March | 11.1 | 2.4 | 6.7 |
| | April | 12.2 | 3.4 | 7.8 |
| | May | 14.6 | 5.0 | 9.8 |
| | June | 17.2 | 8.8 | 13.0 |
| | July | 20.0 | 10.4 | 15.2 |
| | August | 20.2 | 9.9 | 15.0 |
| | September | 19.3 | 8.7 | 14.0 |
| | October | 16.7 | 7.0 | 11.8 |
| | November | 10.4 | 3.2 | 6.8 |
| | December | 7.2 | 2.1 | 4.7 |
| 1965 | January | 7.9 | 2.3 | 5.1 |
| | February | 10.2 | 3.3 | 6.8 |
| | March | 15.4 | 2.4 | 8.9 |
| | April | 13.7 | 4.9 | 9.3 |
| | May | 14.6 | 5.1 | 9.9 |
| | June | 17.8 | 7.5 | 12.7 |
| | July | 21.4 | 9.7 | 15.6 |
| | August | 21.6 | 11.0 | 16.3 |
| | September | 20.9 | 8.4 | 14.7 |
| | October | 18.1 | 8.5 | 13.3 |
| Average | | 14.7 | 5.7 | 10.2 |

Soil Temperature. Average monthly soil temperatures followed normal seasonal trends with minimums in January, February, or March and maximums in July or August. For the 2.5 cm depth the highest monthly average of 22.6° C occurred in the clearcut in July 1965 and the coldest of 2.1° C, also in the clearcut, in January 1965. The long-term average temperature was warmest in the clearcut, intermediate under a light overstory, and coldest under dense timber (table 6).

Analysis of temperatures making up these averages showed that cover class had the greater effect on maximum rather than minimum temperatures. The range in average maximum between the clearcut and dense overstory at 2.5 cm depth was 7.1 degrees centigrade; in the average minimum it was only 0.7 degree C (table 7). Similar results were found by Hodges (1967) under a Douglas-fir stand. Effects of cover on maximum temperature was greater in the summer than in the spring or autumn (figure 10), but temperatures were well within the range for plant growth during the entire season.

Samples of diurnal soil temperature variation provided additional information on temperature environment of seedling roots. On August 5, 1967 under a cloudless sky, maximum soil temperature on the clearcut at 2.5 cm depth reached an extreme of 32 degrees C, while under the dense overstory the extreme maximum

Table 6. Average soil temperature at 2.5 cm, by year, month and cover class

| Year | Month | Cover class | | | |
|---|---|---|---|---|---|
| | | Clearcut | Moderate overstory | Heavy overstory | Average |
| | | ----------Degrees C---------- | | | |
| 1963 | November | 8.0 | 8.3 | 7.6 | 8.0 |
| | December | 5.4 | 6.0 | 5.9 | 5.8 |
| 1964 | January | 4.8 | 5.5 | 5.0 | 5.1 |
| | February | 5.1 | 4.4 | 4.2 | 4.6 |
| | March | 6.5 | 5.7 | 4.2 | 5.5 |
| | April | 10.0 | 8.1 | 5.9 | 8.0 |
| | May | 12.6 | 10.5 | 7.7 | 10.3 |
| | June | 15.9 | 13.8 | 10.9 | 13.5 |
| | July | 19.6 | 15.4 | 12.7 | 15.9 |
| | August | 16.9 | 15.9 | 12.9 | 15.2 |
| | September | 15.8 | 13.9 | 12.1 | 13.9 |
| | October | 12.2 | 11.4 | 10.4 | 11.3 |
| | November | 5.3 | 5.4 | 5.3 | 5.3 |
| | December | 2.9 | 4.0 | 3.4 | 3.4 |
| 1965 | January | 2.1 | 2.3 | 2.3 | 2.2 |
| | February | 6.3 | 5.5 | 4.7 | 5.5 |
| | March | 9.5 | 6.9 | 5.9 | 7.4 |
| | April | 11.9 | 9.5 | 7.6 | 9.7 |
| | May | 14.0 | 10.3 | 8.2 | 10.8 |
| | June | 18.8 | 14.2 | 11.4 | 14.8 |
| | July | 22.6 | 16.9 | 13.9 | 17.8 |
| | August | 20.4 | 17.4 | 14.6 | 17.5 |
| | September | 16.8 | 14.6 | 13.0 | 14.8 |
| | October | 12.8 | 12.8 | 11.8 | 12.5 |
| Average | | 11.5 | 9.9 | 8.4 | 9.9 |

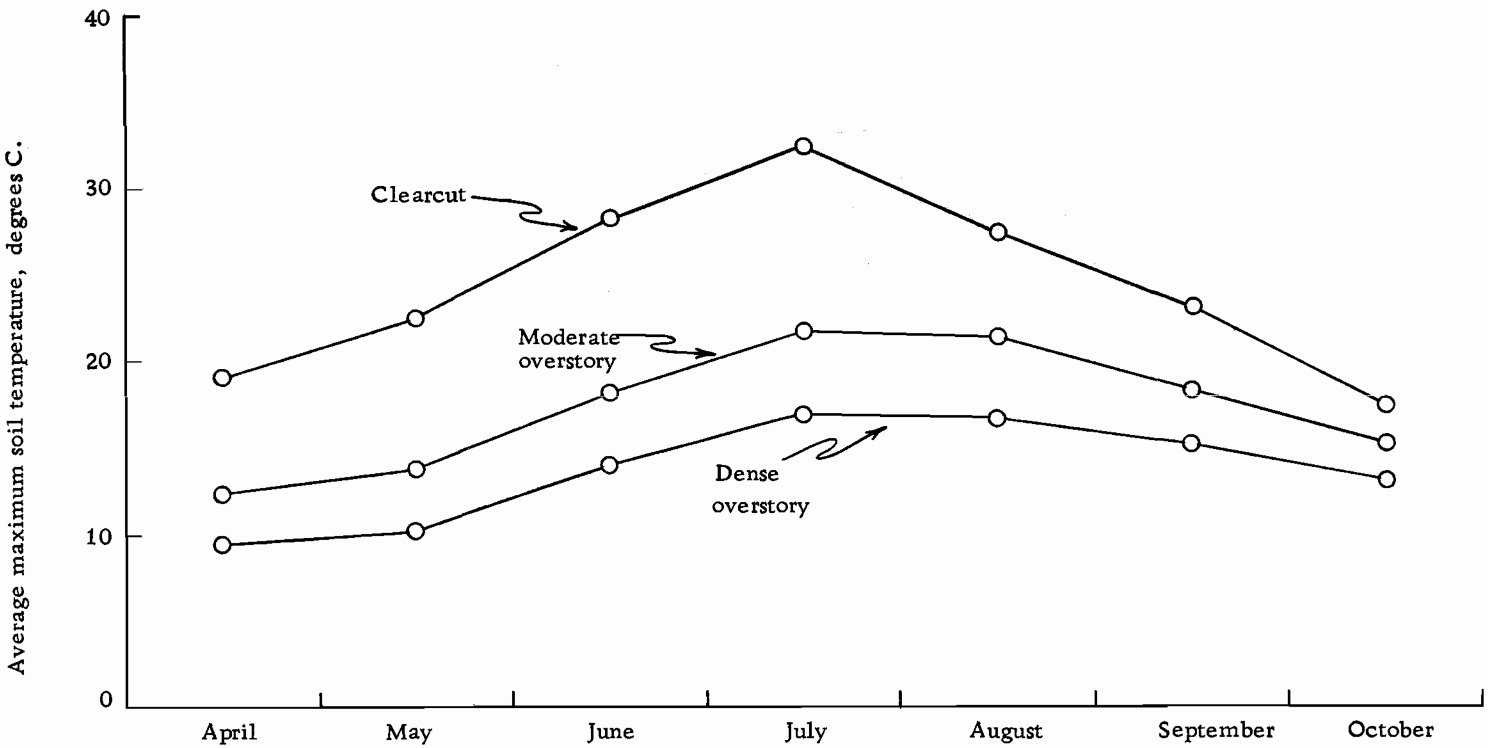


Figure 10. Monthly average maximum soil temperature, depth 2.5 cm, 1965 growing season.

was only 18 degrees. Weather conditions also had an important effect. On September 8, 1965 under an overcast sky, the maximum soil temperature on the clearcut reached an extreme of 18 degrees and under the dense overstory an extreme of only 13 degrees C (figure 11). The irregular shapes of the soil temperature curves from the shelterwood area on a clear day were due to interception of direct sunlight by tree stems.

Table 7. Average maximum and minimum soil temperature by cover class, shelterwood area, November 1963 to October 1965

| Temperature Measurement | Depth | Cover class: Clearcut | Cover class: Moderate Overstory | Cover class: Dense Overstory |
|---|---|---|---|---|
| | Centimeters | - - - - - - - - | Degrees C | - - - - - - - - - |
| Maximum | 2.5 | 16.9 | 12.4 | 9.8 |
| | 5.0 | 15.6 | 11.5 | 9.4 |
| Minimum | 2.5 | 6.3 | 7.5 | 7.0 |
| | 5.0 | 7.4 | 8.3 | 7.4 |

Comparing temperatures by depth class showed that maximums averaged higher and minimums lower at 2.5 centimeters than at 5.0 centimeters (table 7) and that the temperature extreme at 5.0 centimeters lagged about two hours behind those at 2.5 centimeters (figure 12).

Soil Moisture. Soil moisture at zero to 7.5 centimeter depth

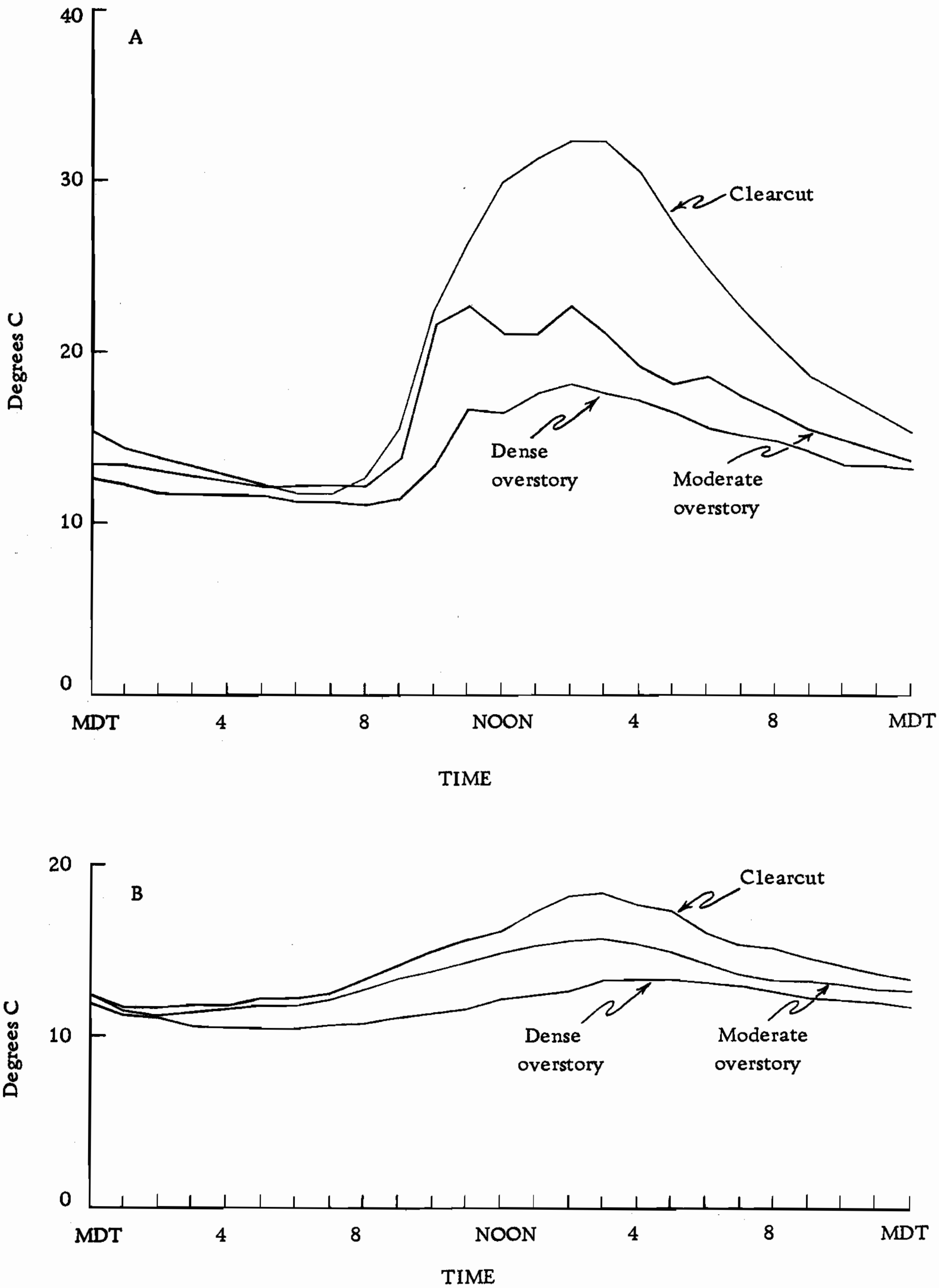


Figure 11. Diurnal soil temperature change by cover class, depth 2.5 cm. A = cloudless sky, August 5, 1965 B = overcast sky, September 8, 1965.

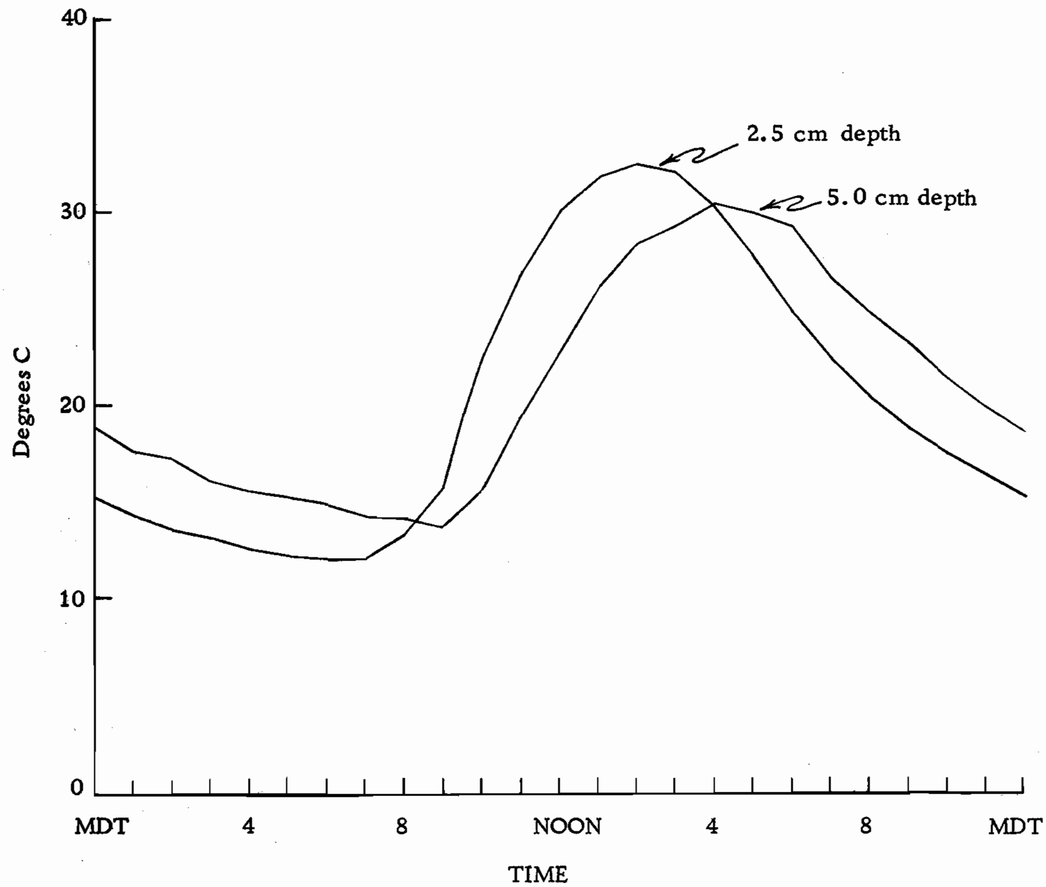


Figure 12. Diurnal soil temperature variation by depth class, clearcut area, August 5, 1965.

on July 29, 1965 after eight days with only 0.02 inches precipitation ranged from a high of 128 to a low of 60 percent, never approaching the low thirties where soil moisture would be limiting for seedling growth. The regression of soil moisture percent on radiation was highly significant indicating a significant decrease in moisture as the forest canopy was opened up and solar radiation increased (figure 13). There was a levelling off and some upward trend of the curve due to moisture percentages in the clearcut which were higher than the lowest percentages measured under the forest canopy.

Soil moisture measurements by half centimeter depth classes provided a better insight into moisture relationships. There was a highly significant difference in moisture percent among the depth classes in the top two centimeters of soil, and in all classes, a highly significant decrease in soil moisture with increasing radiation. There was no significant difference among the shapes of the curves indicating a similar downward trend in moisture for all depth classes (figure 14). In the laboratory test the soil moisture tension in the composite soil sample from line one reached 15 atmospheres at 41.4 percent moisture. Taking this as an estimate of the wilting point, the regression for zero to half centimeter depth passed below this level where radiation averaged only 100 Langleys per day, while the 1.5 to 2.0 centimeter curve did not do so until radiation averaged about 195 Langleys per day. Development of a

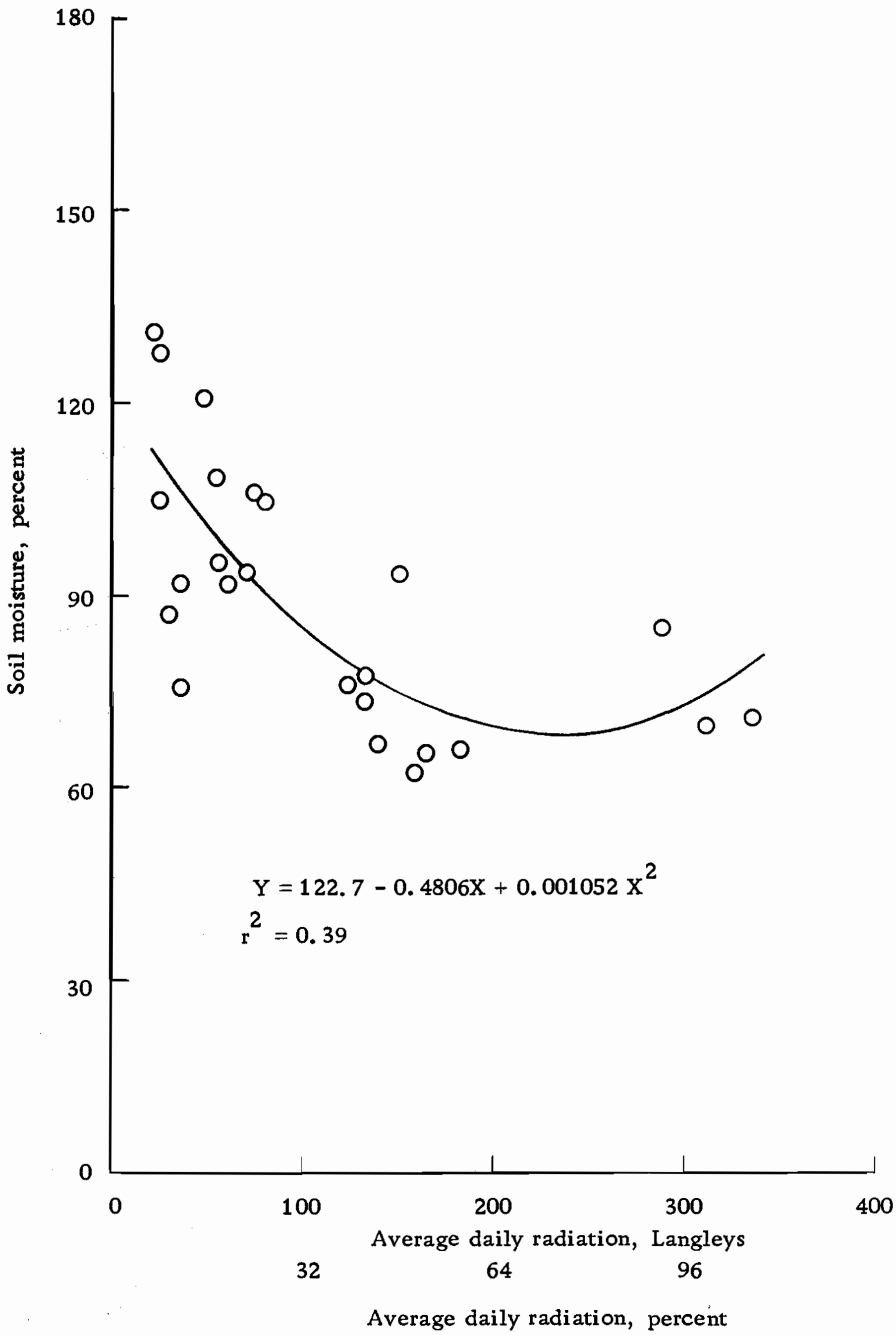


Figure 13. Regression of soil moisture on average daily radiation, shelterwood area and clearcut, July 29, 1965, depth 0 to 7.5 cm.

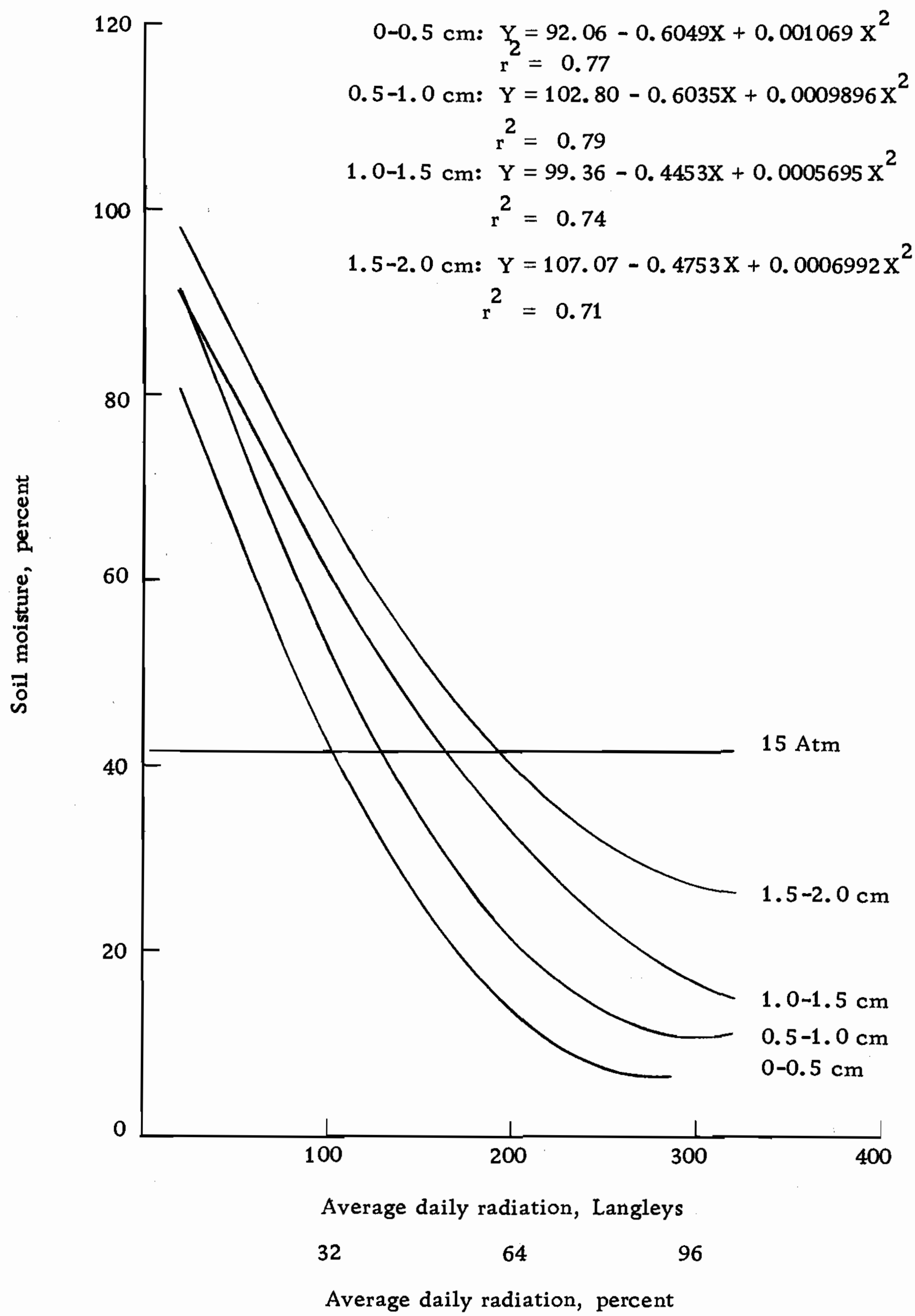


Figure 14. Regressions of soil moisture on average daily radiation in Langleys, by depth classes, shelterwood area, and clearcut, September 9, 1965.

15 atmospheres soil moisture tension at a moisture content as high as 41.4 percent is attributed to an appreciable clay content and a high organic matter content in the soil.

## Seedfall

Seedfall under the shelterwood stand was variable with a good hemlock crop in the 1962-63 seed year and medium spruce and hemlock seed crops in the 1964-65 seed year (table 8). Seedfall began in October each year and was about 95 percent completed by the following April. Absence of Douglas-fir seed the first two years is attributed to seed crop failures while the poor showing of this species relative to spruce and hemlock in 1964-65 was due to the small percentage of Douglas-fir seed trees in the shelterwood stand. All red alder seeds had to drift in from outside the study area, so little seed catch was expected.

Western hemlock seedfall was significantly related to stand density in the 1962-63 seed year when sound seedfall averaged 6,488,000 seeds or about 22 pounds per acre. The regression indicated an increase in seedfall of 20,490 seeds for each square foot increase in hemlock basal area. Even with this heavy seed crop there was considerable variability from trap-to-trap (figure 15). Calculation of curvilinear regressions indicated that curvilinearity was not significant.

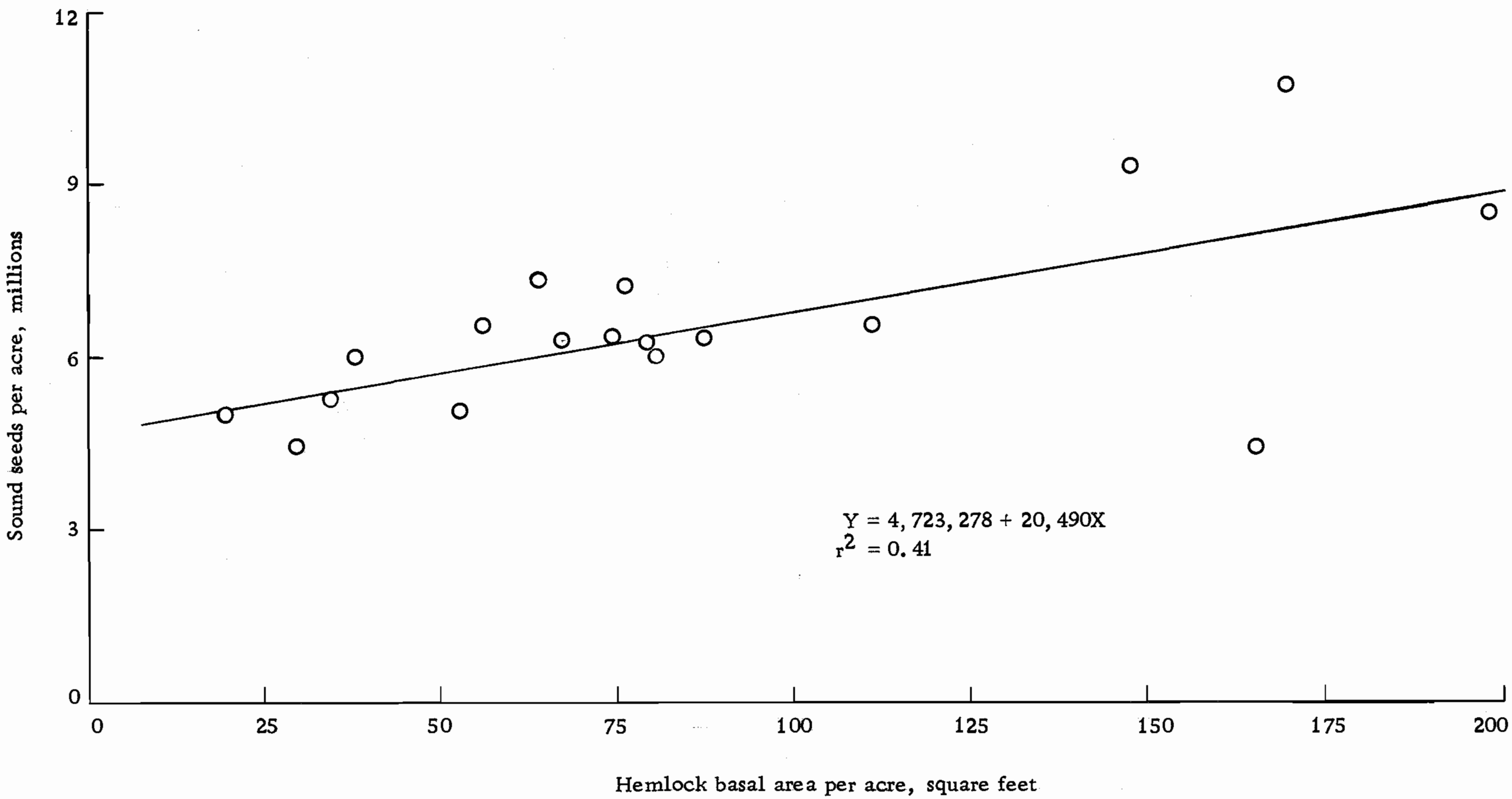


Figure 15. Regression of western hemlock seedfall on stand density, shelterwood area, 1962-63 seed year.

Table 8. Average sound seedfall per acre, shelterwood area, 1962-5

| Year | Sitka spruce | Western hemlock | Douglas-fir | Red alder |
|---|---|---|---|---|
| | - - - - - - - - - - - - - - - | thousands | - - - - - - - - - - - - - | |
| 1962-3 | 509 | 6,488 | -- | 4 |
| 1963-4 | 120 | 16 | -- | 4 |
| 1964-5 | 1,002 | 1,294 | 5 | 7 |

These results support the conclusion from the exploratory study that a spruce-hemlock overstory produces tremendous numbers of seeds and it is unlikely that a shelterwood overstory would be made light enough for seed supply to limit seedling establishment. The single significant relationship between seedfall and basal area per acre indicates considerable horizontal movement of seed. Spruce basal areas around the seedtraps ranged from zero to 136.3 square feet per acre, yet seedfall was not significantly related to basal area. The seeds apparently did not fall directly downward. It appears that tight control of species composition of seedfall will require areas large enough to minimize edge effects. Long dissemination distances of spruce and hemlock seeds into clearcut areas also support this point (Ruth, 1955). Collection of red alder seeds in both shelterwood areas testifies to the wide horizontal movement of seeds of this species.

## Mineral Soil Plots

Number of Seedlings. Establishment of seedlings during the 1965 growing season varied widely among species and areas with all species doing much better under the shelterwood canopy than in the clearcut (table 9). On the clearcut, natural seedfall on the open and 1964 screened seedplots led to early establishment of a few spruce and hemlock seedlings, but by the end of the season all were dead. A few spruce and Douglas-fir survived the season on the direct seeding plots. Under the shelterwood, western hemlock seedlings outnumbered all others when seed came from natural seedfall but spruce outnumbered hemlock on the direct seeding plots. Little difference was found between the open seedspots and 1964 screened seedspots.

Regressions of number of seedlings on examination dates provides a good over-all view of timing of germination and survival on mineral soil. Germination of natural seedfall on the open seedspots and 1964 screened seedspots began about April 1, 1965, the 91st day of the year. Western hemlock started ahead of Sitka spruce and far surpassed spruce in numbers of seedlings per acre (figure 16). Hemlock germination exceeded mortality until August 2 when stocking on the plots reached a peak of 254,000 seedlings per acre; then mortality exceeded germination and numbers of seedlings declined

Table 9. Average number of seedlings on mineral soil plots by species, seed source, treatment, and area, September 1965

| Species | Natural seedfall | | | | Direct seeding on | |
|---|---|---|---|---|---|---|
| | Open seedspots | | 1964 screened seedspots | | 1965 screened seedspots | |
| | Shelterwood | Clearcut | Shelterwood | Clearcut | Shelterwood | Clearcut |
| | ----------Seedlings per acre------------ | | | | --Seedlings per plot-- | |
| Sitka spruce | 96,300 | 0 | 110,000 | 0 | 5.0 | 1.4 |
| Western hemlock | 206,100 | 0 | 267,410 | 0 | 3.0 | 0.6 |
| Douglas-fir | 1,800 | 0 | 38,625 | 0 | 2.8 | 0.8 |
| Red alder | 9,000 | 0 | 0 | 0 | 0.3 | 0 |

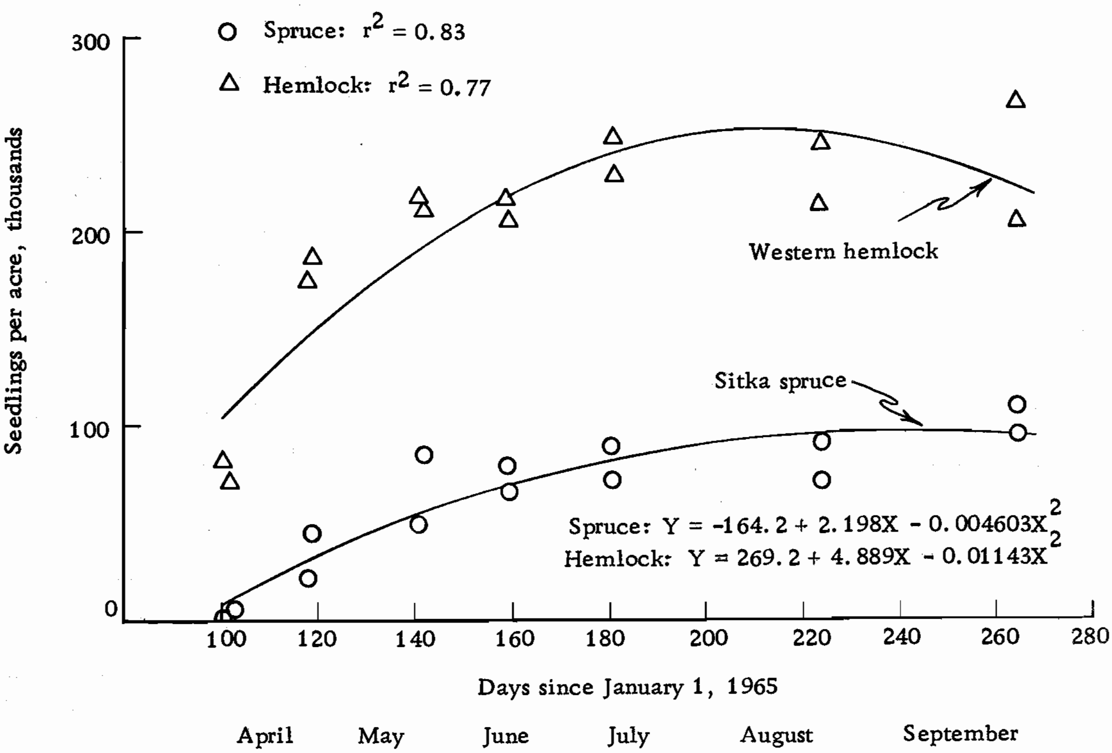


Figure 16. Regressions of 1965 seedlings per acre on time, by species, open and 1964 screened seedspots.

to 228,000 per acre on September 22. This was a ratio of one seedling established on mineral soil to a seedfall of 5.7 sound seeds. Spruce germination exceeded mortality until August 27, when stocking on the plots reached a peak of 98,000 seedlings per acre; thereafter, mortality exceeded germination but number of seedlings declined only slightly to 96,300 per acre on September 22. This was one seedling for a seedfall of 10.4 sound seeds. For both species the increase and subsequent levelling off or decrease in seedlings per acre with time was statistically significant.

Germination of seed artificially sown on the 1965 screened seedspots began about May 10 (figure 17). Hemlock started only a few days ahead of spruce and Douglas-fir a week or ten days after. Start of germination for alder was uncertain because of the small number of seedlings. Alder seedlings per plot climbed only slightly to a peak of less than one on about August 16, then declined to 0.3 per plot at the end of season. This was one seedling per 46.7 viable seeds sown. Hemlock reached a peak of 5.3 seedlings per plot on September 3, then declined to 3.0 per plot at the end of the season. This was one seedling per 6.7 viable seed sown. Spruce peaked at 6.3 per plot on September 20, then declined to 5.0 which was one seedling per 3.8 viable seeds. Douglas-fir peaked at 3.4 per plot on September 28, then declined to 2.8 which was one seedling per 5.8 viable seeds sown.

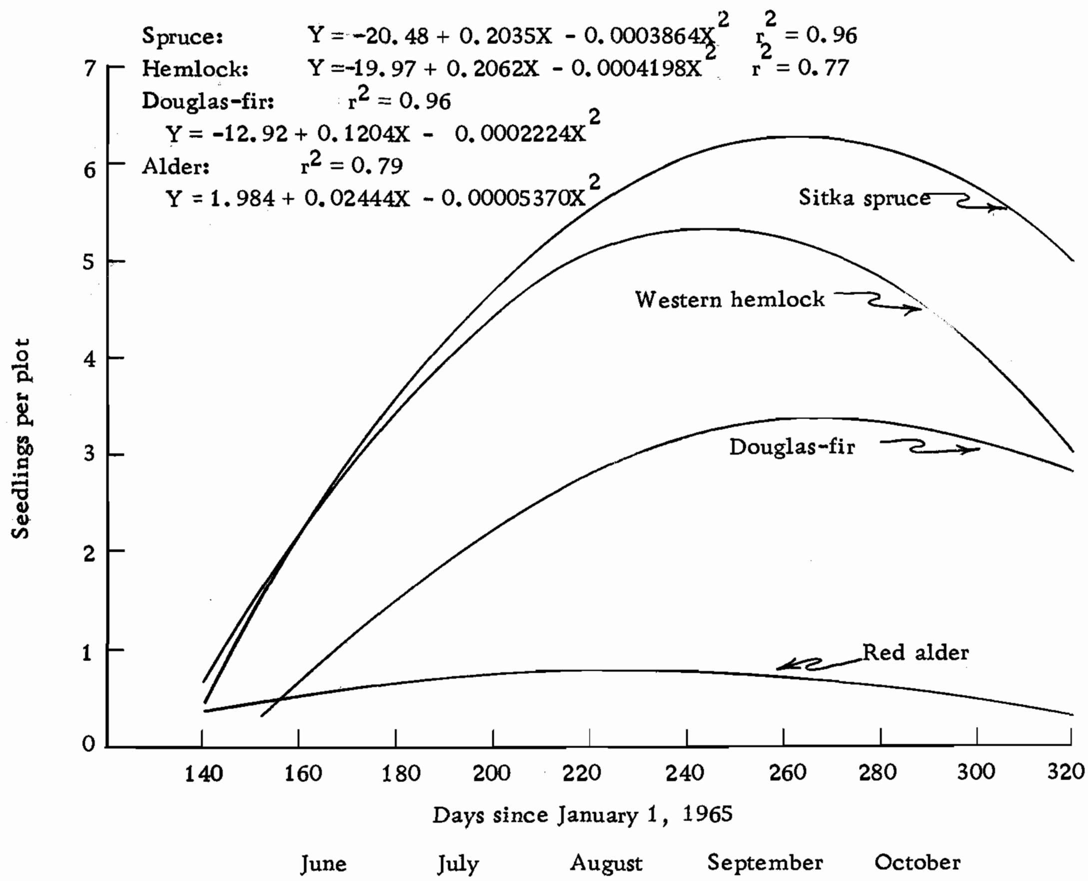


Figure 17. Regressions of seedlings per plot on time, by species, 1965 screened seedspots.

With this general background of timing and magnitude of germination and survival, additional regression analyses were calculated using solar radiation as an independent variable.

First, regressions of maximum number of seedlings versus radiation were used as an estimate of optimum radiation conditions for initial seedling establishment. The first analysis was of establishment of seedlings from natural seedfall on 86 open seedspots during the 1965 growing season. Regressions for spruce, hemlock and alder indicated only spruce establishment had a significant relationship to radiation (figure 18). There was an increase in initial seedling establishment as radiation increased followed by a similar decrease as radiation continued upward. The maximum level of regression was 97 Langleys per day indicating this theoretical optimum for spruce seedling establishment in the shelterwood area. On the clearcut, the maximum number of seedlings on the plots was only two spruce and two hemlock. On a per acre basis, this represented 15,480 seedlings of each species. No Douglas-fir or alder were found.

Next, regression of the number of seedlings per acre at the end of the growing season versus radiation was calculated as a measure of optimum radiation conditions for seedling survival. The spruce regression was significant in this instance also, indicating a significant relationship of survival to radiation with optimum

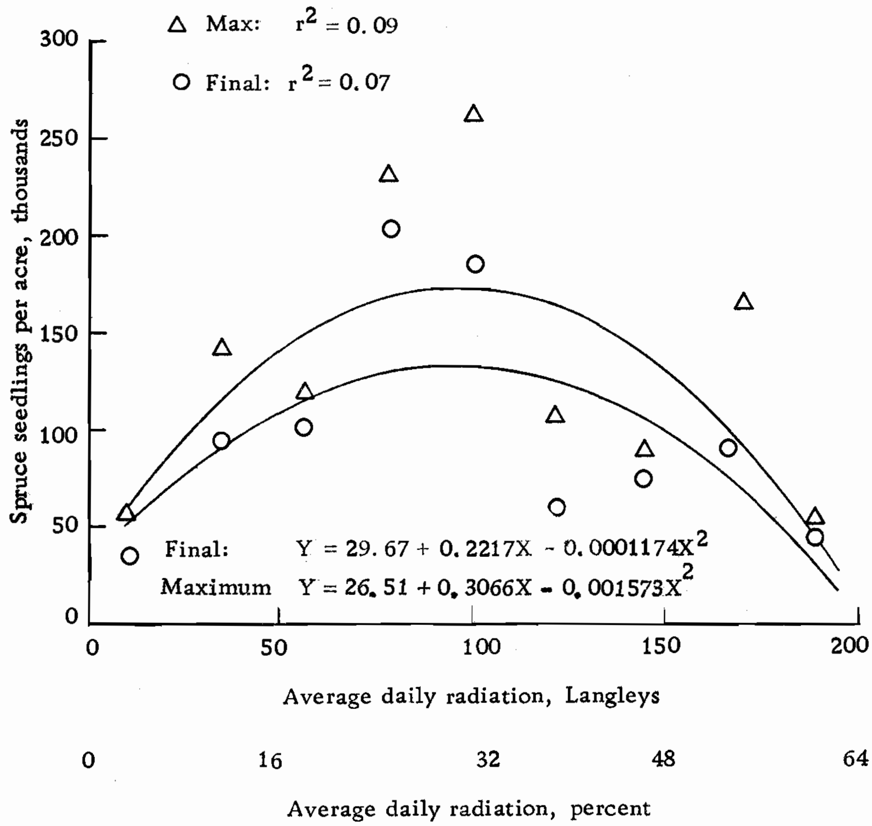


Figure 18. Regressions of Sitka spruce seedlings per acre on radiation by kind of observation, open seedspots.

radiation at 94 Langleys per day (figure 18). Covariance analysis testing for a significant difference between the maximum and final number of seedlings per acre, that is, the shapes of the regressions, revealed no significant difference. Therefore, once spruce seedlings were established, survival to the end of the season apparently was not related to radiation. The covariance analysis did indicate significant mortality had occurred because the average reduction in number of seedlings between the maximum and final observations was statistically significant. These seedlings-per-acre data were highly variable with the coefficient of determination only 0.09 for the maximum number of seedlings and 0.07 for the final number, indicating only nine and seven percent respectively of the variation in seedlings per acre was accounted for by radiation. No seedlings survived the season on the open seedspots on the clearcut area.

The second analysis was of establishment of natural seedlings on the 1964 screened seedspots during the 1965 growing season. Sample size was 42 plots. Regressions were calculated for maximum and final number of seedlings of spruce, hemlock, and Douglas-fir versus radiation. Maximum number of spruce seedlings per acre showed a significant curvilinear relationship to radiation but a non-significant linear relationship. Again this indicated no final increase in initial seedling establishment with increasing radiation, but first an increase followed by an almost equal decrease as radiation continued upward. This time an optimum was indicated at 109 Langleys per day and the coefficient of determination was 0.35. The final number of spruce seedlings was also significantly related to radiation with the optimum at 115 Langleys per day and coefficient of determination 0.14. Covariance analysis of the two spruce regressions, as on the open seedspots, indicated no significant effect of radiation on mortality occurring between the maximum and final observation; although a significant amount of mortality did take place. The linear regression of final number of Douglas-fir seedlings per acre on radiation was significant at the five percent level. The regression coefficient was 0.0403 indicating only a slight increase in final number of seedlings per acre with increasing radiation.

A third analysis of radiation effects on initial seedling establishment and first season survival was on seedling counts on the 1965 screened seedspots. The linear regressions for the maximum and final number of Douglas-fir and maximum number of red alder seedlings per plot were the only ones significant. For Douglas-fir this indicated an increase in initial establishment with increasing radiation as well as an increase in seedlings that survived the first season. The slopes of the two regressions were almost identical indicating no significant effect of radiation associated with mortality occurring between the two observations, but the levels were significantly different indicating that real mortality had occurred. For alder, beneficial effects associated with radiation were significant for the establishment period only (figure 19).

Neither hemlock establishment nor survival was significantly related to radiation in any of the tests.

Seedling Growth. Looking first at the averages for all light levels at the end of the 1965 growing season, Sitka spruce and western hemlock seedlings on the 1965 screened seedspots were similar in all length and weight measurements and in top-root ratio. The average Douglas-fir seedling was taller, had longer roots, and weighed more. Red alder weights and dimensions were variable, but generally intermediate between the small spruce and hemlock and the larger Douglas-fir (table 10). Some interesting relationships are hidden behind these general averages.

First season seedling growth was significantly related to solar radiation in 21 of 28 species-seedling response relationships measured. Except for top-root ratio, linear regression coefficients were all positive indicating, on the average, an increase in seedling weight or dimension with increasing radiation. Curvilinearity, however, was significant inten cases involving hemlock and spruce, indicating some levelling off or reversals for these species at the greater radiation levels (table 11).

Total dry weight is probably the best over-all measure of

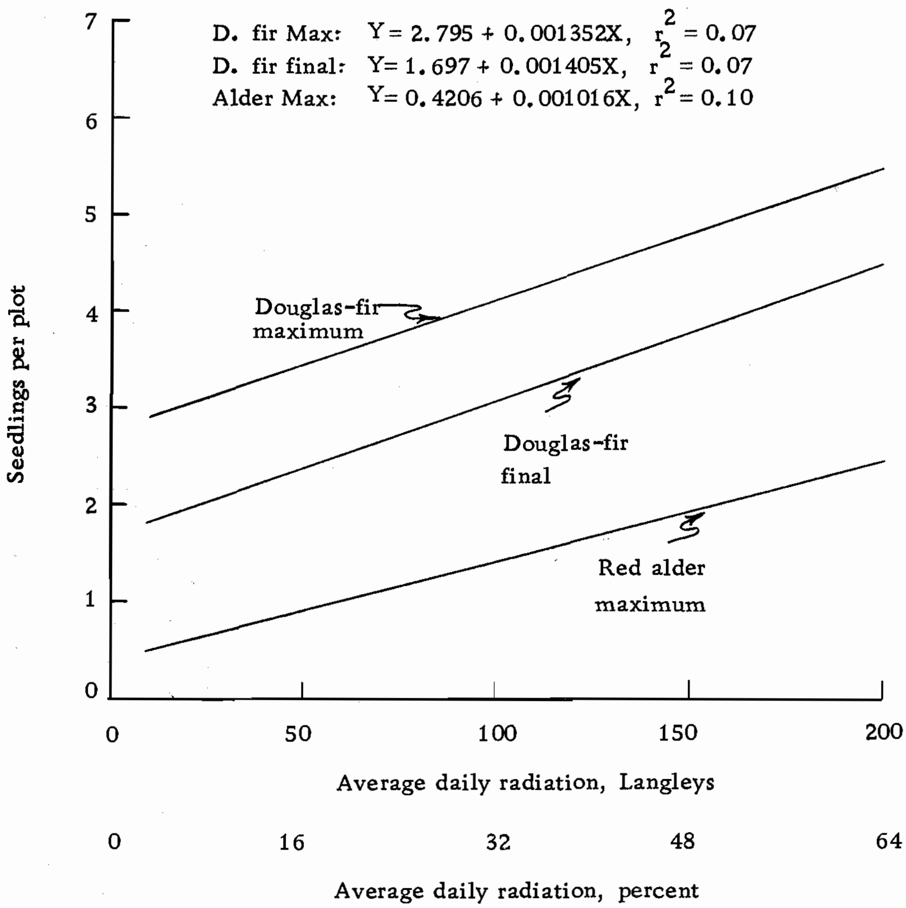


Figure 19. Regressions of seedlings per plot on radiation by species and kind of observation, 1965 screened seedspots.

Table 10. Averages of seedling measurements at end of first growing season by species, 1965 screened seedspots, shelterwood area

| Seedling measurement | Sitka spruce | Western hemlock | Douglas-fir | Red alder |
|---|---|---|---|---|
| Total weight, mg | 13.4 | 13.2 | 35.5 | 22.1 |
| Top weight, mg | 7.9 | 7.8 | 19.5 | 10.7 |
| Root weight, mg | 5.4 | 5.4 | 16.0 | 11.4 |
| Top-root ratio | 2.1 | 1.9 | 1.6 | 1.0 |
| Total length, mm | 63.7 | 69.7 | 102.4 | 72.1 |
| Height, mm | 19.3 | 22.4 | 31.5 | 21.4 |
| Root length, mm | 44.4 | 47.3 | 71.0 | 50.7 |

Table 11. Significance level of regression coefficients for regressions of seedling response on radiation by species and type of regression, 1965 screened seedspots

| Seedling measurement | Sitka spruce | | Western hemlock | | Douglas-fir | | Red alder | |
|---|---|---|---|---|---|---|---|---|
| | Linear | Quadratic | Linear | Quadratic | Linear | Quadratic | Linear | Quadratic |
| Total weight | .01 | .01 | .01 | .05 | .01 | NS | NS | NS |
| Top weight | .01 | .01 | .01 | .01 | .01 | NS | NS | NS |
| Root weight | .01 | .01 | .01 | NS | .01 | NS | NS | NS |
| Top-root ratio | NS | NS | .01 | .05 | .01 | NS | NS | NS |
| Total length | .01 | NS | .01 | .01 | .01 | NS | .01 | NS |
| Height | NS | .01 | .01 | .05 | .05 | NS | NS | NS |
| Root length | .01 | NS | .01 | .01 | .01 | NS | .01 | NS |

seedling growth, and significant positive linear regression coefficients indicated increases in weight with increasing radiation for spruce, hemlock, and Douglas-fir. Significant curvilinear relationship for spruce and hemlock indicated that for these species the higher radiation levels were associated with a downtrend in total weight. Optimum radiation for Sitka spruce was indicated at 140 and western hemlock 156 Langleys per day (figure 20). Covariance analysis testing spruce versus hemlock indicated no significant difference between them in first season dry weight response to radiation. A second analysis testing spruce, hemlock and fir indicated a highly significant difference among the dry weight responses, so it was obviously Douglas-fir that reacted differently from the others. Failure of seedling weights to approach zero at zero radiation was an indication of energy stored in the seed, a much greater amount in the case of Douglas-fir.

Lack of significant response of red alder to radiation may have been due to the small number of seedlings available for measurement. Only 38 seedlings on 15 plots survived to be measured at the end of the growing season.

Top weight and root weight of Sitka spruce, western hemlock, and Douglas-fir seedlings were related to radiation much the same as total weight (figures 21, 22). The linear regressions for all three species had highly significant slopes and significant curvilinear

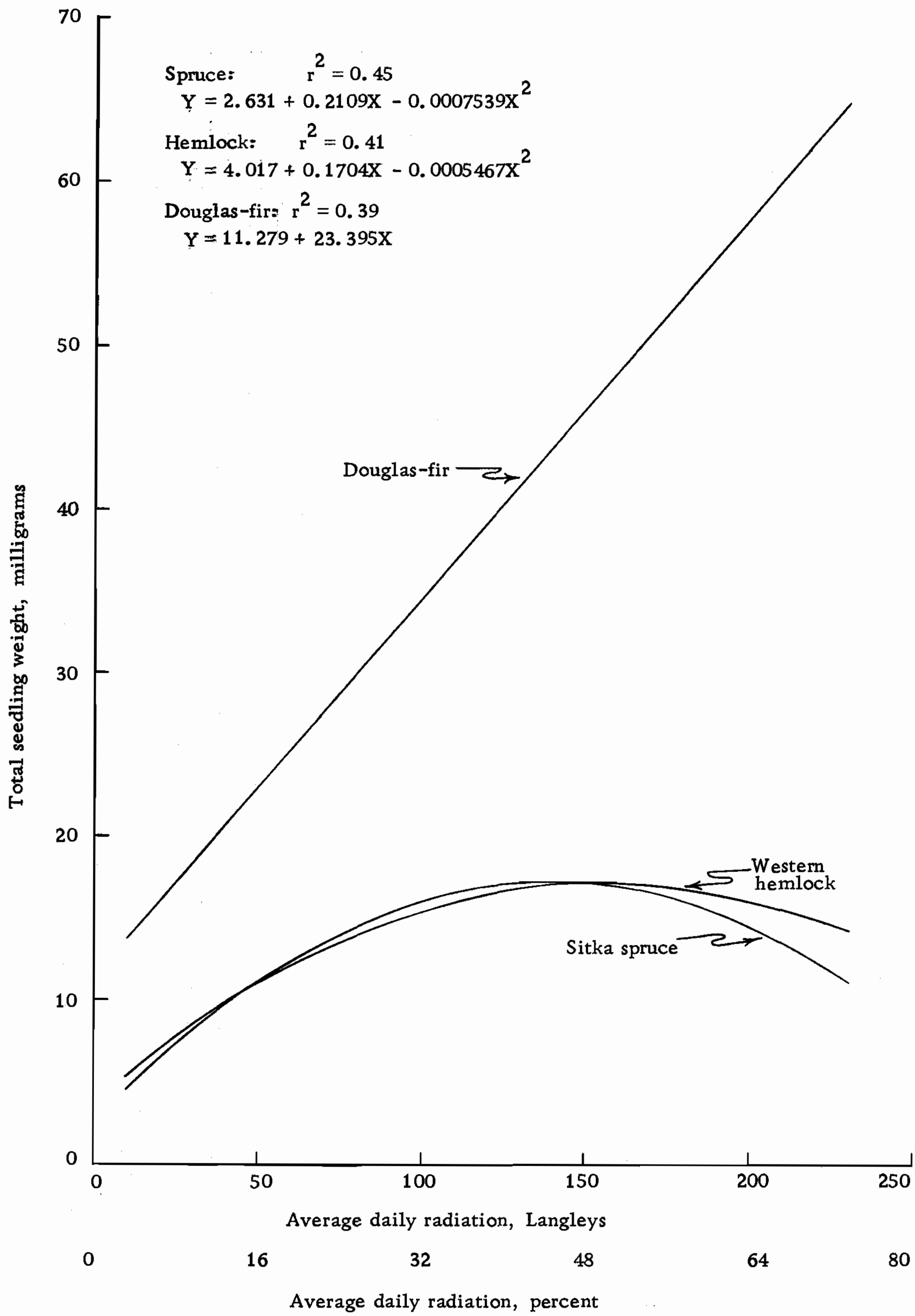


Figure 20. Regressions of total seedling weight on average daily radiation by species, shelterwood area, 1965 screened seedspots.

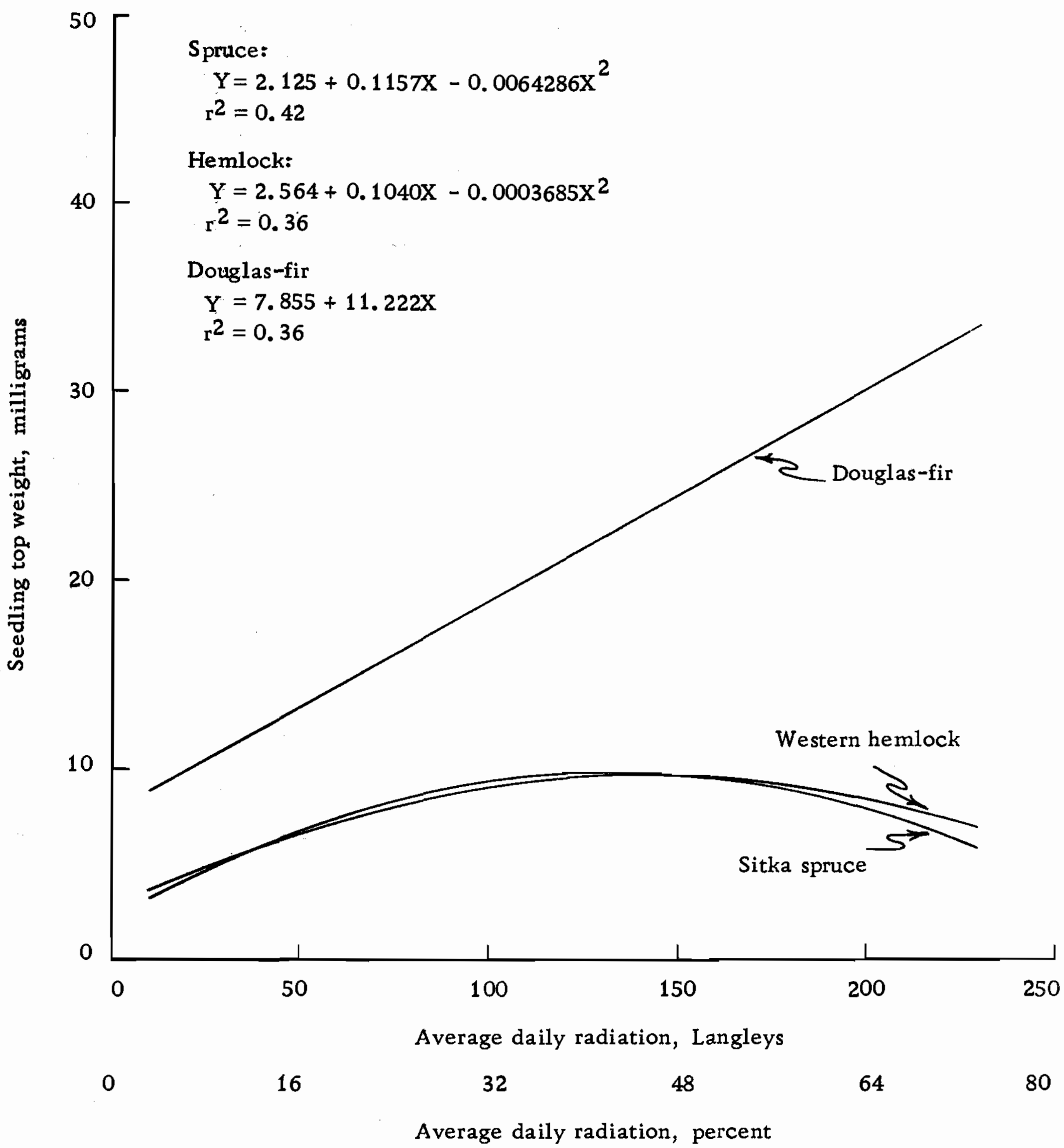


Figure 21. Regressions of seedling top weight on average daily radiation, by species, shelterwood area, 1965 screened seedspots.

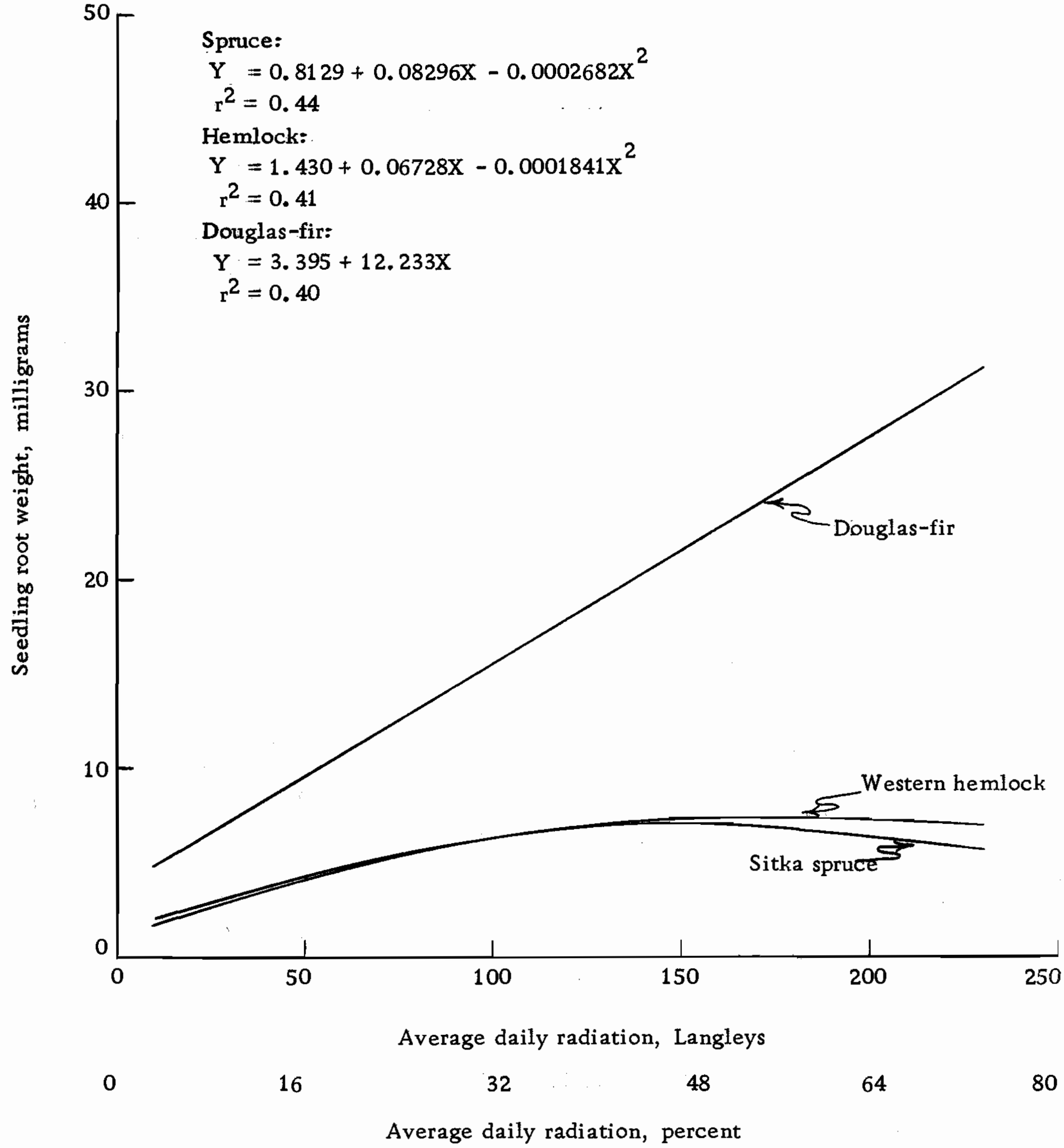


Figure 22. Regressions of seedling root weight on average daily radiation, by species, shelterwood area, 1965 screened seedspots.

relationships for spruce and hemlock again indicated that high radiation levels are associated with a downward trend in growth. The optimum radiation levels indicated by maximum regression levels were:

| | Sitka spruce | Western hemlock |
|---|---|---|
| | ----- Langleys per day ---- | |
| Top weight | 135 | 141 |
| Root weight | 155 | 183 |

Covariance analyses testing for significant differences between spruce and hemlock in top weight and root weight response to radiation level indicated no significant differences. Subsequent analyses testing the three species indicated highly significant differences among them in both top weight and root weight response to radiation. Again, it was Douglas-fir that was responding differently by continuing to increase in weight at the higher radiation levels.

The linear regressions of the top-root ratio on radiation showed highly significant decreases in top weight relative to root weight as radiation increased for western hemlock and Douglas-fir and non-significant changes for Sitka spruce and red alder. Covariance analysis indicated the differences among the slopes of regression were not significant, but there were highly significant differences among the levels of regression. Average top-root ratios were:

| | |
|---|---|
| Sitka spruce | 2.10 |

| | |
|---|---|
| Western hemlock | 1.90 |
| Douglas-fir | 1.63 |
| Red alder | 1.03 |

In the curvilinear regressions, only hemlock response was significantly different from a straight line (figure 23). The minimum hemlock top-root ratio of 1.43 occurred at an average daily radiation of 134 Langleys. Maximum dry weight production occurred at the slightly higher radiation level of 156 Langleys per day.

Linear regressions of total seedling length on radiation indicated a highly significant relationship for all four species (figure 24). Covariance analysis indicated no significant differences among the slopes of the four regression lines, but a highly significant differences among the levels of the lines. A subsequent analysis testing only Douglas-fir and hemlock indicated that fir seedlings were significantly longer. Red alder seedlings were about the same length as spruce and hemlock but had slightly greater response to radiation as indicated by the greater slope of the regression line. However, a covariance analysis testing for a significant difference between alder and hemlock revealed no significant difference in either their response to radiation or in average seedling length. A similar covariance analysis testing red alder against Sitka spruce also indicated no significant difference. Hemlock had a highly significant curvilinear response showing a definite downward trend in total

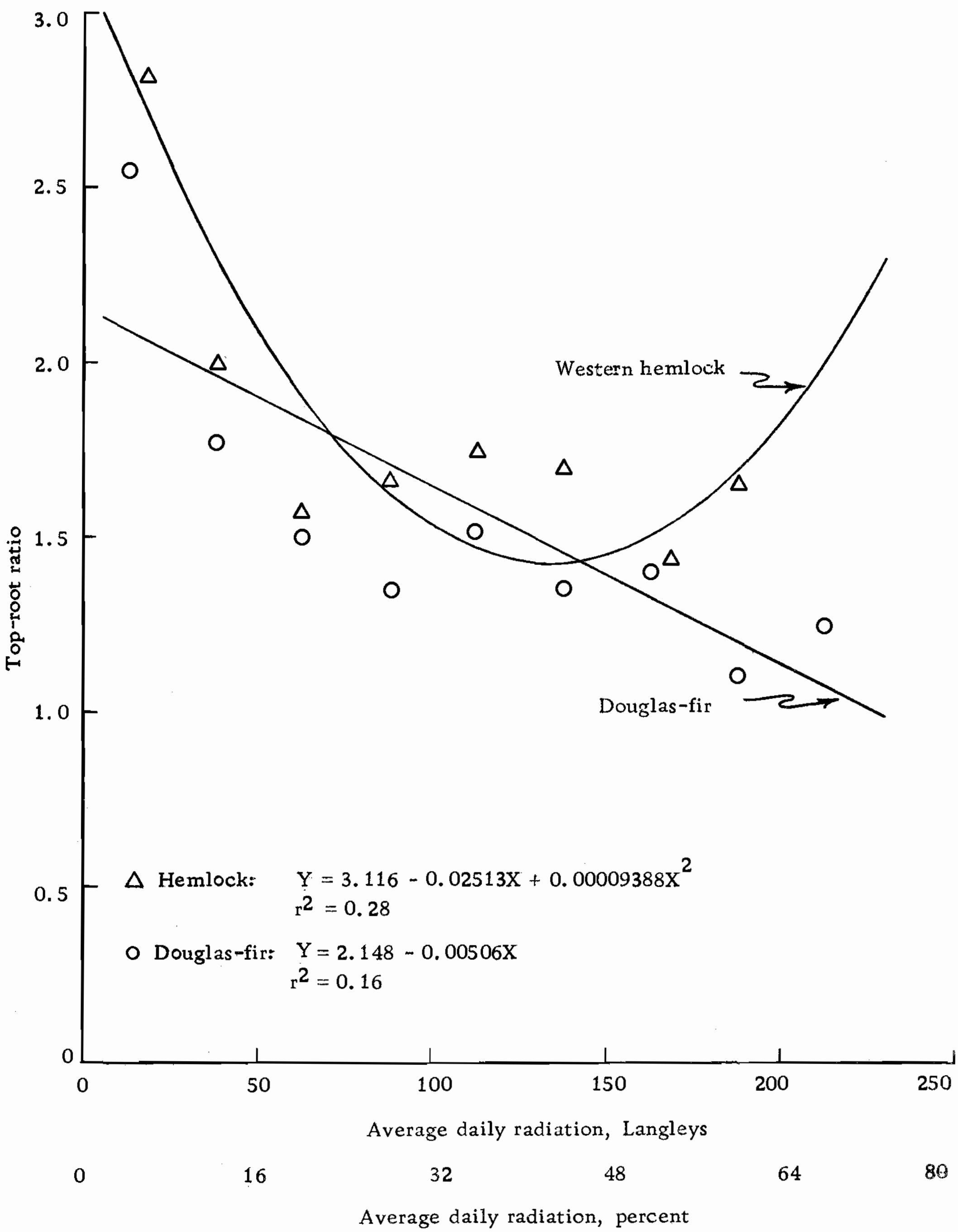


Figure 23. Regressions of top-root ratio on average daily radiation, by species, shelterwood area, 1965 screened seedspots.

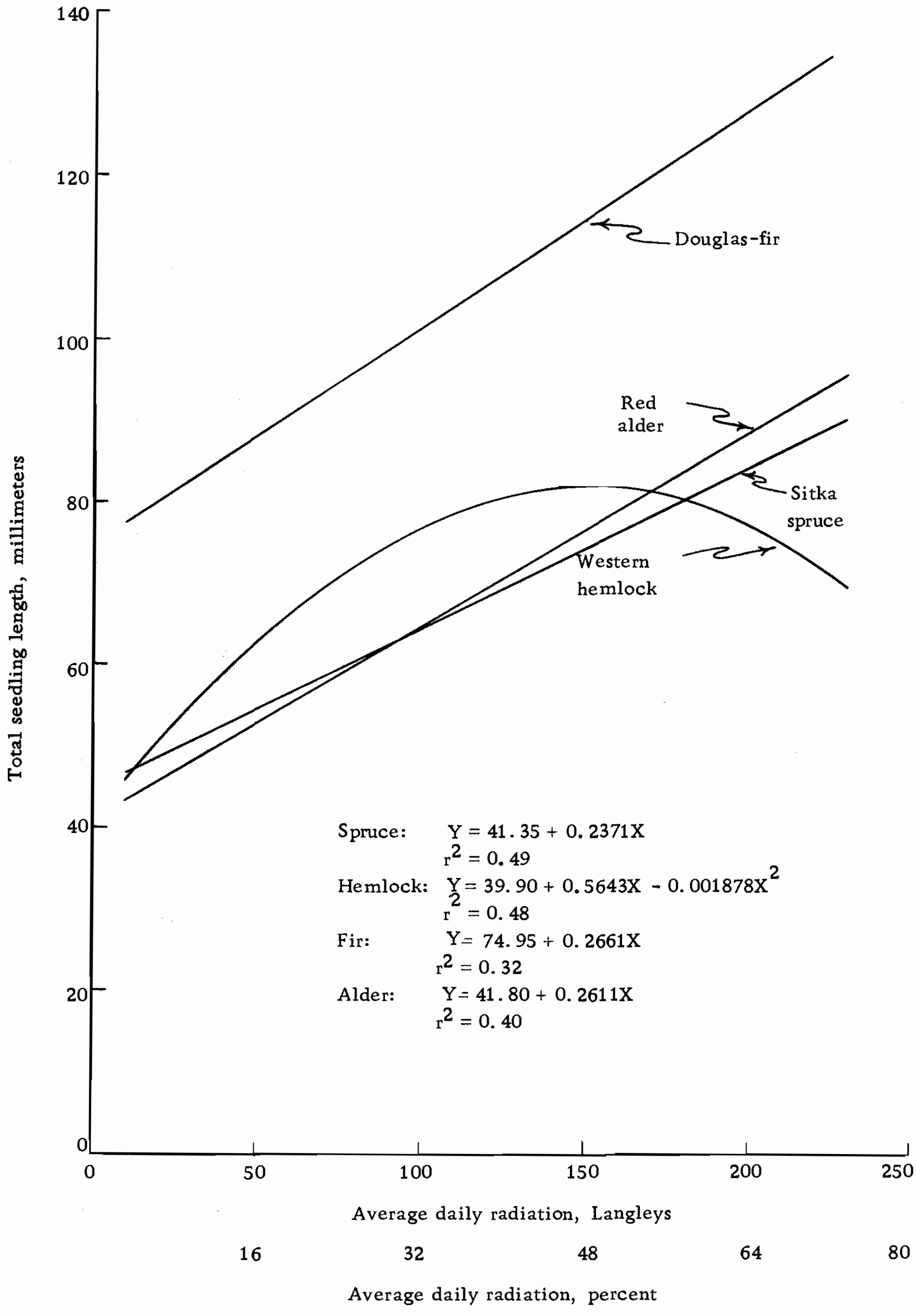


Figure 24. Regressions of total seedling length on average daily radiation, Sitka spruce and western hemlock, shelterwood area, 1965 screened seedspots.

length at the higher radiation levels with an optimum indicated at 150 Langleys per day. Spruce, while responding essentially the same as hemlock on a total weight basis, continued to increase in length with increasing radiation, its curvilinear response being non-significant.

Breaking total length down into top height and root length for separate analyses provided additional information on responses of the four species. All species demonstrated only slight increase in height with increasing radiation, with only hemlock and Douglas-fir having linear regression coefficients significantly different from zero. The curvilinear response in height was significant for spruce and hemlock, again demonstrating adverse effects associated with higher radiation levels for these species. Optimum radiation levels for height growth were indicated at 116 Langleys for spruce and 129 for hemlock (figure 25).

Linear regressions of root length on radiation showed highly significant increases with radiation for all four species. For spruce, the highly significant slope of the linear regression of total length on radiation (regression coefficient 0.2371), the non-significant slope for top height (regression coefficient 0.0093), and the highly significant slope for root length (regression coefficient 0.2279) indicated that on the average for this species the stronger relationship to radiation was in the roots. Hemlock top versus root response

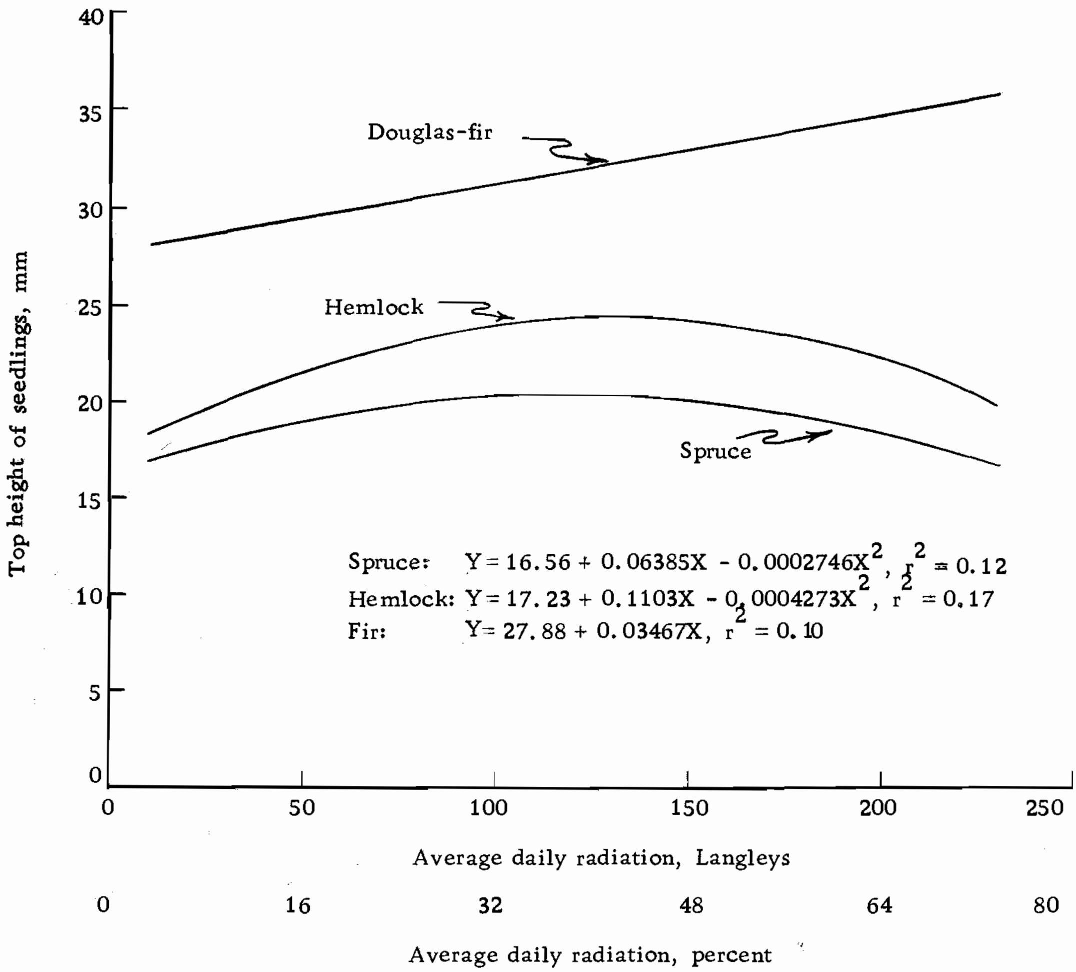


Figure 25. Regressions of top height on average daily radiation, Sitka spruce and western hemlock, shelterwood area, 1965 screened seedspots.

was similar, but the difference between tops and roots was not so great as with spruce. Covariance analysis indicated no significant differences among the slopes of the linear regressions, but a highly significant difference among levels of regression. A subsequent analysis testing only Douglas-fir and hemlock indicated Douglas-fir had significantly longer roots. Western hemlock demonstrated a significant curvilinear response in root length, again indicating detrimental effects associated with high radiation levels on first season growth of this species. Optimum radiation for root length was 156 Langleys per day. Sitka spruce roots continued to increase in length with increasing radiation, the curvilinear response being non-significant. On the average, hemlock roots were significantly longer than spruce (figure 26).

Supplemental plots established on the clearcut provided general comparisons with the shelterwood plots. Compared to the shelter-wood area, Douglas-fir seedlings on the clearcut averaged 83 percent more in total dry weight and there was a redistribution in weight from top to roots as indicated by a reduction in top-root ratio from 1.6 to 1.1. Clearcut data are based on a sample of 14 seedlings. Only ten Sitka spruce seedlings survived the season on the clearcut and they weighed a little less than seedlings under the shelterwood canopy. Only one hemlock and no alder seedlings survived on the clearcut plots (table 12). The clearcut received solar radiation

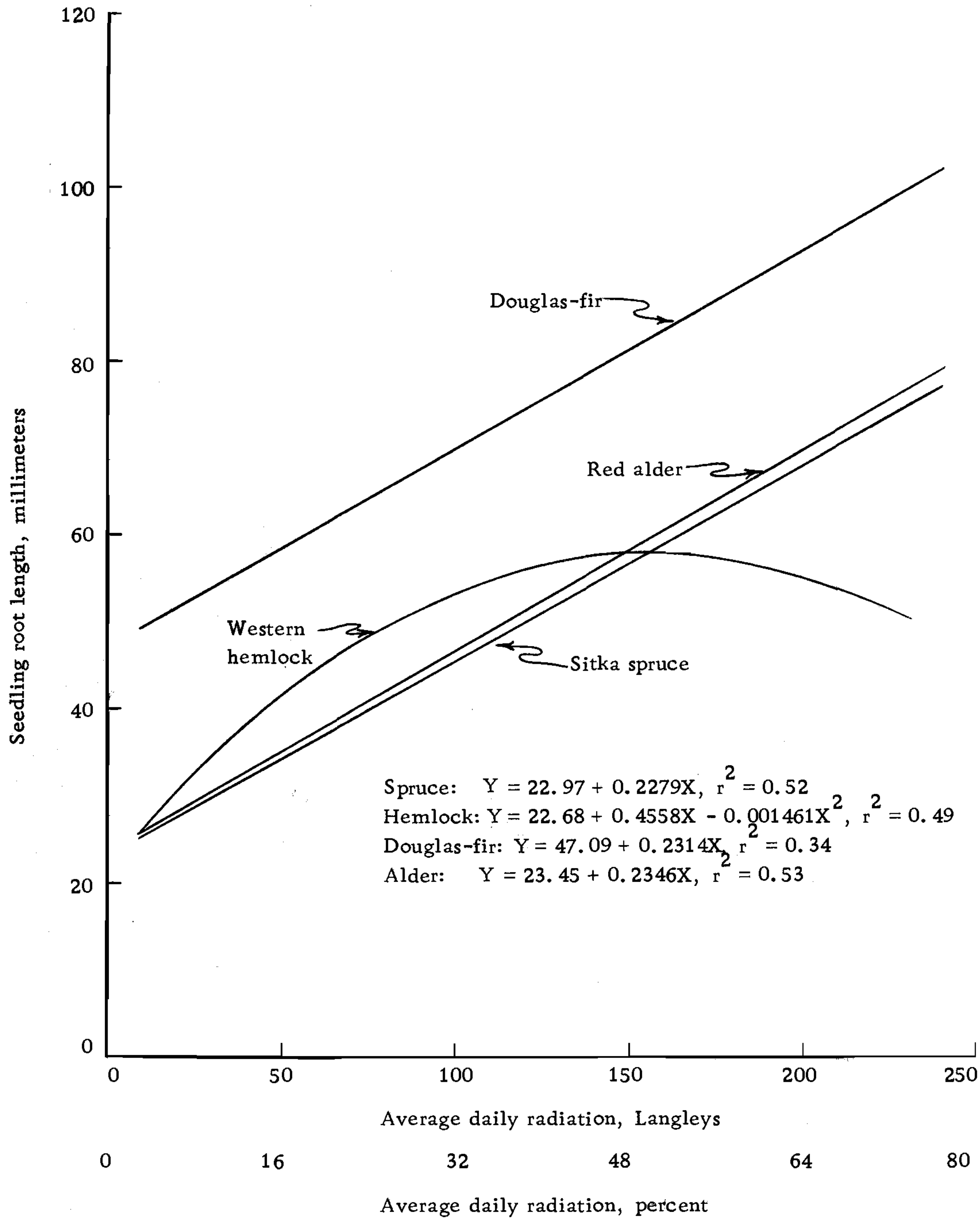


Figure 26. Regressions of seedling root length on average daily radiation, by species, shelterwood area, 1965 screened seedspots.

averaging 311.3 Langleys per day compared to radiation under the shelterwood which ranged up to 215.4 Langleys per day.

Table 12. Average of seedling measurements at end of first growing season, 1965 screened seedspots, by species and area

| Seedling Measurement | Species | | | |
|---|---|---|---|---|
| | Sitka spruce | | Douglas-fir | |
| | Shelterwood | Clearcut | Shelterwood | Clearcut |
| Total weight, mg | 13.4 | 12.0 | 35.5 | 65.1 |
| Top weight, mg | 7.9 | 9.1 | 19.5 | 32.6 |
| Root weight, mg | 5.4 | 2.9 | 16.0 | 32.5 |
| Top-root ratio | 2.1 | 4.4 | 1.6 | 1.1 |
| Total length, mm | 63.7 | 56.1 | 102.4 | 132.2 |
| Height, mm | 19.3 | 15.8 | 31.5 | 27.1 |
| Root length, mm | 44.4 | 40.3 | 71.0 | 105.1 |

## Height Growth Study, Mineral Soil Seedbeds

One-Year-Old Seedlings. Linear regressions of seedling heights measured along tractor roads showed significant increases with increasing radiation for all species. Calculation of curvilinear regressions revealed that red alder suffered large reduction in height at the higher radiation levels. This same tendency was noted earlier in the 1965 screened seedspot data, but the sample was too small to describe the behavior with any precision. With 100 seedlings available in the present study, both the linear and first degree

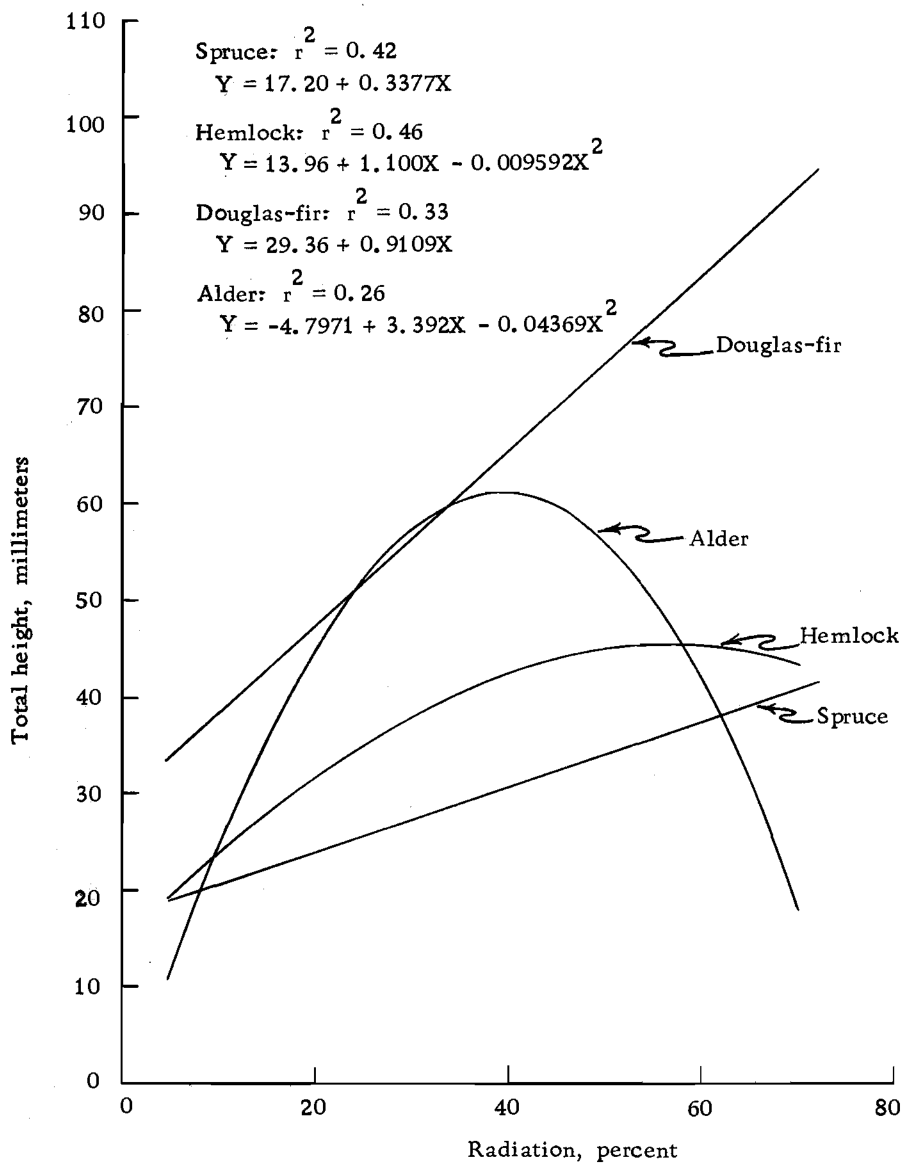


Figure 27. Regressions of height of one-year-old seedlings on radiation by species, height growth study, mineral soil.

curvilinear regression coefficients were significant (figure 27). Hemlock again demonstrated reduction with increasing radiation, but the reduction, while statistically significant at the five percent level, was not so abrupt as with alder. Optimum radiation levels for first-season growth was indicated at 39 percent for alder and 57 percent for hemlock. Curvilinearity was not significant for spruce based on a sample of 172 seedlings nor for Douglas-fir based on a sample of 26 seedlings. Average heights of these one-year-old seedlings from natural seedfall averaged greater than seedling height on prepared seedbeds. Also, on the prepared seedbeds only hemlock and Douglas-fir heights were significantly related to radiation.

Two-Year-Old Seedlings. Regressions of height of two-year-old seedlings showed significant curvilinear response to radiation for both spruce and hemlock (figure 28). Optimum radiation for two-year height growth of spruce was 48 percent and for hemlock 41 percent of radiation in the open. The 1965 height growth was measured and analyzed separately to permit a look at second-season effects alone, and again, curvilinearity was significant (figure 29). Optimum radiation for second-season growth of spruce was indicated 54 percent, and for hemlock, 49 percent of radiation in the open. Samples of total height and second-year height growth of fir and alder were small and no significant relationships with radiation were found.

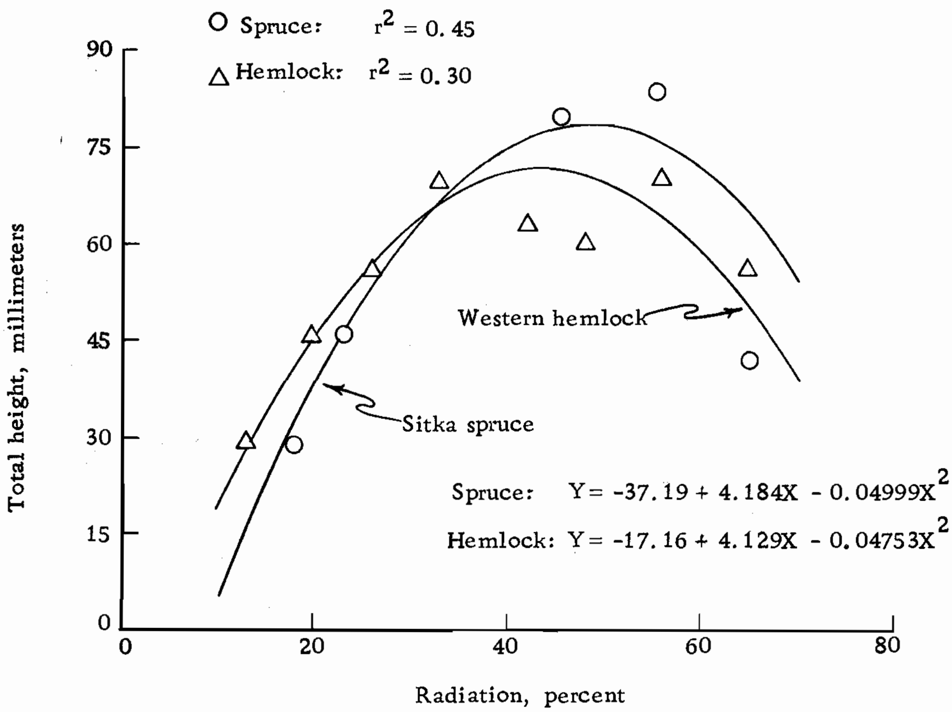


Figure 28. Regressions of height of two-year-old seedlings on radiation by species, height growth study, mineral soil.

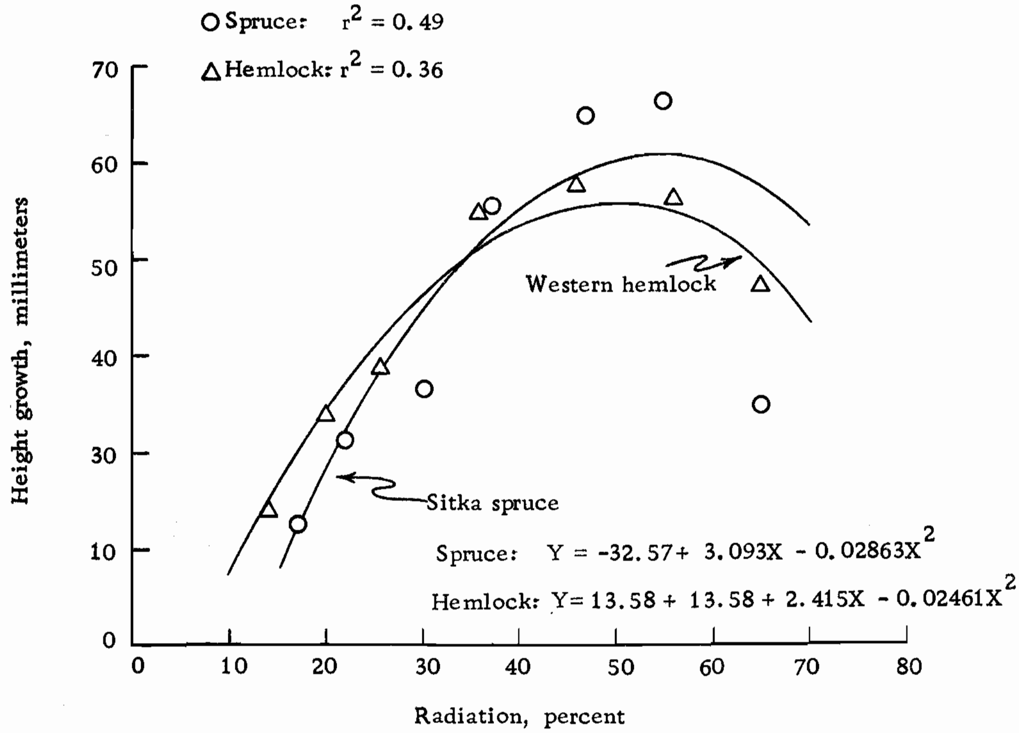


Figure 29. Regressions of 1965 height growth of two-year-old seedlings on radiation by species, height growth study, mineral soil.

## Two-Year-Old Seedling Analysis

Total heights of two-year-old Douglas-fir seedlings varied widely, and even with a combined sample of 90 seedlings on 39 plots, regression analysis indicated no significant relationship with radiation. Average seedling height was 8.4 centimeters.

Average height of red alder seedlings was 10.0 centimeters. The slope of the linear regression of total height on radiation was not significantly different from zero. Curvilinearity, however, was significant at the five percent level indicating that also for this species increasing radiation was associated with reduced growth response. The optimum radiation level was 32 percent of radiation in the open (figure 30).

## Natural Regeneration Survey

The survey of natural regeneration established on variable natural seedbeds under the shelterwood stand showed western hemlock seedlings outnumbering Sitka spruce and averaging one-half centimeter taller. No Douglas-fir or red alder seedlings were established on the plot clusters.

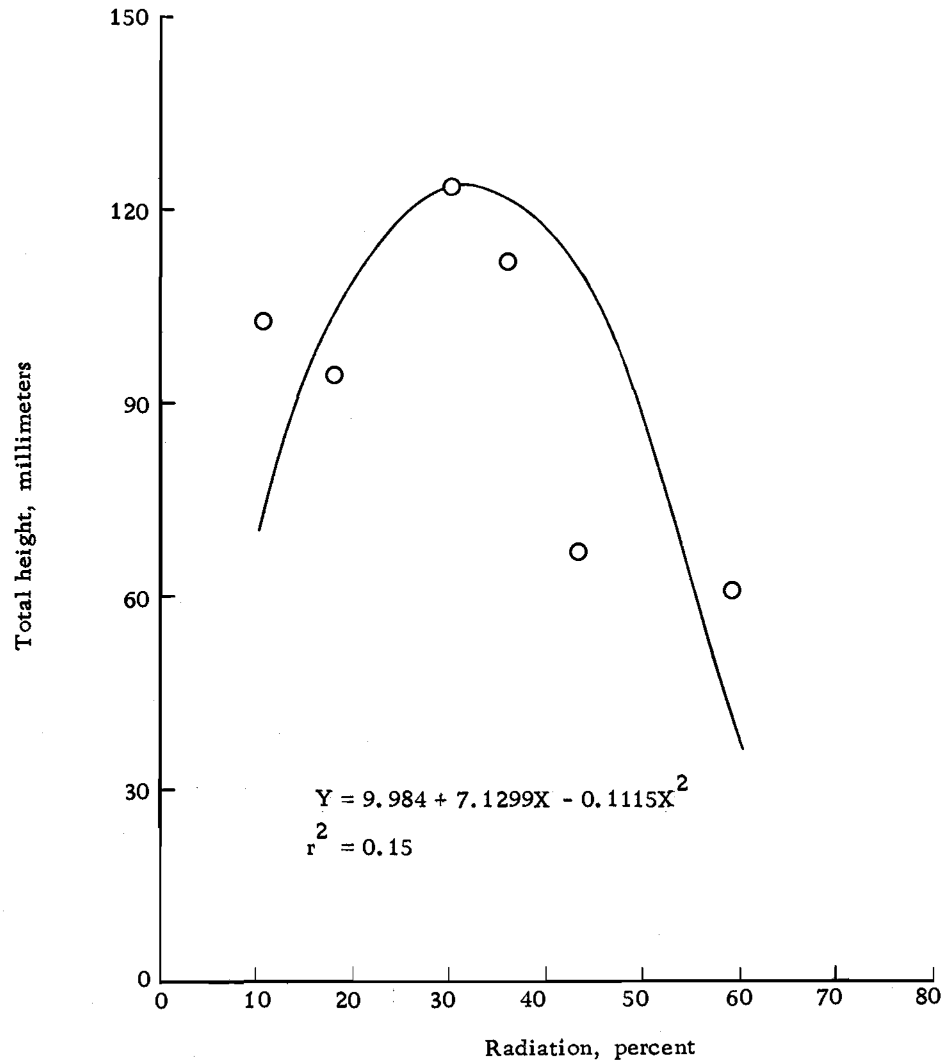


Figure 30. Regressions of total height of two-year-old red alder seedlings on radiation, shelterwood area.

| Species | Average number of seedlings per acre | Average height |
|---|---|---|
| | | Centimeters |
| Sitka spruce | 4,213 | 3.0 |
| Western hemlock | 12,680 | 2.5 |
| Douglas-fir | -- | -- |
| Red alder | -- | -- |

The multiple regression analyses showed that seedling establishment was highly variable and not significantly related to average daily radiation or sum of diameters per acre. The one significant relationship found was between number of hemlock seedlings per acre and basal area per acre of the overstory. Basal area only accounted for ten percent of the variation in numbers of seedlings. The relationship was

$$X = 2598 + 0.5133\ Y$$

where X equals number of seedlings per acre and Y equals basal area per acre in square feet. The relationship was positive indicating increasing seedling establishment with increasing basal area.

## Discussion

On the mineral soil seedbeds Sitka spruce, western hemlock, and Douglas-fir all became established more readily under the shelterwood canopy than red alder. This was demonstrated by the seed-to-seedling ratios on the 1965 screened seedspots. At the end of the season the ratio for the conifers averaged 5.8 viable seeds sown to 1 established seedling compared to 46.7 to 1 for alder. And mineral soil seedbeds generally are preferred by alder (Worthington, Ruth and Matson, 1962). Among the conifers, spruce did best, requiring only 3.8 seeds to produce a seedling compared to 6.7 hemlock and 5.8 Douglas-fir.

The large number of seedlings resulting from natural seedfall under the forest canopy testify to the efficiency of the shelterwood system for initial seedling establishment. Averaging the open seedspot and 1964 screened seedspot data and totalling all species gave 364,617 seedlings per acre established onthe mineral soil plots.

| Species | Seedlings per acre |
|---|---|
| Sitka spruce | 103,150 |
| Western hemlock | 236,755 |
| Douglas-fir | 20,212 |
| Red alder | 4,500 |
| Total | 364,617 |

Hemlock outnumbered spruce by a ratio of 2.3 to 1. Part of hemlock's advantage was due to the seedfall ratio the preceding winter of 1.3 hemlock to 1 spruce seed. But also, hemlock's lower seed-to-seedling ratio seemed to account for its better showing. On these plots it took 5.7 hemlock seeds to produce a seedling compared to

10.4 spruce.

The fact that spruce's seed-to-seedling ratio was above hemlock's based on natural seedfall (10.4 versus 5.7) and below hemlock's based on artificial seeding (3.8 versus 6.7) may have been caused by several factors. For example, spruce seed from natural seedfall germinated later than hemlock. A few days of dry weather could have damaged the germinating spruce more than the more advanced hemlock seedlings.

The poor showing on the clearcut probably was due to several factors. Natural seedfall, at least for the conifers, surely was less than under the forest canopy. Seedfall was not measured on the clearcut, but previous reports for comparable distances from the timber edge indicate a clearcut receives 0.07 (Garman, 1951) to 0.10 (Ruth and Berntsen, 1955) as much seed as received under a dense timber stand. The seedbeds were bare mineral soil with no shade from debris lying on the soil surface or from vegetation. General observations were that the surface soil dried quickly during even short periods of clear weather; so drought and perhaps lethal surface temperatures may have killed germinating seedlings. The better showing on the direct seeded plots was probably due to more seeds and covering the seeds with mineral soil at the time of sowing. Although coastal clearcuts generally regenerate well, these data indicate that initial seedling establishment is better under a shelterwood canopy. After root penetration below drought levels, the clearcut may well be superior for seedling growth.

Although the presence of the forest canopy was very important for seedling establishment, the intensity of solar radiation and, therefore, the density of the canopy had surprisingly little effect. This was true even though radiation ranged from less than 10 to almost 70 percent of radiation in the open. Hemlock, the species considered most tolerant of the four tested, showed no significant positive or negative relationships between number of seedlings and radiation for either natural or artificial seeding. Optimum radiation for spruce establishment from natural seedfall was about 100 Langleys per day or about 32 percent of radiation in the open. However, 50,000 or more seedlings per acre became established under radiation levels ranging all the way from 10 to 180 Langleys (figure 18).

Red alder seedlings that did become established showed a surprising tolerance of shade. This result first was noted in the field when natural alder regeneration appeared on mineral soil under dense timber stands. Alder seedlings seemed to extend back into the dense parts of the forest as far as Sitka spruce, although not as far as western hemlock. Alder seedlings established on prepared seedspots survived the season under very dense forest cover, one seedling surviving on a plot which received an average radiation of 7.2 Langleys per day, or 2.3 percent of radiation in the open. On the open seedspots, neither the maximum nor final number of alder seedlings per acre seemed to be related to radiation, but the sample was limited by inadequate seedfall. On the 1965 screened seedspots where alder was sown artificially, initial seedling establishment did increase significantly with increasing radiation, but radiation only accounted for ten percent of the variation. By the end of the season the radiation effect was no longer observed.

Douglas-fir was the only species showing consistent beneficial effects of increasing radiation on seedling establishment, but even here effects were minimal as indicated by slight slopes of the regression lines.

Perhaps the best way to sum up the effect of radiation on seedling establishment under the shelterwood canopy is to point out that even where significant relationships were found the coefficients of determination were generally very low. Very little of the variation in numbers of seedlings per acre was explained by radiation.

Looking now at seedling growth, radiation averaging about 150 Langleys per day during the growing season was optimum for first and second season growth of western hemlock on mineral soil. This was about 50 percent of radiation on the clearcut adjacent to the shelterwood area. It is only about 35 percent of average daily radiation on the Northwest taken as a whole (Reifsnyder and Lull, 1965). One hundred fifty Langleys per day was also a good radiation level for growth of Sitka spruce.

First-season shade tolerance of red alder already mentioned in terms of seedling survival was confirmed by the regressions of seedling growth on radiation. Alder seedlings grew as well or better than spruce and hemlock at low radiation levels. For example, figure 27 shows height of red alder seedlings exceeding that of spruce and hemlock beginning at about ten percent of radiation in the open. This fact becomes more important when one considers that alder seed weighs only about half as much as spruce or hemlock (U.S.D.A., 1948) and presumably contains a smaller nutrient capital. The optimum radiation for alder height growth was 39 percent compared to an optimum of 54 percent for hemlock on the same plots. An unexpected result was the sharp reduction in height at high radiation levels, contrary to what one might expect of an intolerant species.

The analysis of two-year-old seedling heights indicated that alder's shade tolerance extended into the second season. Heights were more variable and curvilinearity only significant at the five percent level, but numerous seedlings survived and grew at radiation levels below 20 percent. There was still a sharp reduction in height at higher radiation levels.

First season growth of Douglas-fir seedlings increased consistently with increasing solar radiation with all linear and no curvilinear regression coefficients statistically significant. Apparently, beneficial rather than detrimental effects associated with increasing solar radiation were dominant for the radiation levels tested. These ranged up to almost 70 percent of radiation in the open. And Douglas-fir grew well in the clearcut where it received full radiation. Douglas-fir clearly responded more favorably to increasing radiation than spruce, hemlock, and alder. At low radiation levels, however, it reacted much like the other species and showed a remarkable shade tolerance during its first two seasons. For example, two seedlings survived on a plot receiving an average radiation of 10.4 Langleys per day, or 3.3 percent of radiation in the open. Numerous seedlings survived and grew on plots receiving less than 25 percent radiation. Lack of a significant curvilinear relationship between Douglas-fir growth and radiation was also an indication of shade tolerance. Had seedlings been less tolerant, a significant drop in the level of survival and growth at low radiation values should have occurred.

Isaac (1943) also found germination of Douglas-fir under dense stands but, in contrast to results here, few survived the first season. The difference may be due to moisture conditions. Isaac's work was mostly in the Cascade Range where summer drought is much more pronounced than in coastal forests. He found that Douglas-fir seedlings would grow well for at least three years under a shade frame transmitting 20 percent light. Under a forest canopy at least 50 percent light was necessary for survival and reasonable growth. Hofmann (1924) reported that Douglas-fir would grow in 25 percent of full light but its growth is retarded, and more tolerant species such as western hemlock and Sitka spruce have the advantage.

The significant relationships between hemlock and Douglas-fir top-root ratios and radiation may have been merely a function of total seedling weight rather than a true radiation effect. Top-root ratios of woody plants normally decrease as total plant weight increases (Ledig and Perry, 1966). The ratio for western hemlock did so, then increased again as total weight decreased at the higher radiation levels (figures 20 and 23). The ratio for Douglas-fir also decreased with increasing seedling weight.

Significant decreases in soil moisture upward from the two centimeter level, and significant decreases with increasing radiation, have several implications for seedling establishment and growth. Surface moisture needed for germination probably was not a serious problem because natural germination began in April when precipitation was adequate and well distributed. Average April precipitation near the study area is 6.0 inches (Ruth, 1954). Penetration of the radicle into the top half centimeter of soil probably occurs mostly in May when precipitation averages 4.0 inches. A dry period during this process could result in high mortality. In fact, a drought anytime during the season could be disastrous depending on depth of soil drying relative to root penetration. This relationship of soil drought to root pernetration may have been what caused the high mortality on the clearcut. When soil moisture measurements were made on September 9, 1965, moisture at the 1.5 to 2.0 centimeter depth did not drop below the 15 atmosphere tension line until radiation exceeded 200 Langleys per day. When root measurements were made in November, root length averaged from 4.4 centimeters for spruce to 7.1 for Douglas-fir. Apparently spruce was most vulnerable to receding soil moisture and only spruce demonstrated a significant downward trend in number of seedlings per acre at the higher radiation levels (figure 18). Soil moisture tension probably contributed to this downward trend.

Soil moisture tension may also have contributed to the reduced growth of Sitka spruce, western hemlock and red alder at the higher radiation levels. Surely the upper part of most root systems were exposed to tensions greater than 15 atmospheres and most water uptake had to come from deeper in the soil. Soil moisture tensions did decrease significantly with depth, but even low tensions may reduce growth. Recent reviews by Hagan, et al. (1957), Marshall (1959), and Slatyer (1957) have shown that growth retardation can occur at surprisingly low tension values. For example, Zahner and Whitmore (1960) found that growth of loblolly pine (*Pinus taeda* L.) ceased when soil moisture tension was about three atmospheres. Douglas-fir did not exhibit significant growth reductions at high radiation levels, but with its longer roots a smaller proportion of its root system was subjected to high moisture tension. This differential effect of soil moisture on establishment of Douglas-fir as compared to hemlock and spruce was noted by Hofmann (1924). Working on drier sites, he found that Douglas-fir roots often extend 15 to 20 centimeters into the soil the first season, enabling them to survive where more shallow-rooted species fail.

Differences in average soil temperature associated with changing overstory density probably had only minor effects on seedling growth. Soil temperature at 2.5 centimeters under a moderate overstory averaged only 1.5 degrees C warmer than under a dense overstory. Assuming a growth increase of 1.4 percent per degree increase in average temperature (Shirley, 1945), seedlings under the moderate overstory would have grown only 2.1 percent faster.

The next step in this research was to measure growth response to solar radiation with soil moisture held relatively constant.

# SHADE SCREEN STUDY

## Introduction

In the field study of seedling response to solar radiation, only soil, aspect, slope, and competition from brush and herbs could be held relatively constant. The shade screen study was designed to hold these same variables constant and, in addition, minimize variation in soil moisture. Salmonberry (*Rubus spectabilis*) can be an important competitor for tree seedlings, so it was included to obtain a measure of its requirements relative to coastal tree species.

## Methods

Twelve raised seedbeds were prepared by constructing 120 × 120 × 28 centimeter wood frames and filling them with forest topsoil. A textural analysis of the soil was made at the Soil Physics Laboratory, Oregon State University, showing it to be a sandy clay loam to a loam. A sample also was analyzed at the Soil Chemistry Laboratory, Oregon State University, with results shown in Appendix C.

Nine seedbeds were selected for the shade screen study and shade levels assigned by random selection. Shade was provided by eight densities of Saran plastic shade cloth with the ninth seedbed left unshaded. Gaskin (1965) measured the effect of Saran plastic shade cloth on light quality and concluded that shade produced is comparable in light quality to shade by deciduous tree crowns until transmitted radiation becomes less than 25 percent of radiation in the open. When denser shade cloth is used, it absorbs less blue light than the forest canopy. Soil in the seedbeds was carefully levelled and weeds were removed promptly after emergence to eliminate any variation due to slope, aspect, or competition from other vegetation. An irrigation system was installed by wiring perforated plastic hose to stakes around and between the seedbeds (figure 31).

Sixty seedspots arranged in a rectangular grid of six rows and ten columns were laid out in each seedbed. Grid spacing was five centimeters in the row by 7.6 centimeters between rows. A 30 to 45 centimeter border isolated each grid from the edge of the seedbed. Shade cloths were suspended about 15 centimeters above the beds, and, as a further precaution against side effects, were extended at least 30 centimeters past the edges of the seedbeds.

Tree seed sources and stratification procedures were the same as for the 1965 screened seedspot study. Douglas-fir seeds were placed in stratification April 27 and spruce, hemlock, and alder May 4, 1965. Salmonberries were collected on the Cascade Head Experimental Forest in the summer of 1964, sun dried, and stored at -18 degrees C. That December the seeds were scarified by

Figure 31. Raised seedbeds used for shade screen study.

rubbing between two sheets of sandpaper. Then, using a warm plus cold stratification procedure (U.S.D.A., 1948), seeds were placed in moist sand in an ice cream carton, and stored at room temperature until April 1965. They were placed in a three-degree C room until time for planting.

The five species were assigned to the 60 grid intersections at random with the qualification that there be 12 seedspots for each species. A 1.0 to 1.5 centimeter deep trench was dug along each row, and three seeds were seeded together at each grid intersection. The seeds were covered by filling the trench with fine gravel and sand rather than mineral soil to provide good aeration. Seeding was done May 18 and 19, 1965. The seedbeds were watered as needed to keep the surface soil from drying out. This was usually once a day during clear weather, less frequently on overcast days, and not at all during periods of precipitation.

The seedbeds were examined July 28 and seedling emergence was poor. Excavation of a few seedspots revealed that some seeds failed to germinate while other seeds germinated but the hypocotyl failed to reach the surface. It was concluded that except for Douglas-fir the seeds had been planted too deep and that additional planting was needed. Observations were continued through the growing season, however. When more than one seedling emerged at a seedspot, the most vigorous was selected for measurement and the others clipped off at ground level on July 28. The seedlings were counted September 28 and in early November were lifted, soil washed from the roots, and top and root lengths measured. They were oven-dried, tops and roots weighed separately, and top-root ratios calculated.

Cotyledons were missing from a few seedlings at the July 28 examination and this led to discovery of small cutworms in the soil or gravel at the seedling base. They were controlled by a light spray of Ortho Isotox insecticide and subsequent infestation prevented by an application of cutworm bait containing calcium arsenate.

Seeds for the second planting were taken out of stratification June 29, 1965 and placed in germination dishes at room temperature. On July 6 and 7 germinated seeds were planted in the raised seedbeds in mineral soil between the gravel-covered rows of the first planting. The same randomization was used, but only one germinated seed was planted per seedspot making 12 seeds per species per shade class. Planting technique was to make a small hole with a pencil, place a germinated seed in the hole, radicle down, and cover it two to three millimeters with fine mineral soil. Not enough seeds had germinated to complete each grid, so seedlings were planted as they became available in the germination dishes. The final planting was on August 6. Not enough salmonberry germinated to provide an adequate sample and it was eliminated from this second planting. Seedling measurements during the remainder of the season were the same as for the first planting.

Radiation measurements were made by exposing vials of anthracene solution under the shade screens on August 5, August 26, and September 8 to 10, 1965. These measurements were concurrent with those in the shelterwood area and laboratory and computation procedures were the same. The first step in data analysis was to calculate regressions of percent emergence of each species by the July 28 examination versus radiation, with radiation expressed as a percent of that in the open. Secondly, regressions were calculated by species, separately for gravel-covered and mineral soil rows, of seedling weights, top height, root length, and top-root ratios versus radiation. For this second step, seedling data were averaged for each treatment category and the number of seedlings making up the average used as a weight in regression analysis.

## Results

Emergence of seedlings in the gravel-covered rows was generally poor but did show that Douglas-fir was better than the other species in ability to work its way up through the gravel and sand and become established (table 13). The 1.0 to 1.5 centimeter planting depth apparently was too deep for satisfactory emergence of the other species. Calculation of regressions of emergence on radiation showed that only hemlock was significantly affected by shade class and it showed a significant decrease in emergence with increasing radiation. The regression equation was:

$$Y = 46.6 - 0.553X$$

where Y is the percent of seedlings emerged and X is solar radiation expressed as a percent of radiation in the open.

Table 13. Seedling emergence in gravel-covered rows by species, July 28, 1965

| Species | Emergence | |
|---|---|---|
| | Number | Percent |
| Sitka spruce | 73 | 22.5 |
| Western hemlock | 61 | 18.8 |
| Douglas-fir | 210 | 64.8 |
| Red alder | 34 | 10.5 |
| Salmonberry | 19 | 5.9 |

In the mineral soil rows, development of germinated seeds into established seedlings was good for all species but somewhat better for spruce, hemlock, and Douglas-fir than for red alder. There was no apparent relationship to radiation (table 14).

Measurements of survival in the gravel-covered rows from July 28 until the end of the growing season were complicated by emergence of a few additional seedlings, but survival was generally very good and had no apparent relationship to radiation. Survival of germinated seeds planted in the mineral soil rows from the

Table 14. Seedlings in mineral soil rows by species and shade class, September 28, 1965

| Radiation | Species | | | | |
|---|---|---|---|---|---|
| | Sitka spruce | Western hemlock | Douglas-fir | Red alder | Average |
| Percent | Number of seedlings | | | | |
| 21.1 | 10 | 11 | 12 | 12 | 11.2 |
| 25.0 | 9 | 8 | 11 | 7 | 8.8 |
| 39.2 | 10 | 10 | 10 | 7 | 9.2 |
| 40.4 | 12 | 11 | 10 | 9 | 10.5 |
| 43.7 | 10 | 10 | 12 | 7 | 9.8 |
| 52.4 | 10 | 12 | 11 | 8 | 10.2 |
| 63.4 | 12 | 11 | 10 | 7 | 10.0 |
| 69.0 | 11 | 10 | 12 | 10 | 10.8 |
| 100.0 | 8 | 10 | 10 | 7 | 8.8 |
| Average | 10.2 | 10.3 | 10.9 | 8.2 | 9.9 |

Table 15. Seedling survival in gravel-covered rows from July 28 to November 1 and in mineral soil rows September 28 to November 1, 1965, by radiation level, average of four tree species

| Radiation | Survival | |
|---|---|---|
| | Gravel-covered rows | Mineral soil rows |
| Percent | | |
| 21.1 | 95 | 93 |
| 25.0 | 89 | 91 |
| 39.2 | 88 | 98 |
| 40.4 | 125 | 83 |
| 43.7 | 90 | 100 |
| 52.4 | 86 | 89 |
| 63.4 | 100 | 96 |
| 69.0 | 89 | 98 |
| 100.0 | 100 | 96 |

September 28 examination until the end of the growing season was also very good and also had no apparent relationship to radiation (table 15).

At the end of the growing season salmonberry seedlings had by far the greatest dry weight, with Douglas-fir second and red alder third (table 16). Salmonberry seeds in the gravel-covered rows germinated about the same time as the tree seeds, so salmonberry's greater weight could not be attributed to an earlier start. Except for Sitka spruce, seedlings in the gravel-covered rows weighed more than those in mineral soil rows. This difference probably resulted from the earlier seeding in the gravel-covered rows.

Regressions of total seedling weight on radiation were all non-significant indicating that where soil moisture was minimized as a variable, radiation had no significant relationship to dry matter production over the range of shade classes tested.

The distribution of dry weight between tops and roots also showed little relationship to radiation. The only significant regression of top-root ratio on radiation was the quadratic regression for Sitka spruce in the gravel-covered rows. It was significant at the five percent level and indicated a greater proportion of seedling weight in the roots at middle radiation levels (figure 32).

Linear regressions of root length on radiation showed that roots

Table 16. Averages of seedling measurements by species and treatment, raised seedbeds, November 1965

| Species and treatment | Total weight | Top Length | Root Length | Top-root ratio |
|---|---|---|---|---|
| | Milligrams | - - - - -Millimeters | - - - - - | |
| Sitka spruce | | | | |
| Gravel-covered rows | 14.8 | 21.4 | 66.1 | 2.2 |
| Mineral soil rows | 17.6 | 19.4 | 86.0 | 1.9 |
| Western hemlock | | | | |
| Gravel-covered rows | 14.7 | 24.0 | 91.3 | 2.1 |
| Mineral soil rows | 14.2 | 21.2 | 95.5 | 2.1 |
| Douglas-fir | | | | |
| Gravel-covered rows | 71.3 | 40.6 | 182.8 | 1.5 |
| Mineral soil rows | 57.8 | 34.9 | 181.6 | 1.6 |
| Red alder | | | | |
| Gravel-covered rows | 29.0 | 16.3 | 61.2 | 0.9 |
| Mineral soil rows | 18.6 | 13.2 | 67.2 | 0.5 |
| Salmonberry | | | | |
| Gravel-covered rows | 403.1 | 22.4 | 185.1 | 1.5 |

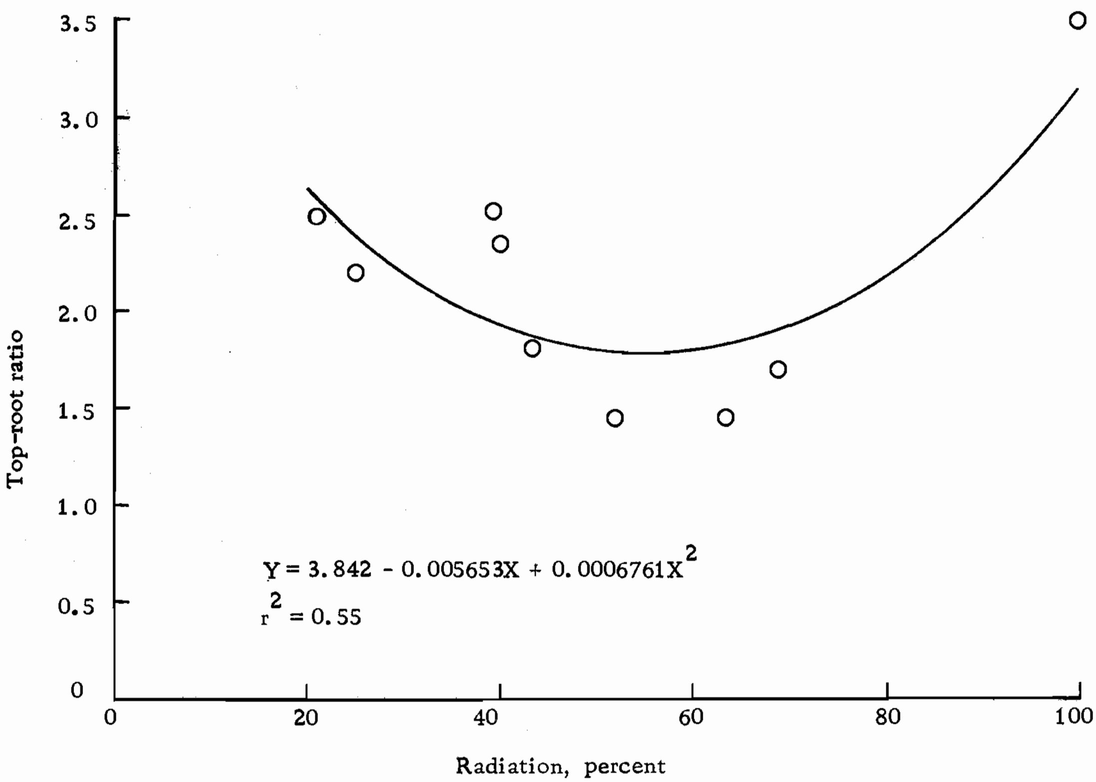


Figure 32. Regression of Sitka spruce top-root ratio on radiation, shade screen study, gravel-covered rows.

of spruce and alder in the mineral soil rows and Douglas-fir in the gravel-covered rows all grew significantly longer with increasing radiation (figure 33). The only significant curvilinear regression was for spruce in the gravel-covered rows. This indicated no over-all increase in root length with radiation, but an initial increase to 73 millimeters at 54 percent radiation followed by decreased root length at higher radiation levels (figure 34).

Regressions of top height on radiation showed that only top heights of western hemlock were significantly related to radiation. The linear regression had a slight but significant downward trend indicating decreasing top height with increasing radiation (figure 35).

## Discussion

The main result of the shade screen study was the few significant effects of solar radiation on seedling growth. With soil moisture provided, seedling dry weights were about the same at all radiation levels. The downtrend in spruce, hemlock, and alder weights associated with high radiation levels in the shelterwood area did not occur in the raised seedbeds. Apparently, soil moisture made the difference. Neither was there a downtrend at low radiation levels. The densest shade screen used, manufacturer's rating ten percent, actually transmitted 21.1 percent of radiation in the open. As a result, the very low radiation intensities observed in the shelterwood

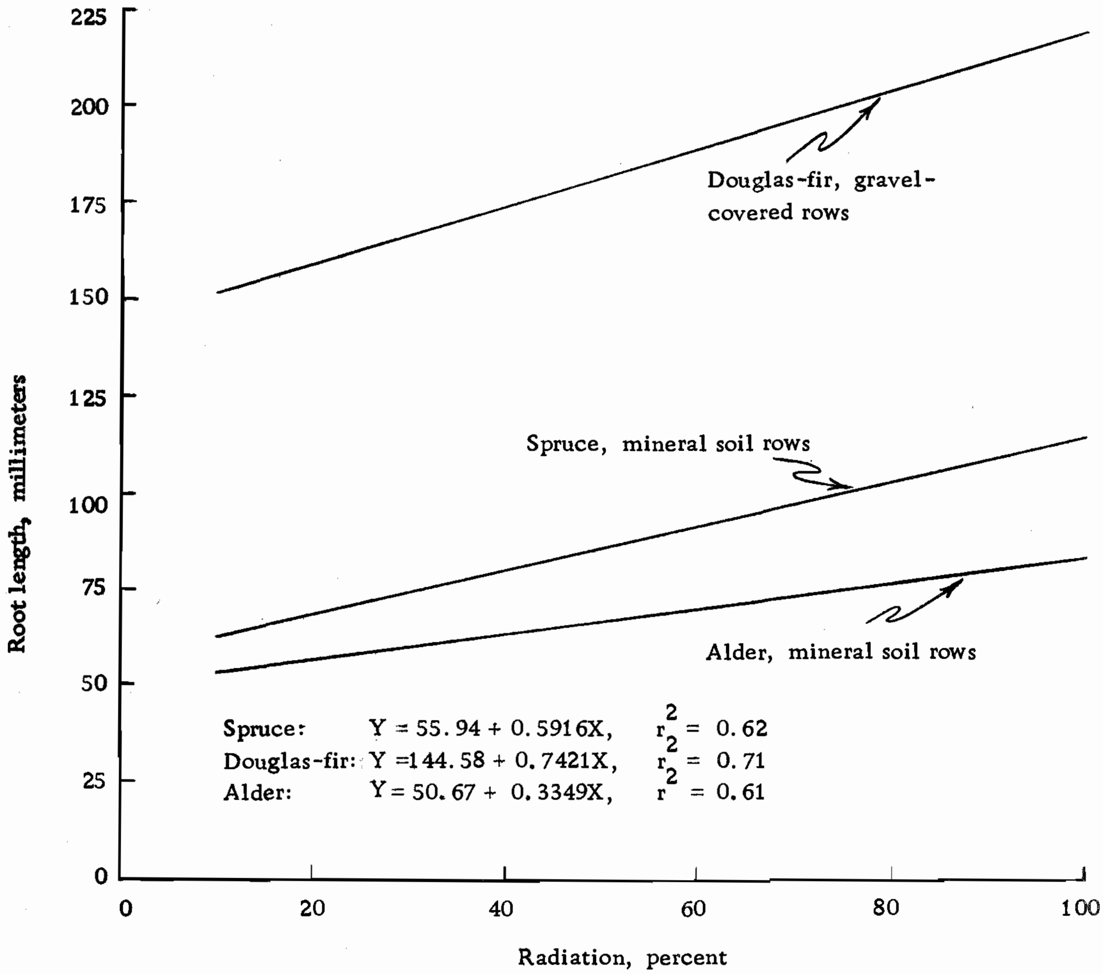


Figure 33. Regressions of root length on radiation by species and treatment, raised seedbeds, November 1965.

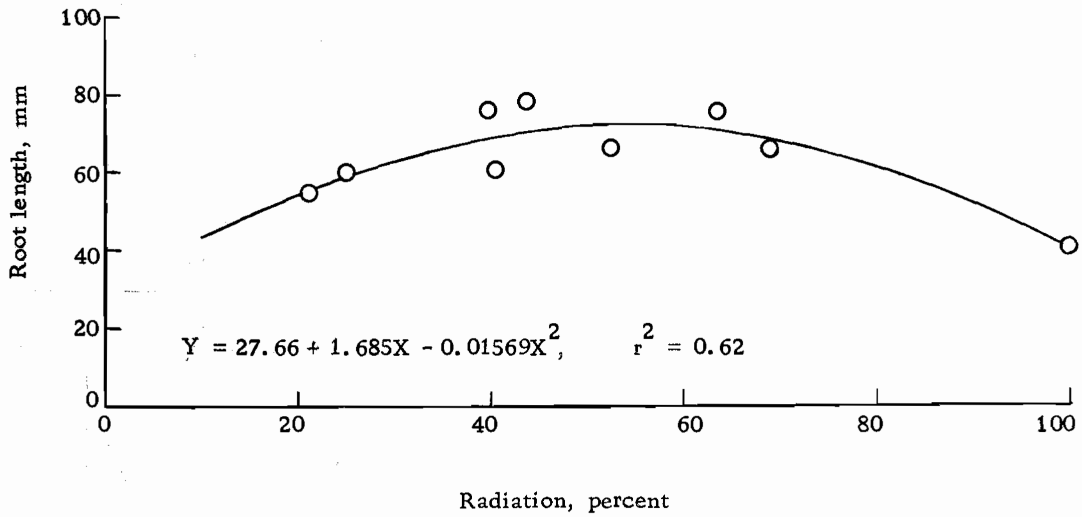


Figure 34. Regression of spruce root length on radiation, raised seedbeds, gravel-covered rows, November 1965.

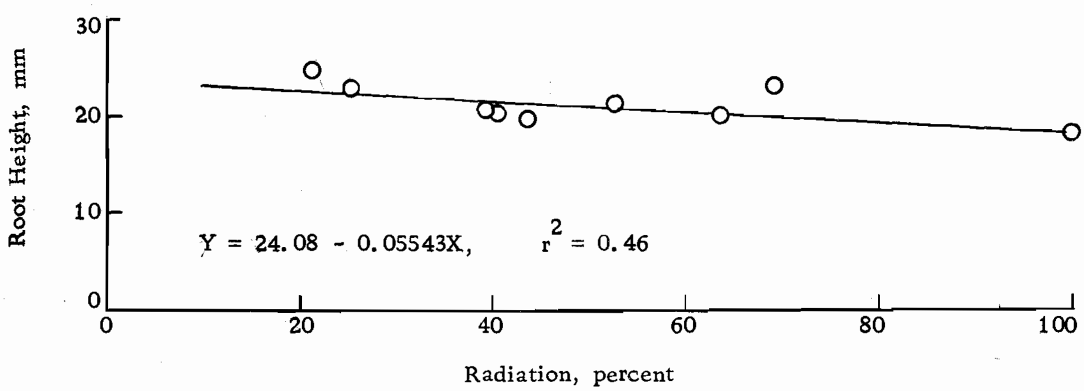


Figure 35. Regression of hemlock height on radiation, raised seedbeds, mineral soil rows, November 1965.

area were not duplicated in the shade screen experiment. Denser shade screens probably would have reduced radiation enough to limit growth.

Significant relationships were found between spruce, alder, and Douglas-fir root length and radiation, and they were similar to those found in the shelterwood area. On the other hand, the decrease in hemlock top length with increasing radiation found under the shade screens opposed the increase found in the shelterwood area. The slopes of the two regressions were not great, however. The very low-radiation levels included in the shelterwood study and the full radiation treatment included in the shade screen data may account for the contrasting trends.

At the end of the 1965 growing season the average seedling in the shade screen study weighed more than the average field-grown seedling in the shelterwood area, even though seeding was done later in the season (table 17). Watering probably made the difference; although there may have been differences in soil and there was more chance for root competition in the shelterwood area. Also, the shade screen study was started later in the growing season than studies in the shelterwood area so environmental conditions were different.

Table 17. Average seedling dry weights, shelterwood area and shade screen study, by species, November 1965

| Species | Average dry weight | |
|---|---|---|
| | Shelterwood area | Shade screen study |
| | ---------- milligrams ---------- | |
| Sitka spruce | 13.4 | 16.2 |
| Western hemlock | 13.2 | 14.4 |
| Douglas-fir | 35.5 | 64.6 |
| Red alder | 22.1 | 23.8 |

# GENERAL DISCUSSION

The main objective of this research was to measure differential effect of solar radiation on seedling establishment under a coastal forest stand. The exploratory test of the shelterwood system demonstrated that both Sitka spruce and western hemlock are readily established under such a stand, but both species responded about the same to the reduced solar radiation. There were more hemlock than spruce seedlings, but this may have been a result of more hemlock seeds, as seedfall was not measured during the entire period of the study. In spite of a limited seed source, numerous Douglas-fir seedlings became established indicating that it too will regenerate under a canopy. No alder seedlings were found, yet 4000 alder seeds per acre fell during one of the three seed years studied and some may have fallen before or after the study period.

The regeneration survey on naturally occurring seedbeds in the main study area also demonstrated how readily spruce and hemlock seedlings become established under a forest canopy, this time under a wide range of radiation levels. There were about three times as many hemlock as spruce seedlings and hemlock averaged one-half centimeter taller. Seedfall measurements indicated the difference in number of seedlings was not due to seed supply (table 8); so apparently hemlock was better adapted than spruce to the understory conditions. Seedling establishment was highly variable and showed little relationship with radiation, basal area per acre, or sum of diameters per acre. The one significant relationship, between number of hemlock seedlings per acre and basal area, explained only ten percent of the variation in number of seedlings. Competing vegetation, which was common and variable in the study area, probably was an important factor. Although the seed supply was limited, the absence of Douglas-fir and red alder on the plot clusters indicated these species were not well adapted to establishment under average seedbed conditions where a high percentage of the seedbeds had competing vegetation. On the other hand, location and measurement of Douglas-fir and alder seedlings for the height growth study showed that they can and do become established under a forest canopy when the seedbed is mineral soil.

The detailed study of solar radiation and seedling establishment, limited to mineral soil seedbeds, also demonstrated that Douglas-fir and red alder also become established under a forest canopy, and under about the same range in radiation levels as spruce and hemlock. But for all species, solar radiation explained only a small part of the total variation in seedling establishment. Apparently other factors were more important. Seed germination will occur in little or no light; so little correlation between germination and solar radiation is to be expected. Extension of the radicle and its penetration into the soil probably depended mostly on soil moisture. Moisture certainly was variable at the soil surface, even during spring germination. It was not monitored closely enough to permit detailed analysis; although later in the season it was shown to be significantly related to solar radiation. Time, of course, was highly significant as numbers of seedlings increased in the spring and, generally, decreased some in the fall. But time cannot be controlled by the silviculturist. That radiation did have an effect was demonstrated by a few significant regression coefficients and by the poor showing of all species in the clearcut where seedlings were exposed to full sun.

An important result measured on the mineral soil seedbeds was the high seed-to-seedling ratio of red alder compared to the conifers. It clearly took more alder seeds to produce an established seedling. Also important was the somewhat variable but quite similar seed-to-seedling ratios for the conifers. Given equal numbers of viable seed, establishment of conifer seedlings on mineral soil apparently would have been about the same, regardless of species.

Solar radiation played a much more important role in first-season growth than it did in numbers of seedlings established, but differential effects among the species were limited. Sitka spruce and western hemlock were almost parallel in their response to radiation with no significant differences in total, top, or root dry weight. On a length basis, however, hemlock was significantly longer. The most striking difference between species was the greater weight and dimensions of Douglas-fir. Surely this resulted from the larger seeds and their greater nutrient capital. But, also, there was a significant difference between Douglas-fir and the other species in response to radiation as illustrated by the shape of the regression lines. Douglas-fir growth continued upward at the high radiation levels compared to reduced growth of spruce, hemlock, and alder.

Reduced growth of spruce, hemlock, and alder at high radiation levels was probably a result of increasing soil moisture tension rather than a direct result of radiation. This possibility was indicated by close correlations between soil moisture percent and radiation (figure 14). Either the increasing radiation, decreasing soil moisture, or some combination could have caused reduced growth. That moisture was the probable limiting factor was confirmed by the shade screen study in which water was provided and growth reductions did not occur.

Optimum radiation levels calculated for spruce, hemlock, and alder apparently resulted from the interacting factors of radiation and soil moisture tension. They are valid for conditions of the study. They may be good approximations for general use. But surely optima would vary with varying summer precipitation patterns. A more droughty summer, for example, probably would lead to calculation of lower radiation optima.

Red alder, generally recognized as an intolerant tree, appears to be very tolerant of shade during its first and probably its second growing season. Its ability to outgrow spruce and hemlock at low radiation levels (figure 27 and table 10) indicated a basic photosynthetic efficiency surpassing these conifers.

This led to a separate, cooperative study comparing apparent photosynthetic rates of red alder, Sitka spruce, western hemlock, and Douglas-fir seedlings (Krueger and Ruth, 1967). Seedlings of the four species, previously grown on the Oregon Coast under 21 and 69 percent solar radiation, were brought to the laboratory at intervals during their second growing season for measurement of photosynthetic rate at five light intensities by infra-red $CO_2$ analysis. The seedlings were well-watered, air temperature controlled at 20 ± 1° C, and humidity allowed to vary within a moderate range near 50 percent. Measurements of $CO_2$ absorption at light intensities ranging up to 5100 ft-c showed that alder seedlings preconditioned under either 21 or 69 percent of full sunlight were capable of higher photosynthetic rates than Sitka spruce, western hemlock, or Douglas-fir. The alder seedlings had thinner leaves, greater leaf area, and more stomata per unit area than the conifers, apparently resulting in more efficient gas exchange. Under low light, alder's photosynthetic rate per unit leaf area was similar to Douglas-fir, but its greater leaf area was still an advantage. Alder's leaves were capable of significantly greater photosynthesis per unit weight. Under high light, alder had these same advantages, and above 2300 ft-c also demonstrated a higher photosynthetic rate per unit leaf area. This study provided a partial explanation for alder's ability to outgrow spruce and hemlock at low radiation levels in the field.

Both the laboratory study and the field plots on mineral soil indicate rapid growth of alder under a forest canopy. But alder seedlings generally do not do well under coastal forest stands. Few surveys of one- and two-year-old seedlings have been made; so young seedlings on mineral soil as studied here may be quite common. For some reason alder seedlings tend to drop out of the understory while spruce, and particularly hemlock, continue to grow. The reasons for this need further investigation.

One explanation was brought out by the laboratory study. Although the photosynthetic rate for alder was greater than the conifers, it also had a higher dark respiration rate. This partly reduced alder's advantage. Another factor is that alder is a deciduous species with photosynthesis virtually eliminated during the winter months. On the other hand, evidence that photosynthesis of conifers continues at substantial levels during winter months is rapidly accumulating (Helms, 1965). Effects of competing vegetation may be another factor. Hemlock and spruce are commonly found growing in competition with other understory vegetation while alder mostly is found on bare mineral soil. Perhaps the conifers are better able to cope with root and crown competition.

Looking now at the practical application of the shelterwood system in coastal forests, several points should be discussed. That the system is feasible was amply demonstrated by seedling establishment, seedling growth, and overstory removal. Seedfall was adequate and, except for questions of favoring or avoiding particular species, apparently presents no problem. Periodic thinnings, surely a part of intensive stand management, apparently will lead to adequate seedling establishment. As rotation age approaches and thinnings give way to harvest cuttings, the greater change may be in objective rather than technique. Thinnings aimed at controlling growth of the existing stand will give way to shelterwood cuttings aimed at controlling growth of the new stand. The main question may be one of relating cutting intensity to height growth of seedlings as they develop under the forest canopy. The present study examined this in detail for only the first two years. Other questions of importance include evaluating growth of the overstory stand during the regeneration period, the economics of shelterwood cutting as compared to clearcutting, and techniques of overstory removal to minimize damage to established seedlings.

The question of using shelterwood cutting to favor particular tree species was answered only in part. The management objective on the Oregon Coast usually is to regenerate Sitka spruce, western hemlock, and perhaps Douglas-fir, yet exclude red alder. With a limited alder seed supply, alder encroachment was not a problem on the study areas; so minimizing alder seed source by harvesting nearby trees should help. Apparently the treated area would have to extend a considerable distance out from the area to be regenerated because of horizontal movement of falling seed. Almost all alder that became established was on mineral soil; so minimizing exposure of mineral soil also should help. And even when mineral soil was exposed, it required many more alder than conifer seed to result in an established seedling. Of course the stocking of a particularly desirable species could be increased by seeding or planting.

The discovery of alder's first and second season shade tolerance and high photosynthetic efficiency was not encouraging from the standpoint of limiting its establishment under a forest canopy. General observations indicate alder does not continue to do as well. On the other hand, it was encouraging to find the early shade tolerance demonstrated by Douglas-fir. Perhaps it can become established in even less light than Wick (1965) found in his survey of Douglas-fir shelterwood cuttings. The parallel response of spruce and hemlock seems to preclude regulating solar radiation carefully enough to favor one or the other, at least on mineral soil during the first two growing seasons. However, on other seedbeds and over longer periods of time low radiation apparently favors hemlock. All these questions would be intriguing objectives for additional research.

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APPENDICES

# APPENDIX A

Definitions of classifications used in exploratory study of seedling establishment under a forest stand.

| Classification | Definition |
|---|---|
| Stocked quadrat: | A quadrat having at least one 2-year-old or older tree seedling of the species in question. Two or more well-placed 1-year-old seedlings could be substituted for the older seedling. |
| Percent cover: | Cover was measured as the vertical projection of the above-ground parts of a plant on to the ground. In the case of two or more layers of vegetation, only the tallest layer was classified. Percentages for a given quadrat total 100. This procedure emphasized the tallest or dominant layer of vegetation considered most important for establishment of conifer regeneration. Crowns of conifer seedlings were measured the same as for other vegetation. Occasional conifer seedlings or saplings established in the understory prior to initiation of the study were included in the cover classification. The shelterwood overstory of mature trees was excluded. |
| Herbs: | Area dominated by aerial parts of herbaceous plants. Includes mosses and plants growing on wood and rotten wood. |
| Brush: | Area dominated by aerial parts of brush plants. |
| Trees: | Area dominated by aerial parts of tree species. |
| Mineral soil: | Predominant surface material is mineral soil. Various amounts of decaying organic material (humus) may be included, but decay has progressed to the point that individual plant parts are no longer identifiable. |
| Duff and litter: | Fresh or partly decomposed organic material that still retains sufficient structure to permit identification of plant parts. |
| Slash: | Tree tops, limbs, twigs, and foliage. Differentiated from duff and litter based on age, size, arrangement, and proximity of logging activity or windfallen trees. |
| Wood and rotten wood: | Logs, stumps, and surface roots not covered with vegetation. |

APPENDIX B

Ground cover on milacre plots by cover class, examination date, and treatment, shelterwood area

| Examination date and treatment | Cover class | | | | | | |
|---|---|---|---|---|---|---|---|
| | Trees | Brush | Herbs | Slash | Wood and rotten wood | Mineral soil | Duff and litter |
| | Percent | | | | | | |
| Before seed cut April 1956 | 19.7 | 8.2 | 52.3 | 8.1 | 10.0 | 0.8 | 0.9 |
| After seed cut March 1957 | 4.0 | 4.2 | 29.3 | 27.0 | 14.1 | 20.9 | 0.5 |
| 3 seasons after seed cut March 1960 | 5.0 | 8.0 | 56.8 | 11.3 | 9.3 | 2.6 | 7.0 |
| 5 seasons after seed cut November 1961 | 7.0 | 19.0 | 52.7 | 7.0 | 7.0 | 1.1 | 6.2 |
| 6 seasons after seed cut May 1963 | 16.8 | 27.9 | 43.1 | 2.4 | 8.0 | 0.5 | 1.3 |
| After 63 percent removal cut Sept. 1964 to March 1965 | 12.7 | 22.9 | 48.6 | 2.6 | 5.5 | 2.1 | 5.6 |
| After complete removal cut Sept. 1964 to March 1965 | 6.8 | 11.3 | 31.8 | 8.0 | 11.6 | 15.9 | 14.6 |

# APPENDIX C

Results of soil chemical analyses, raised seedbeds, shade screen study

| Item | Amount |
|---|---|
| Phosphorus | 2.5 parts per million |
| Exchangeable potassium | 0.74 milliequivalents per 100 g. |
| Exchangeable calcium | 0.4 milliequivalents per 100 g. |
| Exchangeable magnesium | 1.1 milliequivalents per 100 g. |
| Exchangeable sodium | 0.14 milliequivalents per 100 g. |
| Cation exchange capable | 33.24 milliequivalents per 100 g. |
| Total nitrogen | 0.31 percent |
| Organic matter | 6.41 percent |
| Carbon-nitrogen ratio | 12.0 |
| Sum of bases | 1.98 milliequivalents per 100 g. |
| Base saturation | 6.0 percent |
| pH | 5.4 |