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Title LETHAL SURFACE TEMPERATURES AND THEIR INTERPRETATION FOR DOUGLAS-FIR

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The concept is developed that direct measurement of physical factors at the microsite level might provide better criteria than gross features of the landscape for judging whether Douglas-fir clearcut areas will restock naturally. Large scale sampling of microsite temperatures was considered as most promising of possible criteria for initial work.

The percentages of surfaces that exceeded 125°, 138°, and 150°F. on eight Douglas-fir clearcuts in western Oregon were estimated by the use of temperature pellets during 1954. By September 50.5 percent of north slopes and 86.5 percent of south slopes had exceeded 138°F.

Microsite descriptions of the 100 points sampled on each clearcut revealed that most microsites remaining below 138°F. were in perpetual shade. Others were on steep northerly aspects, or in shade of dense or low vegetation. Vegetation giving intermittent shade provided little protection against high surface temperatures.

The meaning of various levels of temperature was tested by placing the temperature pellets near stems of Douglas-fir seedlings and relating heat injury with melting of pellets. The 138°F. pellet was best related to mortality, but the thermal death point in the field seems to range from 125°F. to more than 150°F.

Why some seedlings did not die at very high surface temperatures was the subject of laboratory studies. Seedlings were exposed in a temperature gradient under tungsten lamps at various ages and duration of exposure. Seedbeds tested were peat moss, yellow mineral soil, and quartz sand. Time-temperature relationships at which mortality occurred were significantly different for each material. Seedbed material and duration of exposure were major factors, but the effect of seedling age up to three months was not significant.

Exposure of seedling stems to water bath temperatures under dry conditions was accomplished with a new apparatus. This gave a time-temperature relationship at which mortality occurred, but with lower

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corresponding values than those in dry materials tested.

Heat-lamp tests on 49 materials indicated that there is probably a complete spectrum of such time-temperature curves. Seedling mortality occurred as low as 122°F. at four hours exposure to water bath temperatures and as high as 176°F. at 15 minute exposure in white sand, a range of 54°F. Little evidence was seen of a strong display of natural resistance of individual seedlings to heat injury. Instances of resistance to high surface temperatures in the field could be explained adequately by short duration of exposure or seedbed materials having protective qualities.

Further studies showed that transpiration had no measurable effect on killing temperatures. Thermocouple implantations in seedling stems indicated no biological mechanism that might keep the stems cooler than surrounding surface temperatures. The seedling stem appeared to have temperature characteristics no different than measured inside a plastic tube of similar size filled with water.

The 138°F. temperature pellet was indicated to be a reliable indicator of probable heat mortality on clearcuts, provided durations of exposure and seedbed materials were near the average listed for the eight clearcuts in this study.

The high proportions of south slopes that exceed 125°F., usually over 90 percent, is information of interest to forest managers. The implications that older seedlings may die of heat damage, and that heat killing occurring late in summer may be confused with drought killing, is of interest to researchers. Of theoretical interest are the conclusions that thermal death points vary with the type of material that surrounds the seedling, that heat flow in calories instead of actual temperature is probably the correct measurement unit to express heat injury, and that relatively more heat is transferred at the same temperature into a seedling in organic materials than in mineral soils.

LETHAL SURFACE TEMPERATURES AND THEIR INTERPRETATION FOR DOUGLAS-FIR

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LETHAL SURFACE TEMPERATURES AND THEIR INTERPRETATION FOR DOUGLAS-FIR

INTRODUCTION

Although the forester cuts his crop by acres, he regenerates it by microsites. The Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedling lives in a little world of its own. Its microenvironment may have little in common with that of its neighbor a foot or even an inch away.

This study was aimed primarily at learning about the kind of microsites found on Douglas-fir clearcuts, concentrating particularly on how hot they become from sun's rays and what this heat means in terms of seedling mortality. It covers mainly the interpretation of field temperature data taken with pellets that melt at various temperatures. This concentration on so narrow a segment of the entire problem of Douglas-fir regeneration would seem without broad application. But the acres which the forester exposes in harvesting his crop are simply a vast number of microsites--perhaps all unique, perhaps many somewhat alike.

The application broadens as one considers that seedling loss from surface heat may be highly predictable for any microsite by proper interpretation of temperature measurements. Sampling for the proportion of microsites which become too hot for seedling survival would seem to provide the forester with a characterization of his acre having broad applicability. An area having a very high

proportion of microsites characterized by lethal temperatures would be a poor risk for natural regeneration or artificial seeding whether or not other factors causing seedling loss were operative. In a sense such factors as damping off, rodent and insect damage are of no practical consequence if the seedling germinates in a microsite where it is doomed by high temperatures during the first clear, dry period in its early life. The forester must depend on the microsites that remain below lethal temperatures for successful regeneration.

Can the proportions of such favorable microsites be accurately estimated? Once estimated, how would such a figure be used?

The answer to the first of these questions proved to be far more involved than contemplated. The idea had to be tested that sampling physical factors such as surface temperature might have merit in predicting restocking of individual areas. After that, a new field method of measuring surface temperature had to be found and tested. This method would provide a record of temperatures in areas no larger than the seedling stem. Next, Douglas-fir clearcuts were sampled for proportions of seedbeds exceeding certain temperature levels. Then a field study was made to define the words "lethal temperatures" in terms of these temperature levels in the field. The field studies were not discriminating enough for this. Laboratory studies assessed the meaning of the temperature levels and measured the effect on seedling mortality from age, exposure time, and seedbed material. Further measurements of the role of heat alone, of transpiration as a cooling mechanism in seedlings, and the temperature in the

seedling stem led to a new concept in defining lethal temperature. This placed higher importance on the seedbed than the seedling itself.

The answer to the second question, "How can such information be used?", is somewhat like predicting what might be done with the volume estimate for an acre of forest land to be harvested. With it we cannot tell what our money return will be without knowledge of other variables such as grades, selling price, and logging costs.

At present no one can accurately predict whether a particular clearcut will restock. Statistically the chances of natural restocking are good. Percentagewise, a large share of the cutover land of the past has restocked naturally with no conscious effort on the part of the landowner. Still, with the best kind of forest practice, failures of natural restocking are common. Rather than risk such failures, the tendency is growing to plant all clearcut areas on intensively managed forests. Perhaps research has failed to provide sufficiently reliable criteria for predicting areas that will restock naturally, although a great deal of effort has been given to this problem. Perhaps there are simply too many variables such as seed source, animal and insect population, plant competition, drought, and seedbed conditions among other things. In any case, presently available knowledge still does not provide the tool. Thus, it is important to investigate new approaches to the needed criteria. It is possible that estimations of proportions of unfavorable and favorable microsites may be developed into such criteria even if

they touch only on a single factor. Obviously, the occurrence of a very high portion of the microsites with potentially lethal temperatures would influence the decision to plant an area. But whatever the proportion for a particular clearcut, the measurement of even one of the main variables would reduce the risk in deciding whether the clearcut should be planted or left to restock naturally. Like the volume estimate for an acre, a knowledge of microsite temperatures can contribute to successful management only if wisely used.

REVIEW OF LITERATURE

A literature review seems hardly appropriate. The subject has been a popular one, probably because of its short-time nature which makes it naturally suited to students. Its importance has made it attractive to some of the outstanding forest researchers of the time. No less than 20 reviews have kept the literature well catalogued [Mayr (71), Münch (76), Hartley (35), Bates (6), Toumey and Neethling (95), Bates and Roeser (7), Korstian (57), Baker (4), Roeser (83), Haig (34), Isaac (51), Lorenz (66), Daubenmire (25), LeBarron (61), Baker (5), Vaartaja (97, 99), Smith (91), Owen (79), Place (82), Bever (10), Geiger (32), and Finnis (30)]. The parallel studies on heat damage to other plants and animals make its literature one of the richer collections in the field of biological science (42, 43).

It would be difficult indeed to improve upon the general coverage given by the review of Haig (34), the discussions of microenvironment by Geiger (32), of seedbed temperatures by Vaartaja (97) and Smith (91), and of physiological response to heat by Heilbrunn (43). The reader is directed to these excellent papers in preference to the one to follow, if they are available.

The literature may be grouped under the headings: prediction of future stocking, seedbed temperature and heat injury, determination of lethal temperatures, and theories of heat damage.

Prediction of Future Stocking

For Douglas-fir, several investigators have produced rules of thumb or formulas for predicting stocking.

Isaac (50, 51, 52) studied the physical factors of seedling mortality, distance of seed flight, seed production, as well as natural regeneration trends over long periods. He explained most differences in natural restocking of cutovers upon physical and biotic factors. His prediction of restocking was based on distance from seed source and indicated that adequate stocking was expected up to one-quarter mile from timber on north slopes but often not beyond 100 feet on southerly exposures. Plant cover above or below 25 percent would give progressively poorer stocking. These generalizations he felt were successful to the extent that they expressed the influence of physical and biotic factors.

Staebler (93) studied 15- to 35-year-old stands in western Washington by reconstructing the stand history back to the establishment period by stem analysis. From this he produced a table from which predictions of stocking could be made 15 years into the future. The table applied to areas which he defined as being of good seed source, i.e., within twice the height of trees of seed bearing age. Other variables included brush density, exposure and slope. The data were intended to apply to the management of established reproduction stands.

Bever (10) computed the effectiveness of the seed source

requirements of the Oregon Forest Conservation Act and concluded that leaving two seed trees per acre was adequate to give an average stocking of 55 percent of four-milacre quadrats in five years. He also suggested number of feet of stand edge needed to produce adequate seed at each distance. He concluded that stand edge or seed blocks are less efficient than seed trees. Bever also evaluated the general effect of exposure, plant cover, slash concentration and slash burning on stocking, showing that each of these has a significant relationship to stocking.

Lavender, Bergman, and Calvin (60) studied 13 staggered settings in old-growth Douglas-fir. They advanced a predicting equation for stocking based on degree of burn, exposure, slash condition, and seed source. A similar formula is reported by Hunt (48) in regard to survey of stocking on a portion of the Vincent Creek Burn sown with mustard seed. The equations in both studies were authored by Calvin, and are intended to predict the stocking to be expected at present on quadrats in clearcuts of various ages and conditions. The data in the studies of Staebler (93), Bever (10), and Lavender et al. (60) were taken some years after logging and there is no measure of the change in seed source and seedbed conditions with time after logging. Classifications of seedbed conditions are in relation to exposure, burn condition, and slash density.

Morris (75) studied the regeneration on 63 pairs of plots ranging from Mt. Rainier in Washington to the South Umpqua River in Oregon. One of each pair was burned while the other was left unburned.

Acceptable burned plots were at least two-thirds burned. His samplings of seedbed types on the plots were in terms of rotten wood and bark, branches providing shade, logs, mineral soil and brush. Unburned plots had much more ground covered by rotten wood and bark, more branches giving shade, and less mineral soil than on burned plots. No significant differences were found between number of seedlings six inches and more in height on burned and unburned plots. Tentative conclusions were that burning did not significantly increase or decrese stocking, but it did reduce fire hazard and permit easier control.

It is noted that all the sampling systems aimed at predicting stocking relate to gross features such as exposure, burning, slash condition, seed source, cover, and slope. Seedbed conditions in terms of microsites have not been directly evaluated.

Seedbed Temperatures and Heat Injury

Homén's (47) basic studies in Finland prior to 1893 on the heat economy of granite rock, grassy swamp, and sandy soil are considered by Geiger (32) to have laid the foundation for theories of soil temperatures. Geiger's own contributions in research and evaluation of literature represent the most thorough treatment of microclimate. Vaartaja (97) and especially Smith (91) have considered the application of microclimatic principles to seedbeds and

heat injury of seedlings. Since no literature was uncovered that goes beyond or changes the conclusions of these authorities, the main points pertinent to this study from their work are listed below:

1. Surface temperatures remain below lethal levels in all soils if the surface is moist (32, 34). They become surface dry at different time intervals under the same exposure to sunshine (91).

2. With dry materials, a given amount of heat does not cause different substances to assume the same temperature. Materials of low specific heat, such as organic materials with high air content, reach higher temperatures than materials of high specific heat such as sand (91).

3. Increase in moisture content also increases the specific heat of a substance, as well as its conduction (91).

4. Temperatures measured at the standard weather station level of $4\frac{1}{2}$ feet have little relation to surface temperatures (91).

5. Surface temperatures reach highest levels in clear, dry air when maximum solar energies penetrate the atmosphere (91).

6. Temperatures are highest at the soil-air interface where sunlight first strikes. Energy absorption by dry air is minor (32). From the surface there is a rapid drop in temperature both upward into the air and downward into the soil (97).

7. The processes responsible for dispersion of heat from insolated surfaces are as follows (91):

   a. Reflection, particularly of infra-red wave lengths.

b. Downward conduction through the soil.

c. Intermolecular conduction upward into the atmosphere.

d. Long-wave radiation to space or the atmosphere.

e. Convection or turbulent mixing.

f. Evaporation of water.

8. Convection removes much more surface heat in the upward direction than intermolecular conduction (32). Reflection of different wave lengths from the surface of nonliving materials is variable, but ranges only between 2 percent and 30 percent (32). Water vapor is removed from surface materials mainly by convection, but the evaporation requires substantial amounts of heat (91).

9. Loss of heat downward depends on conduction. In dry materials, increased conduction is commonly related to decreased air space (32).

10. Rough surfaces, and those interrupted by large pores, have more active convection than smooth surfaces. Spatial distribution of absorbing surfaces thus influences temperature (91).

11. The relatively lower temperatures observed on bare mineral soil and on sand are explained by high specific heat and conductivity (91).

12. The comparatively high surface temperatures of insolated leaf litter and peat moss are apparently due to relatively inefficient export of heat by conduction and convection, low reflection of infra-red radiation and low specific heat (91).

A characteristic of seedbeds reaching the highest temperatures is the low proportion of total energy passing downward into the soil (32).

13. Differences in seedbed temperatures due to direction and inclination of the slope follow theoreticl energy values from astronomical calculations on the sun's angle. However, temperatures are modified by diffuse sky radiation, and by morning dews which cool eastern slopes more than western (32).

Determinations of Lethal Temperatures

Studies of heat injury date back about a half century in this country (35) and only a few years longer in Europe (71, 76). The excellent reviews by Hartley (35), Toumey and Neethling (95), Baker (4), Shirley (87), Haig (34) and Lorenz (66) make it unnecessary to cover the subject historically. Only a few key points will be covered concerning the interpretation of temperature levels and associated mortality.

Evaluation of early studies is difficult because of the problem of accurately measuring surface temperatures (32, chapter 13). Vaartaja (97) concludes that most early research with mercury thermometers probably reports temperatures more nearly like those in the soil than at the surface. Even with thermocouples there is difficulty in eliminating errors due to conduction of heat down the wires to cooler layers immediately above or below the surface. Hence, he considers that relatively large errors were possible even when

thermocouples were used in early studies. Usually true surface temperatures were underestimated.

Field Studies

The impression that there is a very narrow range at which heat injury occurs in the field is one of inference from laboratory studies. Field studies are not very clear on the temperature tolerance of seedlings and usually show a tolerance for a considerable range in temperature.

For the Douglas-fir region, Hofmann (45) reported that a surface temperature of 144°F. had been found to kill Douglas-fir seedlings. Isaac (52) reported that heat injury began at 123° to 125°F. Some seedlings survived on surfaces which reached 160°F. during the latter part of the summer. These measurements were made with a maximum-registering mercury thermometer having an offset near the bulb, and placed so the lower half of the bulb was below the surface. At most, only a few thermometers were employed to sample a surface and such measurements are generally not for individual seedlings.

These same procedures apply to Haig's field experiment in Idaho (34) in which mortality of Douglas-fir as well as western white pine (Pinus monticola Dougl.), western larch (Larix occidentalis Nutt.), western hemlock (Tsuga heterophylla (Raf.) Sarg.), and western redcedar (Thuja plicata Donn) were studied. He gave no definite observation on the temperature at which killing began except that it was somewhat below 135° F. (34). However, some seedlings survived

on burnt mineral soil plots in which temperatures reached 152°F. Only a few seedlings germinated on duff and none survived where maximum temperatures of 160°F. were recorded. In both the above studies the instances of survival at these higher temperatures may be due to variations in temperature within the plot. Isaac (51) commented that the shade of weeds late in the season may have protected the seedlings. These investigators and many others such as Baker (4), Roeser (83), Berkley and Berkley (9), Daubenmire (25), and Smith (91) attribute part of the variability to hardening of the stem with age. Smith (92) has begun a study of tissue development of hypocotyl of Douglas-fir in relation to heat injury.

Earlier field studies such as those by Bates (6) or by Toumey and Neethling (95) are more difficult to evaluate because temperatures were taken in the soil. The latter recorded 100 percent loss of eastern white pine (Pinus strobus L.) on all plots reaching 135°F. or above. Newer studies by Smith (91) and Vaartaja (98) which had the benefit of excellent technique do not cover the point except generally. These studies suggest that a wide range of temperatures was associated with the killing in the field. Finnis (30), who studied mustard as a cover crop for Douglas-fir, comments upon this point as follows: "During the period 5 May - 16 June, when the temperature exceeded 138°F. twenty-one times on the plots without mustard compared with thirteen times on the mustard plots, there was no marked difference in mortality under the two conditions. Either

the sample was insufficient to give any accurate indication, or seedlings can withstand higher temperatures than previously expected. This aspect requires further investigation."

Laboratory Studies

Laboratory studies of heat injury to conifers reduce this variability somewhat, but by no means agree on thermal death points. Not only do the determinations range markedly between species but also they range within a species tested by different methods. Five different sources of heat have been employed by various investigators — water baths, ovens, radiators or lamps, electrical resistance devices, and sand. The determinations may be influenced by the method used. They can best be compared if investigators using similar methods are listed together.

Water baths were used in the earliest tests. Sachs (see 4, p. 953) in 1864 published results of studies with aquatic and terrestrial plants in which he determined thermal death points in water. Aquatic plants were injured by an exposure at 45°C. or 46°C. for 10 minutes. Leitch (62), using very critical techniques, determined the growth rate of pea roots (Pisum sativum) in water at various controlled temperatures. He indicated that death occurred with very brief exposure to a temperature of 45°C. Lepeschkin (see 22, p. 206) was among the first to stress importance of both time and temperature in describing thermal death points. Baker (4)

performed tests in which tops of Monterey pine (Pinus radiata D. Don) seedlings were immersed in water for durations of 2 to 15 minutes. Here a time-temperature relationship is apparent with death in 2 minutes at 130°F., 5 minutes at 125°F. and slight injury at 15 minutes at 120°F.

Shirley (87) immersed tops, roots, and entire plants in various temperatures in a controlled water bath. His tests included red pine (Pinus resinosa Ait.), eastern white pine, jack pine (Pinus banksiana Lamb.), and white spruce (Picea glauca (Moench) Voss). Like Leitch (62) he found killing to occur on roots between 44.3°C., the lowest temperature used, and 45.9°C. at 5 hours exposure. Tops required 48.2°C. to 51.3°C. Slightly higher temperatures were usually required to kill with two hours of treatment.

The most basic methodology among water-bath tests with coniferous seedlings was employed by Lorenz (66). He cut thin sections of cortex from stems of 4-year-old seedlings of eastern white pine, red pine, and white spruce. These he immersed in a controlled temperature water bath at various temperatures and for different intervals of time. After immersion the sections were placed in a solution of neutral red, a vital stain which dyed living cells a red color and left dead cells unstained. Using 50 percent stained cells as an index of the thermal death point, he constructed time-temperature curves for these species. The thermal death points determined by the technique were surprisingly high but quite uniform between species. Eastern white pine, for instance, required 10 minutes at 140°F.

(60°C.) or 30 minutes at 130°F. (54.5°C.) to cause 50 percent of the cells to remain unstained.

Perhaps the ultimate in control of temperatures in water-bath studies was achieved by Nelson (78) in studying heat injury to needles of four southern pines. His apparatus was a vacuum-jacketed calorimeter having a perforated cover. Needles to be treated were inserted through the perforations in the cover into the water of the calorimeter. Heat was applied by beams from several 100-watt lamps, and could be controlled within 0.1°C. or very slowly raised or lowered without other means of regulation or stirring. Pronounced yellowing of the treated needles was used as an indication of injury. Excellent time-temperature relationships were found at which this stage of injury was produced. Injury was immediate at 64°C. and appeared in about 11 minutes at 52°C., the lowest temperature tested. Differences between species were small. These temperatures are much lower at corresponding times than those indicated by the curves produced by Lorenz (66).

Incubators or ovens have been employed nearly as often as water baths. Sachs (see 4, p. 953) also used a hand regulated incubator with glass doors in which he tested plants of tobacco (Nicotiana tabacum m.), pumpkin (Cucurbita pepo), corn (Zea mays), mimosa (Mimosa spp.), rape (Brassica spp.) and nasturtium (Tropaeolum). Plants which had previously not withstood temperatures of 49-51°C.

in water withstood such temperatures without injury in air. However, all died or were severely injured at 51°F. for 10 minutes in the incubator. Münch (see 4, p. 954) found no injury to conifer seedlings in an oven at 126°F. but death resulted from exposure to 129-131°F. Bates and Roeser (7) used a thermostatically controlled oven maintained at high humidity, and found some seedlings wilted from all treatments between 111°F. and 139°F. Baker (4) attributes this high variability to possible uneven heating within the oven.

Shirley's "drought machine" (87), an early model of a controlled-environment chamber, was used to determine thermal death points in dry and moist air. Two-year-old greenhouse-grown seedlings of eastern white pine, red pine, jack pine, and white spruce were treated at 80 to 94 percent relative humidity in the moist treatment, and below 15 percent in the dry treatment. After five hours, needles were killed at about 49°C. and stems at about 52°C. in the moist treatment. In the dry treatment, needles were killed between 52.7°and 55.8°C. and stems above 56°C.

Radiators with reflectors were used by Bates and Roeser (7). Baker (4) has reviewed this study and concluded that the shriveling of the cotyledons which the authors describe indicated a different kind of injury from that in the field. Toumey and Neethling (95) used a radiator with reflector to reinforce the sunlight coming through a window. Temperatures were measured with both mercury thermometers in the soil surface and thermocouples and there was little difference between readings of the two instruments. White

pine seedlings occasionally formed lesions at 121° to 123°F. and all seedlings in one treatment formed lesions in thirty minutes during which the temperature was sustained between 135° and 142°F.

Baker's work (4), involving thirteen western conifers, is the most complete of those employing radiant energy. He used an electric radiant heater at a distance of 3 to 4 feet. Pots of seedlings were tilted so the rays reached the soil surface at about 65°. Thermocouples with junctions .18 mm. in diameter were used to record surface temperatures and internal temperatures in seedling stems. The thermocouples were described as being "thrust into the base of the stem of at least two seedlings, invariably through needle holes in the north side, and two other couples were also buried under one layer of sand grains close at hand." His use of "north" was in contrast to the "south" or injured side of the treated seedling. Treatments were continued until a definite lesion appeared and readings were taken. Internal temperatures below 131°F. seldom produced lesions, and almost all temperatures above this produced lesions. Surface temperatures ran from 0° to 42°F. higher than internal temperatures. Baker's study touched upon protective mechanisms which could account for lower internal temperatures such as transpiration, stem mass, conduction and radiation, and shading.

Lamps as a source of radiant energy were used by Daubenmire (25) in studying relative heat resistance of Picea engelmannii, Abies lasciocarpa, Pseudotsuga menziezii, Pinus ponderosa, and

Pinus edulis. Engelmann spruce and alpine fir were killed at surface temperatures which were brought to 45°C. at about five-minute intervals over a six-hour period. Mortality in Douglas-fir began with the same treatment at 55°C., and piñon sustained similar treatment at 70°C. without damage. Some individuals in every species survived the 70°C. treatment. Recent studies using heat lamps are noted. Owen (79), in studying the restocking failures of south slopes near Corvallis, Oregon, used an infra-red lamp to produce lesions artificially on groups of ten Douglas-fir plants grown in clay pots. These were treated at ages of 3, 6, and 12 weeks. The apparatus was in a chamber in which high humidities were maintained during treatment by soaking the cheesecloth sides of the chamber. Potted plants were freshly watered. Under these conditions death first occurred above 131°F. and all seedlings died at 158°F. Owen found that between these temperatures increasing numbers of seedlings were killed with increasing temperatures and lengths of exposure.

Paelinck (80) studied heat damage to 2-year-old ponderosa pine seedlings treated under a cluster of eight 250-watt heat lamps. He measured temperatures in the bark with thermocouples. In one phase of the test, steel wool was packed around the stem to conduct the heat evenly into it. All periods of treatment caused lesions and eventually death of the seedlings. The shortest time period used was one hour and the lowest air temperature used was 55°C.

Hot sand was employed by Roeser (83) in assessing differences in heat resistance for ponderosa pine, lodgepole pine (Pinus contorta Dougl.), Douglas-fir, and Engelmann spruce. Seedlings 58, 71, and 110 days old were threaded through holes in a thin board so that their roots could be hung freely in water. Heated sand was sprinkled uniformly around the stems to a depth of one-quarter inch. Results were presented in terms of the highest temperature likely to be tolerated by all individuals and the temperatures likely to be fatal to all. Between these two temperatures, a range of tolerance from 14°F. to 36°F. was encountered in the species tested. For Douglas-fir 38 days of age, 125°F. was likely to be tolerated by all seedlings and 150°F. was likely to kill all seedlings.

Electrical resistance as a source of heat was used by Daubenmire (25) who used a soil heating cable between rows of seedlings.

In this confusing array of temperatures is a pattern which will be brought out in subsequent discussion.

Theories of Heat Injury

The physiology of heat damage is thought to be the same in both plant and animal cells (43). Animal cells have had more detailed study. The only theory which is strongly supported at present is the coagulation theory, which dates back at least to 1864. Sachs (66), who conducted the earliest temperature studies on terrestrial and aquatic plants, considered it a current view. The preponderance of evidence is against such theories as asphyxiation, destruction of

enzymes, or lipid liberation by heat (42, 73). The evidence for a toxic factor was first demonstrated in plants by the killing of leaves above steam-killed stems (Dixon, 27). Essentially the same effect is shown in animals when a single leg is heated and the animal dies (44). But this seems to be a secondary effect of toxic thrombin-like substances released by heat-killed cells. The primary effect appears to be coagulation of protoplasmic protein.

Heilbrunn (43) has advanced a general theory which regards the effect of heat as involving the same reactions as cold, electric shock, ultra-violet radiation and potassium ions. All these stimuli first cause a liquification of the cell cortex accompanied by the release of calcium ions. Heat appears to do this by dissolving the lipid or changing it in such a way that the lipoprotein molecule is no longer able to bind calcium as it does at lower temperatures. Cold and other stimuli produce the same result, but by other processes. Next, the cortical protoplasm becomes much more fluid and the permeability of the cell is increased. Calcium ions migrate to the interior of the cell where they cause clotting by a surface precipitation reaction. The cell is in delicate balance, possessing substances which can reverse this reaction and return the protoplasm to normal state after stimulation. Over stimulation results in death as the clotting becomes irreversible. The theory embraces the action of anesthetics in preventing heat damage effects, and covers the action of stimuli in cell division, but such questions are not pertinent here.

Kurtz (59) has recently proposed that heat injury results from interference with the supply of vital chemicals, and that heat resistance may be improved by adding the proper substance to the organism. Heat sensitive strains of red bread mold (Nuerospora crassa) were made heat resistant by the addition of riboflavin to the medium in which they grow. Similar results were achieved with thiamin and adenine on other organisms. The theory is in many respects a restatement of Blackman's "Theory of Optimum and Limiting Factors" (12) or the ideas of MacDougal (see 74, p. 1063). Most of the examples given by Kurtz apply to mutants which became about as heat resistant as the wild types after these chemicals were provided.

That plants and animals vary considerably in their tolerance of high temperature is illustrated by the algae that are heat killed below 20°C. while others live in hot springs at temperatures always above 65°C. (42).

Resistance to heat injury in plants usually involves tissues with low water content such as seeds and spores, or protection by outer tissues having a low thermal conductivity such as cork cells (73). Heilbrunn (42) has also called attention to the possible relationship between the melting point of cellular oils and the temperature at which the coagulation of protoplasm begins. Organisms whose fats are liquid at normal temperature usually are heat sensitive, while those having high melting point fats usually are more resistant to high temperatures. No study of the melting point of fats in conifers was uncovered although McNair (72) has investigated

melting points of fats of many commercial plants.

The resistance to high surface soil temperature of the stems of coniferous seedlings is considered by Baker (4) to be a function of stem size and some control of internal environment. He measured temperatures at soil surface 12-17°F. lower inside the stems than outside by implanting fine thermocouples in the stem. Shirley (87) postulated, from experiments in which pine withstood temperatures in dry air better than in moist, that transpiration was the important factor. However, Curtis (24) and earlier Culm (22) demonstrated that transpiration was ineffective in cooling the leaves. Usually leaves in sunshine were warmer than the surrounding air. Conversely, Shaw (86) has shown that leaves are cooler than surrounding air at night due to radiation from leaf surfaces. Such studies do not eliminate the possibility that the transpiration stream may be cooling the stem of coniferous seedlings. However, Baker (4) decapitated the seedling and sealed the stem with collodion and found little difference in stem temperature between normal and decapitated seedlings subjected to high surface temperatures.

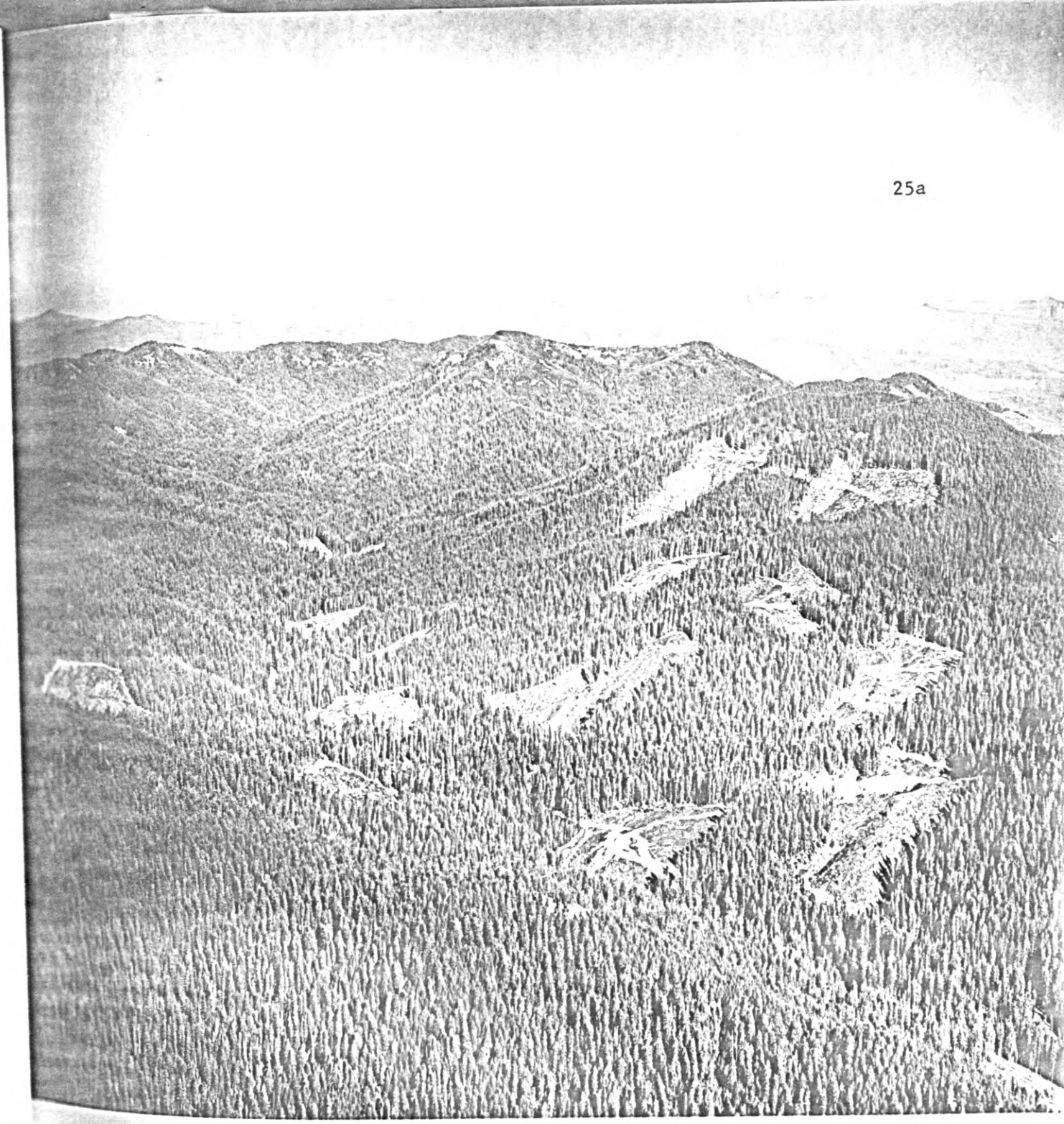
A REGENERATION SURVEY OF DOUGLAS-FIR CLEARCUTS

A survey of regeneration of Douglas-fir seedbed types is brought briefly into this study for several reasons. It sets the stage by describing where the field phases were made. Its data tell the proportions of seedbed types as they occur following clearcutting and logging in old-growth Douglas-fir, showing that some seedbeds appear to consistently restock better than others. But the main feature is that this survey furnishes on one hand a comparison between the complexity of trying to define and predict stocking in terms of seedbed types, and on the other hand the relative ease of showing a direct tie between stocking and physical factors of seedling mortality. Because the survey results will be published in greater detail elsewhere (103) only the salient information is given here.

The clearcuts are all on or near the H. J. Andrews Experimental Forest, which was established in 1948 on the 15,000-acre drainage of Lookout Creek in the Cascade Mountains of Oregon (Figure 1). These particular clearcuts were planned and cut under the author's supervision as part of a pilot plant test of the staggered-setting method of clearcutting.

Lookout Creek is typical of most drainages in the Oregon Cascades. Stream pattern is complex and elevations range from 1,500 feet at the mouth of the creek to a rim of peaks 2,500 to 5,200 feet high. Only about one-fifth of the area is gentle topography. The remainder is steep with occasional rock outcropping. Old lava flows

Figure 1. The H. J. Andrews Experimental Forest. Clearcuts in this view were sampled both for a regeneration survey and a study of the extent of surface that exceeded lethal high temperatures.
(Photo courtesy U.S.F.S.)



have formed lines of bluffs at some elevations. The drainage is covered mostly with a 400-year-old Douglas-fir stand in various stages of preservation. It is in this age of stand that all clear-cuts are made. In addition, many patches of young growth are found mostly near ridgetops where crown fires killed the old stand.

Field Procedures

The survey was begun in the spring of 1953 on five clearcuts on which logging and slash burning had been completed during 1951 and 1952. Other clearcuts, up to the 15 planned for in the study, were added as they were logged, but this was over a five-year period. Thus, the present analysis is presented for only these five clearcuts as this will be adequate for the purposes listed. No strikingly different conclusions are expected when the data is complete.

In gathering this field data, 40 circular four-milacre plots were placed mechanically across each clear-cut unit and permanently marked for repeated examinations. The plots were located at intervals along two north-south lines 1/3 and 2/3 the distance between east and west extremes of the clearcut. Plots were placed along these lines at an interval of 1/40 of the total length of the two lines as scaled from the topographic map. No effort was made to maintain a given number of plots in either line.

Although information on seedbed, stocking, and occurrence of lesser vegetation was recorded on every plot, the latter information has been separately reported (103) and is not covered. In recording

the percentage of the plot in each seedbed type, the burned surfaces were divided into two classes: (1) hard burn, in which the soil had been subjected to enough heat to burn out the organic matter producing a distinct red color, and (2) light and medium burn which included all the remaining burned area. Light and medium classes were combined because field distinction between the two types was difficult. Unburned surfaces were classified as to: (1) mineral soil, (2) mineral soil with light debris, meaning ground disturbed in logging, (3) litter and light slash, (4) medium to heavy slash, and (5) rotten wood. Non-seedbed surfaces such as fresh logs, stumps, water or rocks were recorded separately. The types were made mutually exclusive and together totalled 100 percent, although difficulties were sometimes encountered in drawing sharp distinction in the field between types. Further records were taken of the aspect in eight compass points, the slope in percent, and the percentage of the plot in skid trails or landings.

When seedlings were found on the plot, the seedbed types on which they grew were listed, along with the year of germination, species, slope and aspect. Seedbed information was recorded to correspond to the classes of seedbeds above so that the number of seedlings per acre could be computed for each class.

Results and Discussion

The data in Table 1 gives seedlings per acre by seedbed types two or three seasons following logging and slash burning. The

Table 1.—Number of Douglas-fir and hemlock seedlings per acre by seedbed types 2-3 seasons following logging and slash burning[1] on five clearcuts of the H. J. Andrews Experimental Forest

Clearcut designation	Seedbed types: Soil disturbed in logging	Soil undisturbed in logging[2]: Unburned			Soil undisturbed in logging[2]: Burned			Non-seedbed	Weighted average
	Mineral soil	Mineral soil with debris	Litter and light slash	Medium and heavy slash	Rotten wood	Light and medium	Hard burn		
1 B	287	920	336	286	930	100	740	0	331
1 C	483	202	393	349	789	126	0	0	244
1 D	1371	714	184	120	588	52	0	0	538
1 F	593	1040	333	183	200	19	0	0	288
1 G	488	511	576	103	430	14	0	0	165
Average	644	677	364	208	587	62	148	0	313
Percent of area in sample	21.3	10.6	11.5	8.7	3.2	32.9	2.2	9.7	100.0

1/ Clearcuts 1B and 1C were sampled 3 seasons following logging and slash burning.
2/ A small portion of the burned area may have been disturbed in logging.

proportion of seedbeds in each class is not equal but vary greatly from 32.9 percent light burn to only 2.2 percent hard burn. For this reason the weighted average stocking is sometimes quite low, usually being brought down by the large percentage of the clearcut in burned seedbeds, here 35.1 percent of the total area. These seedbeds average less than 100 seedlings per acre because they are one or two seasons behind the unburned portion in restocking period. The higher average stocking of hard burn seedbeds is entirely due to a few stocked plots in Unit 1B, and has no general significance. Morris (75) indicates that the stocking on burned and unburned surfaces would be expected to become equal in about five years.

Besides showing that the burned seedbeds are slower to restock, Table 1 shows a distinct superiority for the seedbeds disturbed in logging, both with and without the logging debris which often is scattered over them. The seedbeds on which soil was disturbed in logging accounted for about 32 percent of the area and average 644 and 677 seedlings per acre in the two classes.

Undisturbed seedbeds, which are made up of litter and light slash, medium and heavy slash, and rotten wood classes, are about average in stocking, or between 208 and 587 seedlings per acre. Rotten wood has a high initial stocking in these figures but, with the small sample here, is not significantly different from the other undisturbed seedbeds. The trend of less stocking with increasing density of slash is apparent but not significant statistically, although it does substantiate similar trends found by Lavender et al.

(60) and Bever (10).

The two classes of disturbed seedbeds are significantly different in stocking (5% level) from the two classes of burned seedbeds. All other seedbed differences could be expected to occur by chance.

When these data are considered from the standpoint of practical use, they are found difficult to apply. The descriptive definitions of seedbed types cause their interpretation to vary from one individual to the next. This was found true to some extent even when great care was taken to train the field crews toward uniform interpretations. The line between the various slash classes, or burn classes defy exact definition. In addition, each season can make a marked change in the seedbeds themselves through weathering, movement, and decay. The leaves fall from the slash, the steeper slopes often sluff, and revegetation as well as weathering obliterates the sharp line that once marked the edge of the slash fire. Furthermore, the variability within the broad classes is so large that microsites within them on which seedlings grow may be actually similar.

The data are most interesting in providing some descriptions of the proportions of various seedbeds. The fact that about a third of the area is disturbed in logging, and that this portion tends to restock better, has practical applications. That about 10 percent is non-seedbed in terms of initial stocking is also surprising.

The Regeneration Survey Approach Versus Sampling of Physical Factors

Some small but important items of additional information were provided by this survey. The percentage of seedlings in the shadow of the stand edge on the south side of the clearcuts was unusually high. On two clearcuts (Units 1B and 1C) all the milacre plots found in these locations were fully stocked.

Another such item was the proportion of seedlings having midday shade. The hours of shade were estimated by approximate astronomical methods for each seedling occurring on the plots. This was done in a relatively simple way. The observer carried a protractor which was placed with its index mark at the seedling stem and oriented with the 90° mark toward the south. Because the latitude was approximately 45°N (44° 15') the protractor had only to be tilted at a 45° angle toward the north to align its surface with the celestial equator. This is the apparent path of the sun on March 21 and September 21. The path of the sun for the six spring and summer months lies somewhere in a band 23° wide north of the celestial equator marked by the protractor edge. Shadows of any objects giving shade to the stem at ground level must intersect the skyward projection of the imaginary band. Since the sun moves along the imaginary band at the rate of 15° per hour (the earth rotation in degrees per hour) the hours of shade received by the seedling can be estimated with the protractor in terms of degrees and finally in terms of hours.

This was done for every seedling to an accuracy well within

one-half hour (or a $7\frac{1}{2}^{o}$ arc). Such accuracy could be attained even for seedlings in positions where the protractor could not be fitted against the stem. In such cases a pencil with point held at the seedling stem could be swung on approximately the sun's apparent path, and the demarcation between sun and shade referred to distant objects in line with the pencil. Difference in the azimuth between such distant points would be translated into hours of shade. The principles for such approximations are found in any general surveying textbook (15).

A record was made of shade for the entire seedling, and also for one-quarter inch at the base of the stem. Results were remarkably consistent. Table 2 gives the percentage of the seedlings found on nine clearcuts receiving shade for various periods between 6 a.m. and 6 p.m. There was no pattern to the record of shade over the entire seedling. Almost as many were in the open as were shaded to any degree. Only 27.2 percent were shaded continuously.

However, between 75 percent and 90 percent of the seedlings on each clearcut received stem shade the entire day. Those shaded in this manner at least four hours during the 6 a.m. to 6 p.m. period averaged over 90 percent of all seedlings. An analysis of 35 seedlings in this record which were without either top or stem shade was conducted to determine seedbed conditions which might account for their survival without shade. Of the 35, all but 12 were in mineral soil on northerly slopes steeper than 40 percent, hence were receiving reduced amounts of energy per unit of surface. Of the

Table 2.—Percent of seedlings shaded for various hours between 6 a.m. and 6 p.m. sampled in five clearcuts of the H. J. Andrews Experimental Forest

Clearcut designation	Seedlings sampled	Hours of shade						Hours of shade					
		0	2	4	6	8	12	0	2	4	6	8	12
		Entire seedling						Stem base only					
1 B	50	16	8	14	2	24	36	0	0	6	0	16	78
1 C	39	33	3	5	3	8	48	15	3	0	0	3	79
1 D	87	54	11	12	8	7	8	10	0	1	4	0	85
1 E	38	40	2	11	2	8	37	5	0	0	0	5	90
1 F	47	28	2	2	4	2	62	4	0	0	0	9	87
1 G	27	48	11	15	11	4	11	4	0	4	0	0	88
1 H	96	64	7	11	7	3	8	14	2	2	4	0	78
2 A	12	25	0	0	33	8	33	0	0	8	8	8	75
2 C	29	28	7	3	7	10	45	7	0	0	0	7	86
Weighted average		42.6	6.8	9.2	6.3	7.9	27.2	8.2	0.7	1.8	1.9	4.7	82.7

remaining 12, seven were on yellow mineral soil. The other five seemed to have no protection from surface temperatures.

Since the same seedlings were involved in both the analysis of general seedbed types and in the study of shade, a further comparison can be made. The regeneration survey as an approach to predicting the course of restocking of clearcuts to Douglas-fir seemed to be only a very rough method compared with the attempt here to evaluate physical factors. The information concerning restocking along the shaded timber edge of clearcuts and the measurement of shade on the stem of the seedling was principally concerned with only one or at most two physical factors. These are the reduction of surface temperature and possibly drought. Even so, direct evaluation of physical factors appeared to have enough promise as a more exacting method for predicting stocking to initiate a search for methods of measuring such factors on a large scale.

From this time onward, the regeneration survey approach received less emphasis: attention was turned instead toward surface temperature evaluations as the most promising of the physical factors on which to begin study.

EXTENT OF LETHAL SURFACE TEMPERATURES ON DOUGLAS-FIR CLEARCUTS

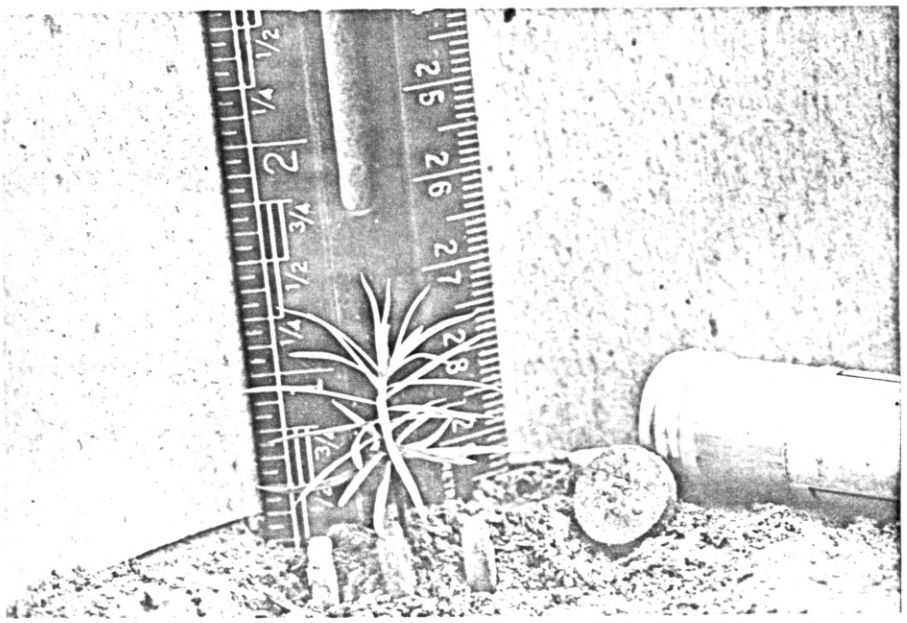
From preliminary results of the regeneration survey, the problems were crystallized. How much of each clearcut reaches surface temperatures that are critical to Douglas-fir, and exactly what temperatures are critical? What microsite characteristics are related to the lethal temperatures?

Direct evaluation of surface temperatures on a large scale had never been done. Available instruments were costly and most investigations of soil surface temperatures were necessarily limited to a relatively few samples.

Commercial temperature pellets (Figure 2) were found for the purpose which in some ways are superior to more expensive instruments such as thermometers, thermographs, and thermocouples. They are cheap enough to permit extensive sampling and they provide an accurate measure of the temperature in the hairline at the surface of the soil. The methods for using the pellets are described by Silen (89). Other uses of low melting point materials to measure surface temperature are described by Buxton (19) and Geiger (32).

Explorations to measure the percent of clearcut surfaces which exceed the lethal surface temperature were began with a small trial in 1953, and expanded to a survey of eight clearcuts in 1954. They have provided figures showing amazingly high proportions of the clearcuts on the H. J. Andrews Experimental Forest in the Oregon Cascades to be unsuitable seedbeds because of high temperature.

Figure 2. Temperature pellets with melting points of 125°F., 138°F., and 150°F. placed near stems of seedlings indicated that the 138°F. pellet was best correlated with seedling mortality. Eight clearcut units were sampled with such pellets to determine the proportion of seedbeds on clearcuts that exceed such temperatures.
(Photo courtesy U.S.F.S.)


1/2
1/4
2
3/4
1/2
1/4
3/4
25
26
27
28
1/2

Companion studies with the pellets placed near the stem of seedlongs showed that the melting of certain pellets corresponds very closely with actual mortality.

The 1953 Trial

The first attempt at measuring the surface area exceeding a certain temperature level was made on a single 36-acre clearcut in a 400-year-old stand. This was on a northerly aspect having steep slopes up to 80 percent at the north end, but grading out to 10 percent slopes at the south end. Elevations ranged from 1,900 to 2,200 feet. The staggered-setting clearcut had been logged and burned the previous fall.

A systematic sample of the clearcut was obtained from eight lines, oriented north-south, having ten temperature stations per line spaced 50 feet apart. The points sampled with pellets of 138°F. melting point were confined to the available seedbed; obviously unsuitable surfaces like streams, swamps, rocks, stumps, and roads were omitted. Alternate stations were mechanically chosen whenever such unsuitable locations were encountered. These amounted to 10 percent of the samples.

A continuous record of air temperature at $4\frac{1}{2}$ feet and surface temperature on a burned surface was provided by a Foxboro recording thermograph. The sensitive elements are gas-filled tubes about three-sixteenth inch in diameter connected by cables to the recorder. Such large elements would provide readings somewhat lower, but

closely correlated to actual surface temperature. The surface sampled was one of the hottest kinds found on the clearcut.

On this clearcut in 1953 the estimated percentage of surface reaching temperatures above 138°F. climbed quickly during late June and early July to 68.5 percent, the maximum for 1953 (Table 3). The progression of maximum air temperatures attained between observations and corresponding maximum surface temperatures is given for each observation date. The rapid rise after June 25 in estimated surface exceeding 138°F. reflects the oncoming of dry summertime conditions after the last spring rains. No more pellets melted after the maximum temperature of July 6.

It was decided to continue explorations during 1954 with samples of a number of clearcuts and for a wider range of temperatures. Detailed microsite descriptions made for the 80 stations in 1953 furnished leads for more accurate descriptions in planning the 1954 study.

1954 Sampling of Clearcuts for Lethal Temperatures and Associated Microsite Conditions

Surface temperatures were studied in 1954 on eight clearcuts on or near the H. J. Andrews Experimental Forest. Four units were on northerly slopes at about 2,000 feet elevation. These had been logged and burned one, two, three, and four years. Only two clearcuts logged one and two years previously were available at 2,000 feet on south slopes, but a three-year-old and a four-year-old clearcut

Table 3.--Maximum air and surface temperature and estimated percent of clearcut surface exceeding 138°F. by dates on a Douglas-fir clearcut

Examination date	Maximum air temperature at 4½'	Maximum surface temperature on burned soil	Surface area exceeding 138°F. 1/
	°F.	°F.	Percent
June 16	87	138	17.5
June 25	88	145	32.5
July 5	98	152	57.5
July 6 2/	104	157	68.5

1/ Basis: 80 temperature stations.

2/ Date of maximum summer temperatures, 1953. No additional pellets melted after July 6.

were available near 4,000 feet.

Exposure, slope, and vegetation were not uniform on the clearcuts. Abrupt changes from the general exposure were encountered in minor drainages on some. Vegetation was practically absent on both of the one-year-old clearcuts, but increased to an almost continuous cover on the four-year-old clearcuts (Table 4).

Field Procedures

In 1954 sampling methods were changed slightly to give more information and to allow for statistical comparisons. Two lines of fifty temperature stations were established in each clearcut on a strict mechanical point sampling. Each station was sampled with pellet fragments melting at 125°F., 138°F., and 150°F. The 138°F. fragment was placed at the exact point to be sampled. The other pellet fragments were placed on each side within one-half inch (89).

Detalied microsite descriptions were made to cover items that might explain differences in surface temperature. Only surface material immediately surrounding the point sampled by the 138°F. pellet was considered. Actual surface materials were listed descriptively to avoid any tendency to place them into artificial or preconceived groupings. If the surface was indefinite such as in duff, the point of a pencil was lightly probed into the spot and the materials touching it were described. If the point fell on suspended material such as limbs or slash, the point was considered to be on the soil below. Non-seedbed materials such as rocks, stumps,

Table 4.—Estimated surface area on 8 clearcuts 1 to 4 years old that exceeded certain levels of surface temperature through June and through the entire summer of 1954

Clearcut description				Percent surface area with temperature (°F.) above					
Area	Age in years	Aspect	Average slope in percent	125°	138°	150°	125°	138°	150°
				By July 2			By Sept. 28		
North Facing Clearcuts									
2E	1	NE	30	35	20	9	68	45	19
2C	2	N	30	47	36	18	67	52	44
1D	3	N	20	37	26	11	68	49	28
1B	4	NW	40	33	23	5	56	46	23
South Facing Clearcuts									
3F	1	SE	30	90	82	24	99	97	85
3A	2	SE	50	71	54	23	97	88	54
R6	3	S	20	86	60	17	95	89	65
R4	4	S	20	57	46	17	79	69	54

sound logs, large chunks of wood, streams, and swamps were not sampled. When encountered they were described, and an alternate point was established five feet either to east or west on a random choice. Thus, the proportion of such microsites was determined, but a uniform size of sample was taken exclusive of non-seedbed microsites on each clearcut.

Degree of burn, whether light, medium, or heavy, was recorded according to the definition provided by Morris (75). Light burn has recognizable organic material on the surface. Medium burn is defined as that in which loss of recognizable surface organic material by fire is complete. Heavy burn is characterized by red appearance of the soil. The division between light and medium burn was not completely satisfactory for microsites but no better one was devised. Microaspect was recorded in eight compass points and microslope estimated to the nearest ten percent.

Shade was estimated to the nearest half hour listing the time that the 138°F. pellet fragment was in shade. This was done by tracing the sun's path through the sky during summer by astronomical approximations in relation to the sampled point (see page 31).

The installations were all completed during a rainy period in early June, so that the same periods of high temperatures would apply to all the data.

Weather records were taken at McKenzie Bridge Ranger Station, a location central to these clearcuts but at 1,200 feet elevation.

Only two examinations were made. It proved impossible to cover the 800 temperature stations after each successively hotter period as was done in 1953. The first examination was during a rainy period from June 28 to July 2. The intervening period in June had included a series of four hot days between rainy periods when an air temperature of 86°F. on June 21 was accompanied by temperatures on burned surfaces exceeding 150°F. The second examination was made in mid-September. The hottest day recorded in this interval, July 22, had an air temperature of 89°F. Two percent of the pellets were missing at the first examination and 9.4 percent were missing by fall. Surface movements accounted for this in great part as most occurred on steep slopes. Shifting of small surface objects to this extent was not expected during summer months. Some missing pellets had undoubtedly melted so completely as to leave no trace. Computed percentages of melted pellets are based on number at stations found intact at each examination date. The total loss was believed too small to bias the samples.

Results From Temperature Data

Results from the July 1 examination (Table 4) show that 46 percent to as much as 82 percent of the stations on south-slope clearcuts exceed 138°F. temperatures, with the freshest logged clearcut being the hottest. Corresponding percentages are quite different on north-slope clearcuts. Temperatures exceeding 138°F. occurred on only 20 percent to 36 percent of the stations.

Differences in percentages of melted pellets between the clearcuts on north and those on south slopes are significant at the five percent level. The September examination showed that 138°F. pellets were melted at 69 to 97 percent of the stations on south-slope clearcuts and on nearly half the stations on all north-slope clearcuts. In other respects the September examination data are in line with early summer results.

The effect of years since logging on surface temperatures for north and south slopes (Figure 3) is a trend toward lower temperatures with time. This possibly reflects shading effect from revegetation. On the south slopes the trend was significant both on July 1 and in September, but not on the north slopes. In this regression analysis, lines of 50 pellets were considered the sampling unit, and the 1953 data from Unit 2C were also used. Among the north-slope clearcuts, the freshly logged Unit 2E had fewer melted 138°F. pellets than might be expected. This is because nearly two-thirds of the stations fell on north slopes steeper than 50 percent where no high temperatures were recorded. Among south-slope clearcuts, Unit 3A is also out of the expected order because a considerable number of stations fell on north slopes of minor drainages. All other clearcuts in the study fell into the expected order. A suggested reduction of 10 percent per year on south slopes and 1 to 4 percent per year on north slopes is indicated by these regressions.

Results on one clearcut unit on a north slope studied for two years tend to confirm the predicted decrease in surface temperature

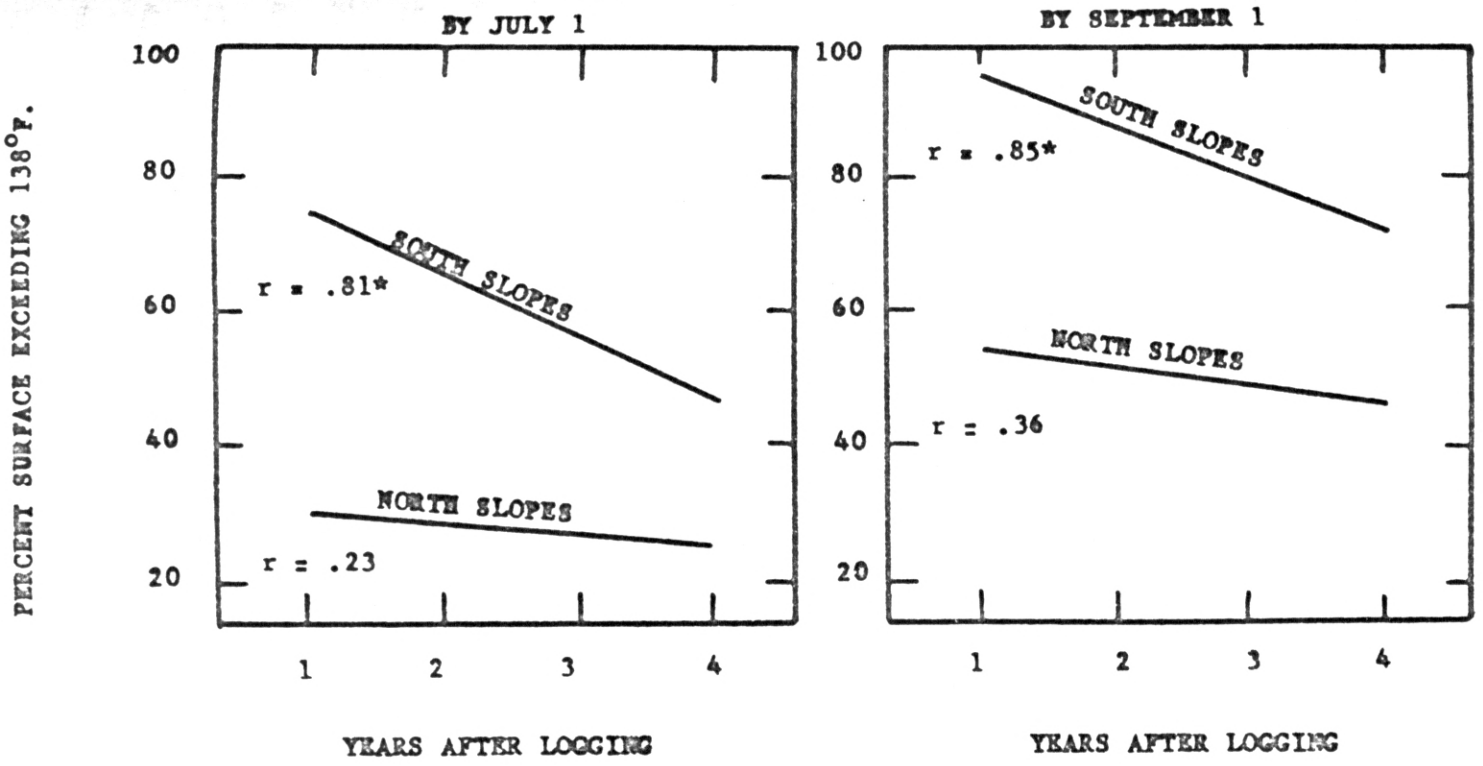


Figure 3.--Estimated decrease of surface temperature with years after logging on north- and south-slope clearcuts.

with time. Measurements the first year after logging were made on June 25 when 32.5 percent of the 138°F. pellets had melted. By July 5, 57.5 percent had melted. Measurements taken the second year on this clearcut showed 35.5 percent melted on June 30. An interpolation of the first year data gives an estimated 45 percent of the pellets melted on June 30. This indicates about a 10 percent decrease. Late summertime meltings, 68.5 percent the first year and 52.5 the second year after logging, show a 16 percent decrease.

This decrease should not be envisioned to imply an improvement in seedbed conditions, for it is associated with increase in competition from vegetation. It merely suggests how much change may be taking place in the extent of certain temperatures. Microsite evaluations, to be considered next, alter these conclusions somewhat.

Results From Microsite Data

Tabulated microsite information (Table 5) aids considerably in evaluating temperature information. None of the clearcuts had predominantly north or south microaspects. Each had considerable proportions of the stations falling on flat areas. Flat microaspects averaged 23 percent of all clearcuts (Table 5a). Although the north-slope clearcuts had only 9 percent of the stations with southerly aspects, about 21 percent were on flat and another 29 percent facing east or west. Only 41 percent actually faced in a northerly direction. On south-slope clearcuts, 16 percent had northerly microaspects, 25 percent were flat, and 18 percent faced east or west.

Table 5a.—Percent of microsites on north and south clearcuts by microaspects

Microsite class	North slope clearcut					South slope clearcut					All slopes avg.
	2E	2C	1D	1B	N. slope avg.	3F	3A	R6	R4	S. slope avg.	
Flat	19	23	31	9	21	17	6	34	43	25	23
N	40	20	24	19	26	5	13	9	4	8	17
NE	13	11	5	8	9	4	13	8	1	6	7
E	20	13	13	24	17	12	20	8	9	12	15
SE	3	2	3	5	3	19	11	7	8	11	8
S	2	3	6	3	3	36	17	12	13	20	11
SW	0	3	5	2	3	5	17	9	7	10	6
W	1	19	7	19	12	2	1	8	12	6	9
NW	2	6	6	11	6	0	2	5	3	2	4

Table 5b.—Percent of microsites on north and south clearcuts by burn classes

Microsite class	North slope clearcut					South slope clearcut					All slopes avg.
	2E	2C	1D	1B	N. slope avg.	3F	3A	R6	R4	S. slope avg.	
Light burn	34	48	27	19	32	47	17	17	21	26	29
Medium burn	6	17	4	2	7	15	5	3	3	6	7
Heavy burn	1	7	1	3	3	3	0	3	0	2	2
No burn	59	28	68	76	58	35	78	77	76	66	62

Table 5c.—Percent of microsites on north and south clearcuts by seedbed classes

Microsite class	North slope clearcut					South slope clearcut					All slopes avg.
	2E	2C	1D	1B	N. slope avg.	3F	3A	R6	R4	S. slope avg.	
Mineral types											
Yellow mineral	29	4	26	28	21	6	12	27	9	14	18
Dark mineral	8	12	15	12	12	31	31	9	20	22	17
Gravel or stones	0	0	1	5	1	1	8	0	0	3	2
Sand or fine gravel	4/41	0/16	0/42	0/45	1/35	1/39	0/51	0/36	0/29	0/39	0/37
Burned types											
Charred duff	10	20	3	2	9	14	5	3	2	6	9
Charred rotten wood	10	4	3	2	5	3	0	0	1	1	3
Charred mineral	8	19	4	8	10	13	3	10	5	7	9
Cinders and ashes	0	4	4	2	3	5	3	3	4	4	3
Red burn	1/29	6/53	1/15	3/17	3/30	1/36	0/11	4/20	0/12	1/19	2/24
Organic unburned types											
Duff-needles	15	12	12	17	14	9	19	23	22	18	16
Rotten wood	4	4	7	8	6	9	3	5	7	6	6
Bark, wood, chips & twigs	4	1	8	2	4	4	2	5	9	5	4
Broadleaves	0	0	3	1	1	0	2	2	12	4	3
Moss	0	3	4	4	3	0	6	0	1	2	2
Sawdust	0/23	1/21	0/34	0/32	0/27	0/22	2/32	1/35	0/52	1/36	1/32
Non-seedbed types											
Logs and stumps	5	5	8	6	6	3	4	9	7	5	6
Rocks	2	3	1	0	1	0	2	0	0	1	1
Water	0/7	2/10	0/9	0/6	1/8	0/3	0/6	0/9	0/7	0/6	0/7

Table 5d.—Percent of microsites on north and south clearcuts by number of hours in shade from 10:00 a.m. to 4:00 p.m.

Microsite class	North slope clearcut					South slope clearcut					All slopes avg.
	2E	2C	1D	1B	N. slope avg.	3F	3A	R6	R4	S. slope avg.	
Hours											
6	28	22	20	42	28	3	7	6	16	8	18
5	13	8	7	4	8	5	6	8	5	6	7
4	5	9	6	4	6	4	6	7	7	6	6
3	10	11	8	5	9	6	8	9	9	8	8
2	6	13	8	18	11	11	13	14	8	12	12
1	22	17	9	13	15	26	24	10	10	17	16
0	16	20	42	14	23	45	36	46	45	43	33

Only 41 percent faced in a southerly direction. In this respect clearcuts were well matched. They also averaged about 29 percent in slope. This coincidence was accidental since the choice of clearcuts on the upper McKenzie River of the desired age and exposure was very limited at the time. The figures serve to illustrate that micro-aspects may be quite different than the general aspect of a clearcut.

Only about 3 percent of the area is in hard or heavy burn, the bulk of these clearcuts (62 percent) being untouched by fire, or so lightly burned (29 percent) that organic material was still present on the surface (Table 5b). The extent of the area covered by fire and intensity of the fire are entirely dependent on the pattern of drying weather during fall. Burning under extremely dry conditions such as on Unit 2C covered practically all the surface having any fuel (72 percent). In contrast, only 22 percent of the clearcut 3A was covered even if burned only a few weeks later but after an additional rainy period. For this reason, as well as for topographic differences, each clearcut is more of a case history than a sample in a progression in age on north or south slopes. Microsite differences may be more extreme within a clearcut than between them.

Perhaps each of the 800 microsites described in the study was unique. They cannot be reported, however, without some grouping into seedbed types. The groupings used indicate an attempt to place together seedbeds of comparable heating properties (Table 5c). Seedbeds are divided into mineral soil types, types altered by fire, and unburned organic types. Among the mineral types, those without

appreciable humus are yellow mineral subsoil, broken rocks, gravel or sand. Those mineral types containing humus fall under the dark mineral classification. The types altered by fire include charred duff, charred rotten wood, blackened mineral soils, cinders, ashes, and hard red burn. Organic types include numerous duff materials such as needles and small pieces of cone scales, catkins, twigs, bark flakes, broadleaf fragments, animal droppings, moss, lichens, wood slivers, rotten wood, and sawdust.

All the above seedbed classes have some artificiality. When several occurred together, an arbitrary choice was made of the dominant one without regard to inclusion of materials that might reach higher temperatures. Some of the microsites in burned areas were listed among the mineral types because the fire had left no visible effect. Finally, the classification presupposes the ability to compare seedbed materials. Even with these shortcomings the classification is roughly correct in placing similar seedbeds into a class.

About seven percent of the clearcuts were non-seedbed (Table 5c). Almost six percent were covered by logs or stumps, and about one percent was divided between rocks and water. Gravel roads were not sampled.

The mineral types occupied about 37 percent of the clearcuts, with 18 percent in yellow mineral, 17 percent in dark mineral, and about 2 percent in gravel or sand types. Unburned organic types covered about 32 percent of the surface, divided between duff (16 percent), rotten wood (6 percent), bark and wood chips (4 percent),

broadleaves (3 percent), moss (2 percent), and sawdust (1 percent). Those altered by fire covered the remaining 24 percent. These included 7 percent charred duff, 3 percent charred rotten wood, 9 percent charred mineral soil, 3 percent cinders or ashes, and 2 percent red burned soil. The figures are averages for eight clearcuts (Table 5c). For individual clearcuts the types may vary greatly from these averages.

Hours of shade for the microsites (Table 5d) reflect the true effect of topography. On north slopes 28 percent of the microsites were in shade from 10 a.m. to 4 p.m.; on south slopes only 8 percent were in similar shade. On south slopes 43 percent were exposed to sunshine this important six-hour period daily, as compared to only 23 percent on north slopes. These figures include the intermittent sun through plant cover as well as full sunlight. This was done because high surface temperatures were consistently measured under such intermittent shade. Hence, the figures serve to compare clearcuts without effect of revegetation on shade. Note should be made that on north and south slopes the four-year-old clearcuts have definitely higher numbers of microsites under full shade. Thus, topography prior to any revegetation contributed markedly to the lower temperature found on these clearcuts.

Surprisingly, a steep northerly aspect was in itself no sure protection against high temperatures. Temperatures over 125°F. were recorded on 70 percent north slopes when duff seedbeds were fully exposed. Even mineral soil exceeded 125°F. on 50 percent north

slopes. However, shade was more abundant on north slopes than on other aspects. Even very low objects gave adequate shade which leads to the illusion that a steep north slope was effective alone. Needless to say, other aspects were also ineffective as they received the sun's rays at higher angles.

Organic seedbed types as well as charred and dark mineral types reached high temperatures even on short exposures. This could be determined only from stations in sun for brief periods each day. There were many instances of melting of the 150°F. pellets exposed for two hours or less on these types, and relatively few instances in which these seedbeds remained below 150°F. with three hours of exposure. Yellow mineral soil occasionally reached 150°F. with two hours of exposure, but often required four or five hours. In a few instances this seedbed type remained below 125°F. even with five and six hours exposure. Dark mineral soils were much hotter under similar conditions than yellow mineral soil. In fact they ranged among the hotter types if organic material such as rootlets and humus were plentiful in them.

Inspection of microsite information revealed that most of the stations remaining below 125°F. on July 2 were in moist situations. If not perpetually shaded they were either on northerly exposures or under intermittent shade of vegetation or slash. When the ground became very dry after July 2, few except the perpetually shaded stations remained below 125°F. Hence low seedbed temperatures in the early examination were tied to conditions that delayed drying.

Intermittent shade of most vegetation gave illusive protection. Except for delays in drying, high temperatures were reached under senecio (Senecio sylvaticus), fireweed (Epilobium angustifolium), red huckleberry (Vaccinium parvifolium), blackberry (Rubus ursinus var. vitifolius), dogwood (Cornus nuttallii), willow herb (Equilobium paniculatum), hazel (Corylus cornuta var. californica), rhododendron (Rhododendron macrophyllum), ceanothus (Ceanothus velutinus), bigleaf maple (Acer macrophyllum), or a thin overstory of Douglas-fir. Of 130 microsites in continuous shade of such plants, 105 reached temperatures above 125°F. Only plants forming low dense mats like whipplea (Whipplea modesta), twinflower (Linnaea borealis var. americana), oxalis (Oxalis oregona) and ferns (Polystichum munitum), and dense plants like vine maple (Acer circinatum) gave continuous enough shade to prevent elevated surface temperatures. Microsites under vegetation were usually of organic types that heated easily.

This would seem to contradict the trend toward lower temperature with time shown earlier (Figure 3). The trend proves to be real in two ways. Low or dense plants provide increasingly more perpetually shaded microsites with time. Also a small percentage of the taller plants do provide enough shade. But some of the trend shown in Figure 3 is a coincidence. The four-year-old clearcut on south slope had somewhat more microsites with dead shade than the others (Table 5d). Hence, for south slopes the 10 percent change per year in 138°F. temperatures (Figure 3) is probably an over estimation.

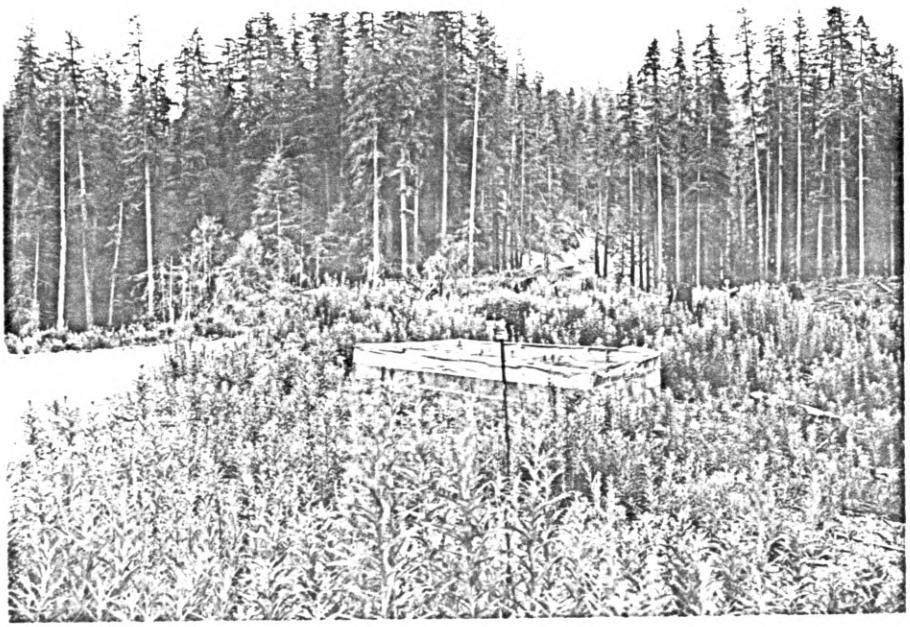
Comparisons of Surface Temperature with Seedling Mortality

The level of temperature that would correlate best with actual seedling mortality was not known in advance. This information was gained from field tests of natural seedlings on the H. J. Andrews Experimental Forest, the Cascade Head Experimental Forest on the Oregon Coast, and at the Siskiyou-Cascade Research Center near Roseburg, Oregon.

The tests consisted of observations of small fragments of 125°F., 138°F., and 150°F. pellets placed very near the stem of each seedling. All fragments were placed to the north of the seedling to prevent shading. Records of melted pellet and seedling damage were made weekly during early summer and approximately at monthly intervals during August and September. On each area 44 to 80 seedlings were sampled after omission of those seedlings which were clipped by mice or cutworms, buried, or had failed to root. Most of the seedlings in all three field plots were on mineral soil of skid roads and road fills—the only type of area where adequate numbers of seedlings could be found in 1954.

To assure a large number of additional seedlings for the test, two four-milacre exclosures were constructed to keep out rodents and birds. These were artificially sown with Douglas-fir in early April. One exclosure sampled an exposed south clearcut slope at 1,600 feet and the other a flat clearcut area (Figure 4) at 2,000 feet elevation. Each was located to include a variety of seedbeds. About half

Figure 4. Two 14-foot square study areas enclosed in hardware cloth and aluminum band, and covered by 1-inch screen. Mice and birds were successfully screened from the two exclosures during tests correlating seedling mortality with melting of 125°F., 138°F., and 150°F. temperature pellets placed near the stems of seedlings. In upper photograph, nearby stake with aluminum flashers marks a station used to sample the clearcut for surface temperatures. Other stations are seen in the distance. Note freshly logged and burned conditions of the lower photograph.

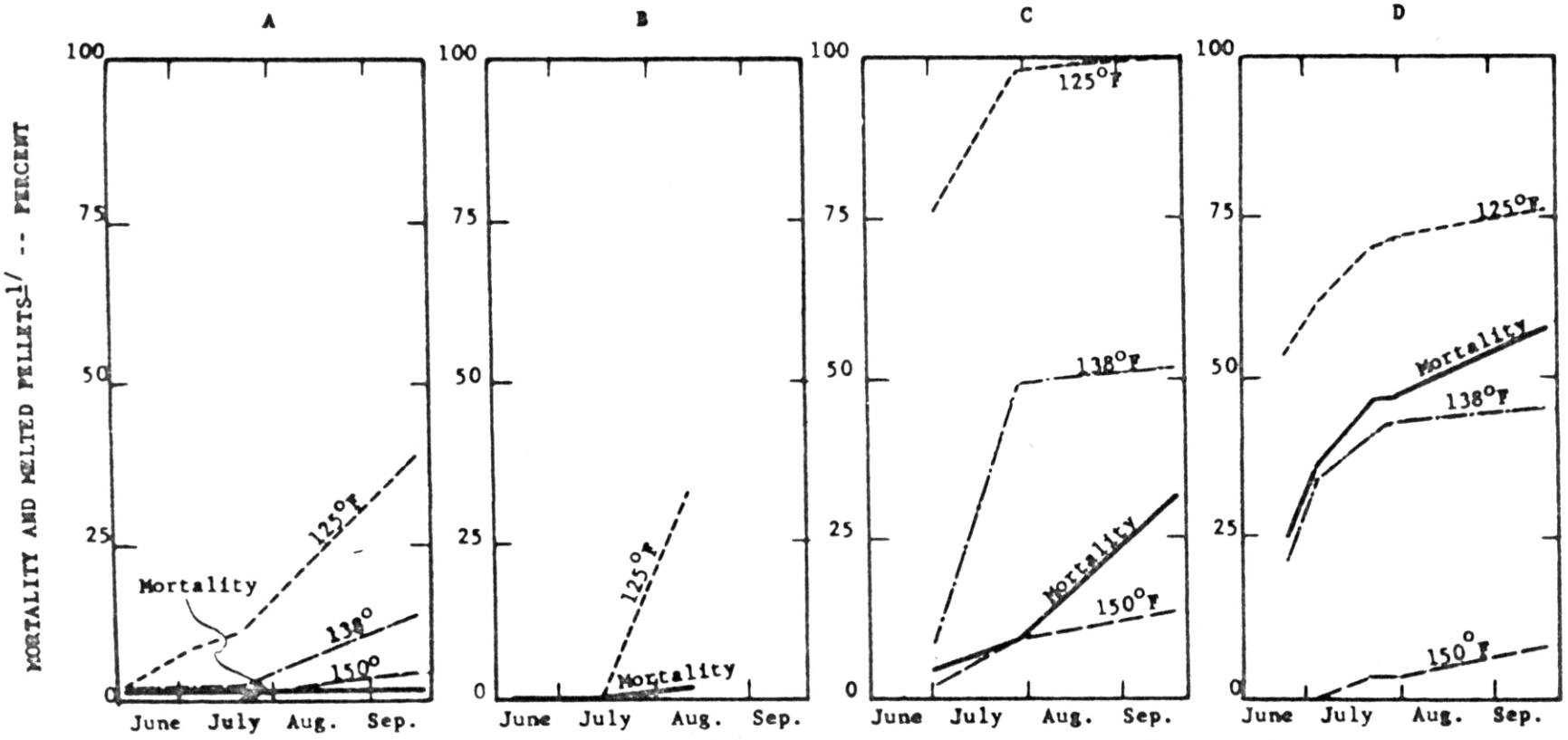


of each area was on burned surfaces. For this reason the exclosures provided more variable seedbed conditions than the other samples.

Weather conditions made 1954 an ideal year for a temperature and mortality comparison. Soaking rains up to July 1 and again in early August prevented any prolonged drought; hence most of the mortality through the entire summer of 1954 was a direct result of stem lesions from high surface temperatures. In most years the losses can be attributed to drought of late summertime as well as to early heat damage. Animals, presumably mice or insects, clipped 19.3 percent of the seedlings on field plots. Comparisons of surface temperature and mortality do not include clipped seedlings to avoid any confusion in the interpretation of temperature effects.

Relatively light mortality occurred on the three samples of natural seedlings located on mineral soil of skidroads and road fills (A., B., and C. Figure 5). An inspection of the surface temperatures shows that less than 10 percent of the surface on field plots had exceeded 138°F. by July 1—far below the 44 percent average of the sampled clearcuts. While the figures illustrate the relative effectiveness of mineral soil in resisting high surface heat, the field plots cover too narrow a range of seedbed types. Hence they fail to give a clear picture of typical seedling mortality on the eight clearcuts. The data from the two exclosures (Figure 5-D) cover a greater range of seedbeds, and give a better correlation of the progression of temperature and mortality on the clearcuts. Here 35 percent of the 138°F. pellets were melted by July 1—a figure well

Figure 5.--1954 seedling mortality from high temperatures and percent of pellets that melted at four locations



H. J. Andrews Exp. For. Field Plot

Cascade Head Exp. For. 2/ Field Plot

Siskiyou-Cascade Res. Cen. Field Plot

H. J. Andrews Exp. For. Exclosure Samples

1/ Basis: 44, 80, 54, and 92 seedlings for A.B.C. and D. respectively.

2/ No 138° or 150°F. pellets melted. Observations were terminated after heavy rains beginning August 1.

within the range of the clearcuts sampled. However, no distinction was made between the various samples in the analysis; the pellet melts and early mortality followed closely (see Table 6) and statistical analysis gave highly significant relationships in every case.

In spite of a variation that ranges from no mortality from heat at Cascade Head Experimental Forest to a 36 percent mortality in the exclosures at the H. J. Andrews Experimental Forest, the correlation with 138°F. pellets that had melted on each area up to July 1 is very close. For instance, 35 percent of the pellets had melted and 36 percent of the seedlings were dead in the exclosure sample; 2 percent were melted, 2 percent were dead at the H. J. Andrews Forest; 8 percent were melted, and 4 percent were dead at Siskiyou-Cascade; and 0 percent were melted and 0 percent were dead at Cascade Head.

Lest the above correlation be misconstrued, the melting of the 138°F. pellet did not always mean that the nearby seedling would die. In fact 11 of the 278 seedlings were alive on July 1 in such locations, and 22 had resisted such temperatures by mid-September. Moreover, 3 seedlings, all on the Siskiyou-Cascade plot, survived temperatures in excess of 150°F. sometime during the summer. However, the 138°F. pellet was much more closely related than either the 125°F. or 150°F. pellets as determined by X^2 tests for single plots and for all plots. The close relationship on July 1 between melting of 138°F. pellets and mortality stems from the fact that there were about as many seedlings that died at temperatures below 138°F. as

Table 6.—Comparison of seedling mortality[1/] and melted 138°F. pellets on four areas

Area	Location	No. seedlings	Cumulative mortality (first figure) and melted 138° F. pellets (second figure) on: June 2-4	June 24	July 1-2	July 16-28	Sept. 10-Oct. 10
					Percent		
A	H. J. Andrews Expt. For., field plot	44	2 - 2	2 - 2	2 - 2	2 - 2	8 - 2
B	Siskiyou-Cascade Res. Cen., field plot	54			8 - 4	48 - 8	57 - 33
C	Cascade Head Expt. For., field plot	80	0 - 0		0 - 0	0 - 0	0 - 1
D	H. J. Andrews Expt. For., exclosures	92		22 - 26	35 - 36	42 - 47	47 - 59
	Totals	270	2 - 2	24 - 28	45 - 42	92 - 57	112 - 101

1/ Up to mid-July only mortality from heat injury is recorded. After mid-July all mortality except by rodents and trampling is shown.

lived above this temperature. The same may be said for the September data on all plots, but there was more variability between individual plots by late summer. These relationships are shown in the contingency tables from which highly significant X^2 values were computed (Table 7).

Discussion of Field Studies

The field studies provide data covering six points: (1) the temperature pellets provide a simple, effective field method to sample for proportions of clearcuts exceeding certain levels of temperature; (2) such sampling shows surprisingly high proportions of clearcuts that exceed 138°F.; (3) the 138°F. pellet is better related to actual mortality of seedling from heat than the 125°F. or 150°F. pellet; (4) this relationship is close on individual areas up to July 1, but becomes less close thereafter; (5) for individual seedlings the temperature at which mortality occurs varies from about 125°F. to over 150°F.; (6) effect of revegetation in reducing surface temperatures is not great. These points each need some qualification.

Except for problems of finding the tiny pellet fragments this point sampling method was otherwise quite trouble-free. Loss of pellets was not serious, amounting to only 9.4 percent by the end of summer. Some of this loss was from the complete melting of all the pellets. Sometimes they left so little trace that no distinction could be made between such loss and disappearance by surface movements. Major loss, however, was from soil movement on steeper

Table 7.--Contingency tables showing number of living or dead seedlings in locations remaining below or exceeding 138°F. and Chi-square values

Temperature	Number of seedlings			X^2 value
	Alive	Dead	Total	
		July 1		
Below 138° F.	220	10	230	
Above 138° F.	11	29	40	122.61 1/
Total	231	39	270	
		Late September		
Below 138°F.	169	20	189	
Above 138° F.	22	59	81	103.19 1/
Total	191	79	270	

1/ Highly significant.

ground. No doubt techniques could be developed to reduce losses.

By themselves the figures are surprising in showing that a high percentage of the area in clearcuts attains elevated temperatures. The percentage of 138°F. pellets that melted range from 20 percent to 82 percent by early July and from 45 percent to 97 percent by late summer. It is likely that the eight clearcuts sampled are not extremes, and that both higher and lower percentage figures would be found if samples were taken elsewhere.

Delayed departure of moisture on shaded microsites appeared to be the main factor in keeping seedbeds cool before July 1. After the soils became thoroughly dry, nearly all seedbeds exposed to sunshine for an hour or more reached 125°F. or higher. This was also true on microsites shaded the entire day by plants. The exceptional instances of full exposure to sun without attaining excessive temperatures seemed to be associated with combinations of mineral soils and northerly exposures.

Mortality is best related to melting of 138°F. pellets but the relationship is not a simple one. Field determinations of lethal temperature are even more complex than the literature on thermal death points would indicate (Leitch (62), Baker (4), Shirley (87), Lorenz (66)). By July 1 no seedlings had died where temperatures remained below 125°F. But between this temperature and 138°F. 39 seedlings died and 68 lived; all seedlings died where 150°F. temperatures were recorded. Temperatures were determined within 1/8 to 1/2 inch of a seedling stem. Even so, the field measurement of a

thermal death point was not definitely at any of the measured temperatures nor between them. Of the three pellets tested, the melted 138°F. pellet gave by far the best correlation with average mortality. As an indicator of mortality for the individual seedling it was also best. The number of seedlings that lived in locations where this temperature was exceeded about balanced the number of seedlings that died in locations remaining below 138°F. In fact, the July 1 prediction of mortality using the percent of 138°F. pellets that melted was quite accurate on the four widely separated areas.

From July 1 onward the situation becomes very complex. Many seedlings with lesions from early high temperatures lived on into the summer before they died. In some cases they were still alive and apparently recovering in the fall. Meanwhile, temperatures continued to climb as the surfaces became very dry, confusing the record as to which temperature caused the fatal damage. Curves of cumulative mortality and temperatures (Figure 5) show that the melting of 138°F. pellets was far more prevalent than mortality on the mineral soil of the Siskiyou-Cascade and H. J. Andrews field plots. However, at Cascade Head and in the variable seedbeds of the exclosures on the H. J. Andrews Experimental Forest, melting of 138°F. pellets underestimated mortality in late summer. Thus, over all the plots but not for individual plots, the two percentages were close because of the compensating effect of one plot on the other.

Thus the extent of lethal surface temperatures on the eight clearcuts seems to be estimated fairly well by the proportion of

138°F. pellets that melted. This would mean that seedbeds on more than a third to a half of north-slope clearcuts and two-thirds to practically all of the south-slope clearcuts were unsuitable for seedlings because of high surface temperature.

The initial lay of the land appears more important in determining the proportion of high temperature seedbeds than revegetation during the first four years. Even four-year-old clearcuts, the coolest sampled on south slopes, had a higher percentage of stations with melted 138°F. pellets than any of the north slopes. A north aspect without shade was not effective alone in preventing high temperatures. The available shade was simply more plentiful at the microsite level.

The effect of revegetation is a mixed one. Though providing shade, competing vegetation is often detrimental to seedlings and no substitute for shade without competition. The shade of vegetation gave little protection from high temperatures in late summer, but did delay drying of the seedbeds for a period after rains. However both of these factors may have a role in protecting the seedling when the importance of duration of exposure is later demonstrated.

The important microsites to the forester are those that remain below 125°F. Some occur on even the most exposed south-facing clearcut, but occur in higher proportion on other aspects. A portion of these are unsuitable for other reasons such as those in heavy slash or in stony areas. The remainder must furnish the site for most of the early stocking that does take place. However, appreciable

numbers of seedlings seem to survive where high temperatures are measured. A better understanding of microsite variation in this respect was the subject of subsequent field and laboratory studies to be reported in the next section.

The study points to a possible use of the 138°F. pellets. They may serve to approximately delineate areas that might restock naturally from those that probably will not and must be planted. The pellets evaluate clearcuts only with respect to mortality from heat, hence considerable testing would be required to determine what a certain percent of melted pellets may mean in terms of eventual restocking of a clearcut.

LABORATORY STUDIES

The field studies alone were perhaps adequate in pointing up the importance of high surface temperatures on Douglas-fir clearcuts. However, a feature of the information that could be subjected to widely differing interpretation was involved in the words "lethal temperature". Apparently the lethal temperature could range from about 125°F. to over 150°F. There was no certain information from the field study that specified conditions for which either extreme applied. Experiments were needed to weigh the individual contributions of various factors that might influence the lethal temperature.

Among the possible influencing factors were seedling age, duration of exposure to high temperature, kind of seedbed material, seedling size, and physiological difference in resistance to heat injury. The first laboratory experiment was designed to test independent contributions of the first three factors. Other laboratory experiments followed on the effect of heat alone, the role of transpiration in cooling the stem, and the temperature inside a seedling stem.

Variations of Lethal Temperature Due to Seedling Age, Duration of Exposure, and Seedbed Material

This experiment was designed to study the contribution of seedling age, duration of exposure, and seedbed materials to heat injury as these factors varied over a range at least as large as the

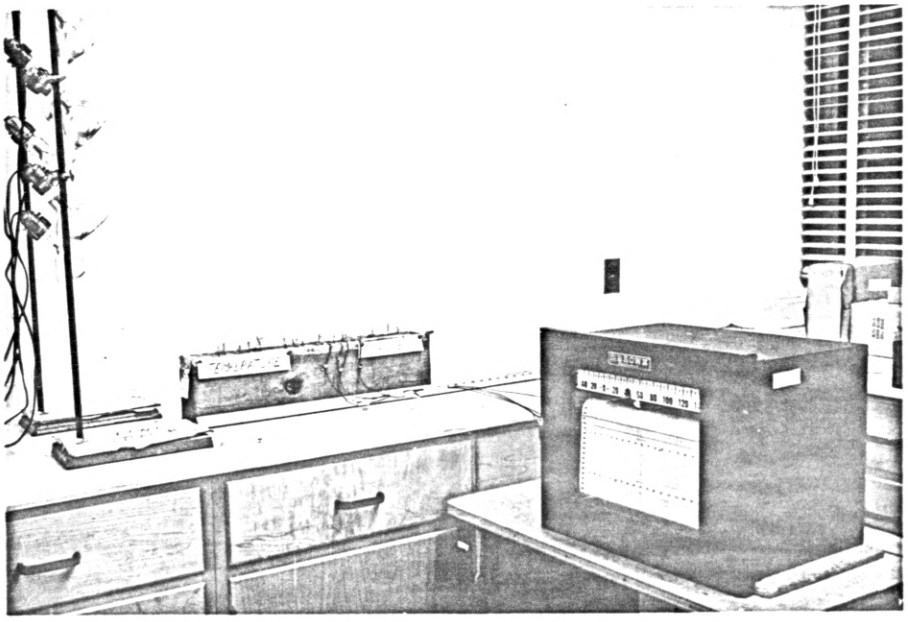
extremes encountered in the field study. Five ages of seedlings, four durations of exposure and three seedbed materials were used in this experiment. All other factors were controlled to a high degree.

Materials and Methods

A radiant energy source consisting of six tungsten 150-watt spot reflector lamps clamped on two 36-inch-tall ring stands was set up on a laboratory table. Lamps were closely grouped and each was aimed downward at about a 45° angle. A sand filled box 6 inches deep with top surface 3 by 24 inches was placed in the beam of the lamps and its position marked on the table. Lamps were carefully adjusted so that each spot overlapped the next along the center line of the box. After considerable adjustment the intensity of the light from the six lamps dropped off with distance along the sand surface in an approximately straight-line relationship. The result was a "temperature gradient" on the surface of the sand.

This provided a range of surface temperatures grading from about 200°F. at the end of the box nearest the lamps to about 105°F. at the other end (Figures 6 and 7). Temperatures at four points were measured with thermocouples made of No. 24 copper and constantin wire. A Brown recording potentiometer, Model 153 X O P 4 - X - 62 F 4, provided a chart record of temperatures at the four junctions registered at two-minute intervals. Such a setup permitted a single operator to carry on the experiment without loss of information.

Figure 6. "Temperature gradient" apparatus used in studying effect of seedling age, duration of exposure, and seedbed material on seedling mortality from surface heat. Lamps provide surface temperatures that grade uniformly from about 200°F. to 105°F. along the box. Temperature records of each treatment are made in chart form by the recording potentiometer at right. Thermocouple wires at four positions record surface temperatures. Lower photograph was made from illumination provided by the six center lamps.



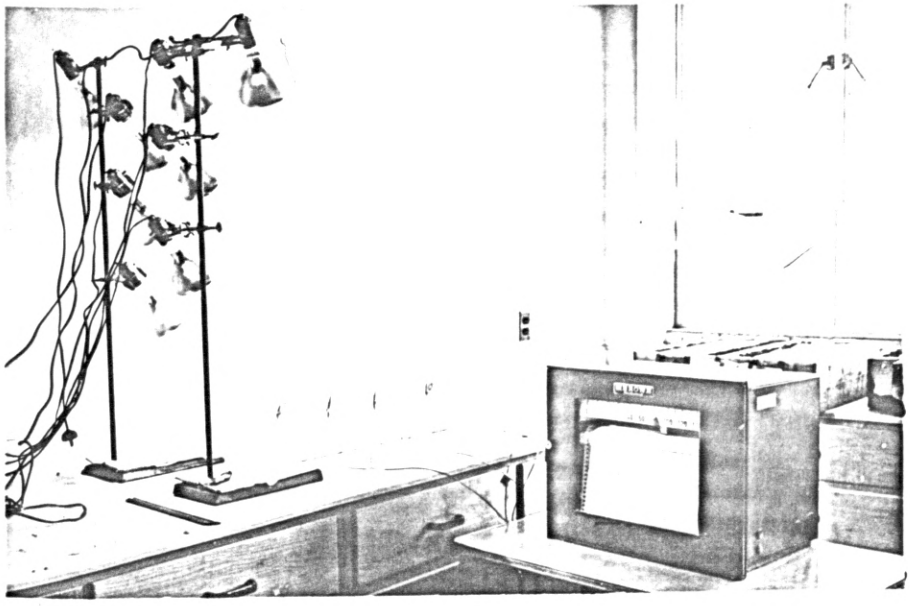
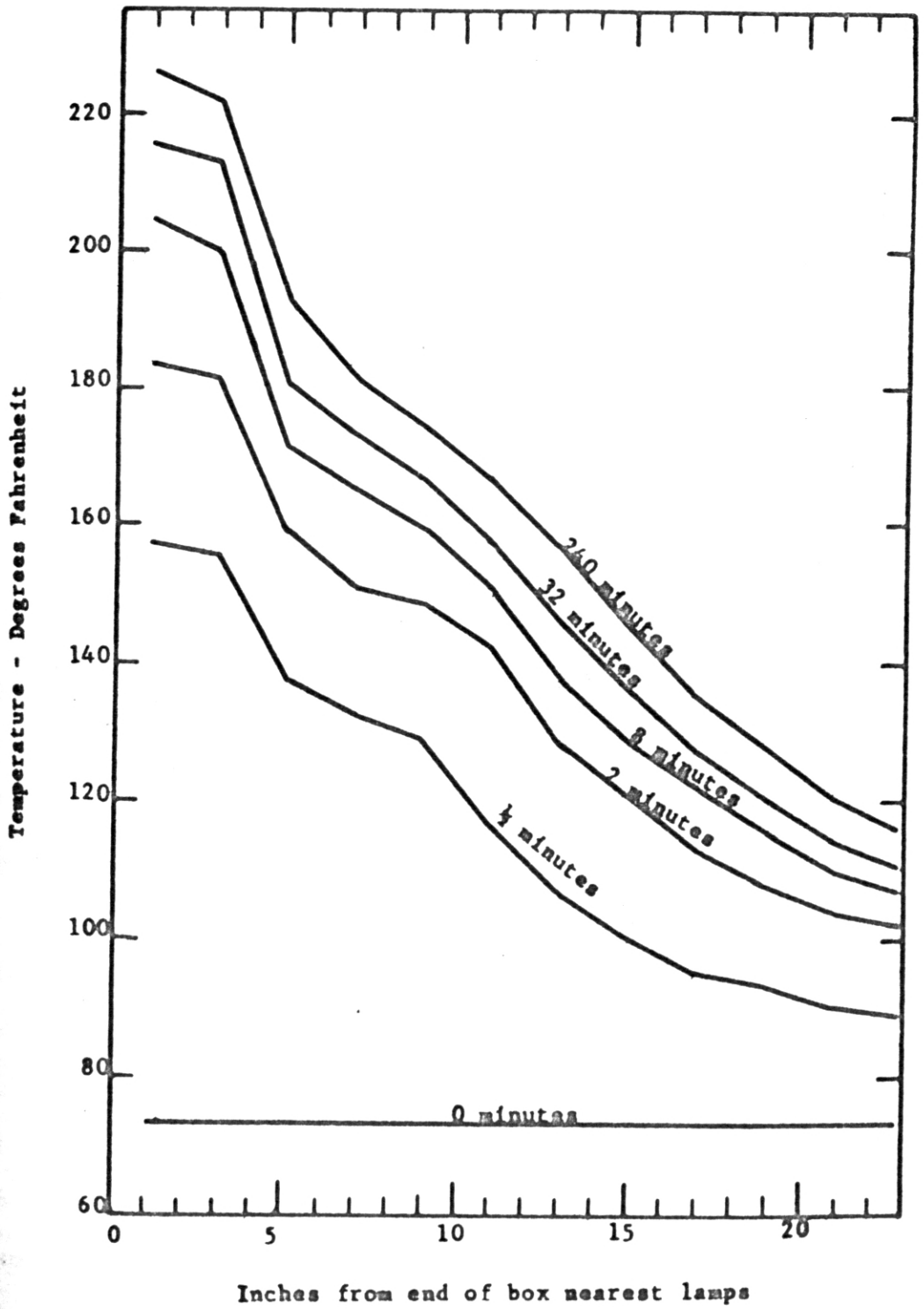


Figure 7. Temperatures attained along the temperature gradient after various durations of exposure on a peat moss surface. Note greatest rise is in first minute. After eight minutes the rise is very slow. This pattern is typical of materials used in the study.

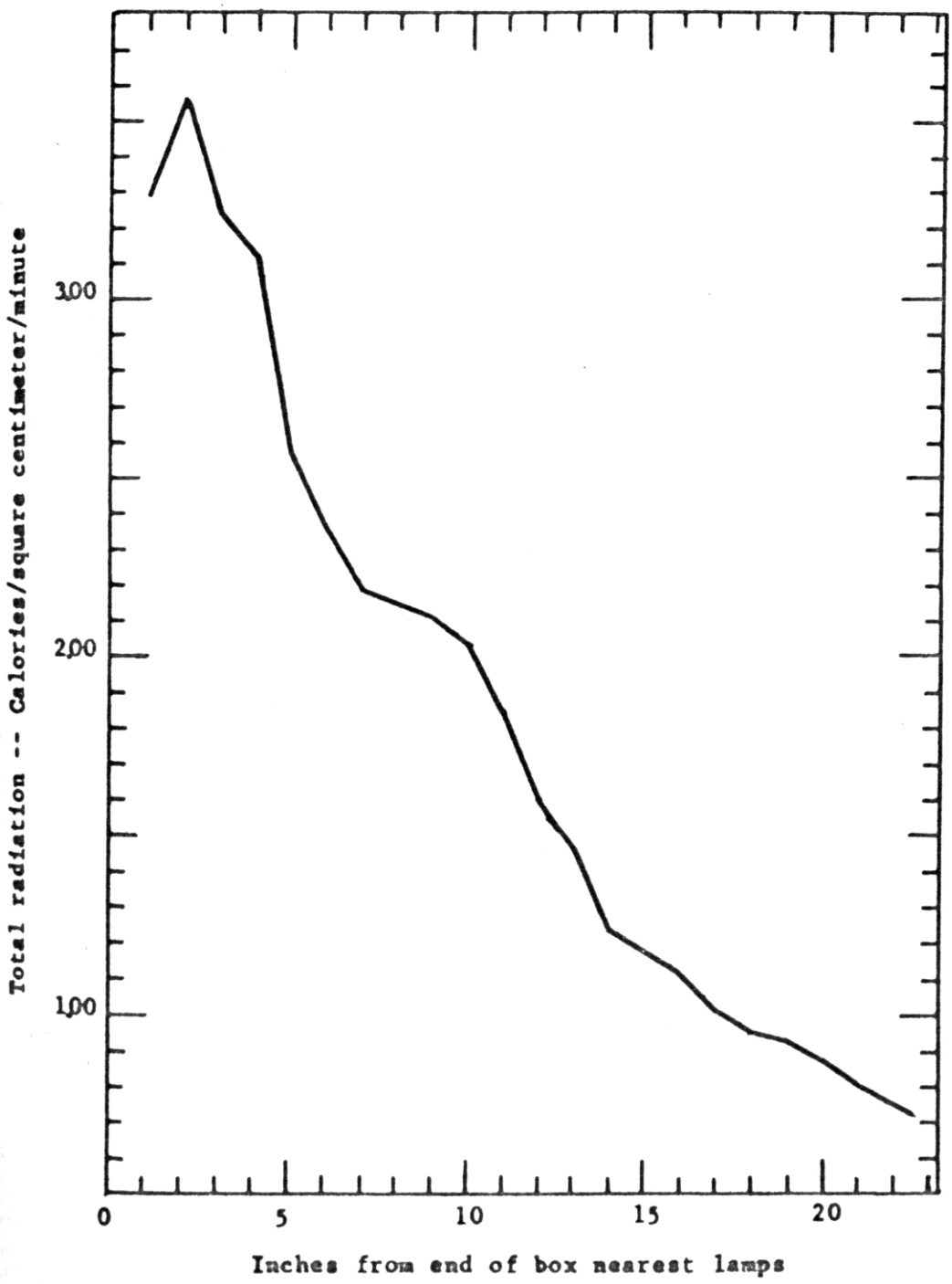

Temperature - Degrees Fahrenheit
220
200
180
160
140
120
100
80
60
0
5
10
15
20
240 minutes
32 minutes
8 minutes
2 minutes
½ minutes
0 minutes
Inches from end of box nearest lamps

Total radiation at points along the temperature gradient was also measured with an Eppley pyrheliometer connected to a Northrup-Leeds student potentiometer. This gave readings directly in millivolts that could be converted to corresponding energy in calories per square centimeter per minute (Figure 8). The gradient has a curved appearance in the middle portion. A similar curvature is indicated from the temperature data (Figure 7) but less definitely. The lower energy at one inch than at two or three inches was not considered of any importance due to its position at the end of the gradient where deaths were almost certain to occur. Neither of these small irregularities has an effect on conclusions.

Seedlings for the study were all from a 200-pound lot of Douglas-fir seed collected by personnel of the Willamette National Forest at 2,500- to 3,500-foot elevation. Most planting on National Forests is presently at this elevation. A one-pound sample of this lot was well mixed and stored at 0°F. in a commercial deep freeze. Such storage has preserved seeds at least a decade without serious loss of germinative energy. Amounts were drawn as needed from this sample. The sample was a mixture of seed from many trees.

All the boxes in which seedlings were grown were of one-half inch redcedar, and carefully cut to an exact 24-inch by 3-inch by 6-inch interior dimension. Each was lined with polyethelene to prevent rapid loss of moisture, but the plastic was slit at the bottom to allow adequate drainage. Boxes were filled to three inches in depth with loam, then filled to the top with river sand. After some

Figure 8. Total radiation in gram calories per square centimeter per minute by inches along the temperature gradient as measured with an Eppley pyrheliometer. Total radiation values of 1.00 to 1.60 calories per square centimeter per minute would cover the range encountered on Douglas-fir clearcuts during sunny weather in the growing season.

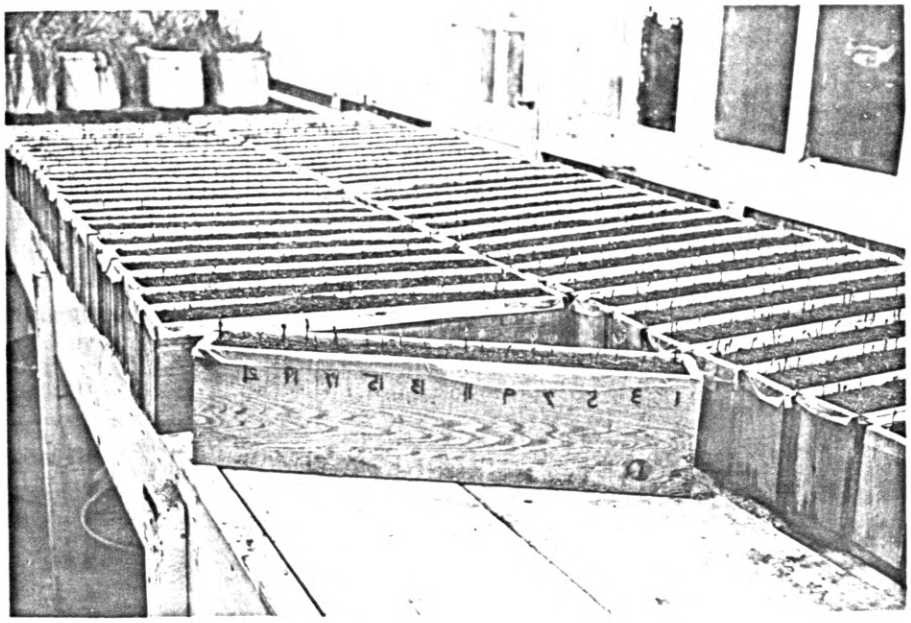

Total radiation -- Calories/square centimeter/minute
3.00
2.00
1.00
0
5
10
15
20
Inches from end of box nearest lamps

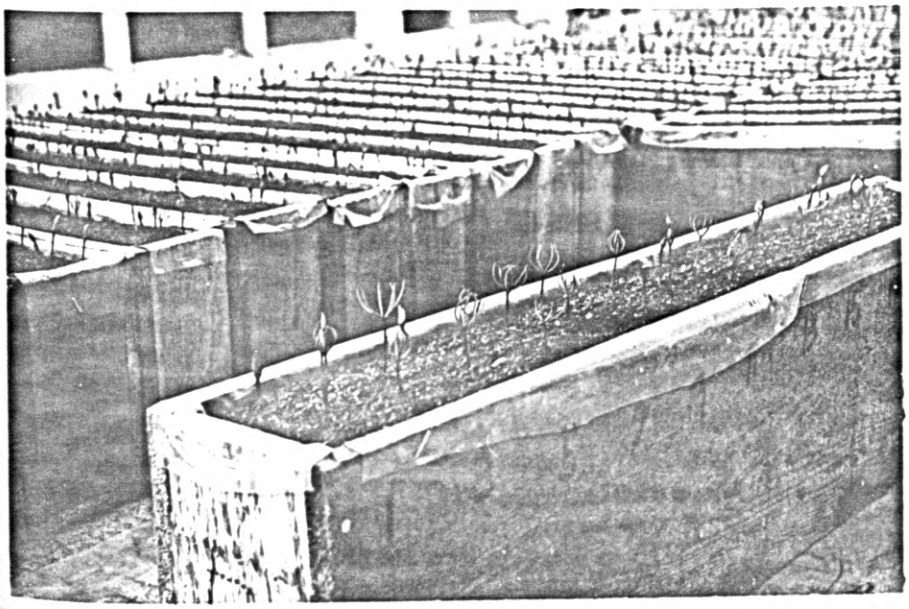
settling the sand level was adjusted in all the boxes to a $5\frac{1}{2}$-inch height as measured from the laboratory table.

Each box had an identical planting arrangement. Templates were placed on the box through which 23 conical holes an inch apart were made about an inch deep in the moist sand for insertion of the hypocotyl of a seedling. A staggered arrangement was used to prevent the cotyledons of one seedling from shading the next during treatment. The first hole was toward the left side of the box, the next in the middle and the next toward the right. This pattern of placement was repeated down the box (Figure 9).

Germination procedures sought to produce seedlings that were of like developmental stage. Naked stratification was practiced according to the method of Allen (1). A feature of the method that produces a high percentage of early germination is the slow loss of moisture over the two to six weeks period during moist storage at 35°F. This seems to precondition the seeds so that over 60 percent of the seeds in this lot would germinate between the 4th and 8th day. Flat pans lined with blotters were used for germinators. Freshly germinated seedlings were individually transferred to the sand filled boxes. This was done with tweezers when the hypocotyls were 1/2 to 3/4 inch in length. Thus every seedling in any box was in the same stage. Boxes were all planted within a four-day period.

Seedlings grew normally and uniformly under greenhouse conditions. No losses were experienced from damping off. Only major loss was by birds that entered through the open greenhouse





ventilators. Treatments were started in early spring so the length of day increased during the treatment period as would be normal in the field. Watering was done on alternate days. With these many precautions, variations between seedlings in any treatment was at a minimum. Size variation of individuals was sometimes considerable after several weeks, but the variation in physiological stage was small. As evidence of this, breaking of the first bud would generally occur within a three-day period for all seedlings within a box.

Several procedures were tried in developing a suitable one for treatment of seedlings under the lamps. It was hoped that the box of seedlings could be exposed until a certain surface temperature was reached, then the seedlings shaded one by one proceeding from the hot to the cool end of the temperature gradient. This proved impossible. Temperatures at the hot end of the gradient attained and passed a certain temperature so rapidly that great errors would certainly result. Finally, it was decided that the entire box of seedlings should be exposed for a certain period of time, and that surface temperatures would be measured at four points along the gradient, interpolating if necessary for temperatures between points.

Boxes were treated in a surface-dry condition. Watering was halted three or more days before treatment. At least a half inch of dry sand was desired on the surface to minimize effects of soil moisture on surface temperature. Ample moisture for growth was usually available in the loam layer of the box even after two weeks without watering. However, to insure that the seedling roots had

ample water during the exposure under the lamps, boxes were placed in an inch of water and observed until new moisture could be seen entering the sandy layer two to three inches below the surface. Even one-week-old seedlings were rooted deep enough to permit such a procedure. After this the boxes were set aside to drain while awaiting treatment.

Seedbed materials tested were confined to three types intended to bracket most of the variation in surface heating properties encountered among natural or artificial materials. Tests of many materials heated under lamps, subsequently to be described in more detail, indicated that the materials reaching a particular level of temperature in a given time varied between a very light white soil conditioner as the hottest and a white quartz sand as the coolest. Yellow mineral soil was intermediate between these, but among the coolest natural materials encountered. The test was planned for these three materials, but a substitution for the soil conditioner had to be made. The surface was so fluffy and indefinite that no consistency could be attained in determinations of surface temperatures measured with thermocouples. Peat moss, also among the hottest materials, proved a satisfactory substitute. Enough of a single lot of each material was set aside for all the experiments. A two-millimeter screen was used to remove coarse material from the peat moss and yellow mineral soil.

Durations of exposure under the lamps of 5, 15, 30, and 60 minutes were used initially. It became apparent after the six-week

treatment that even 60 minutes truncated the information desired on duration of exposure. A three-hour duration was added to the seedlings treated at eight weeks and a four-hour duration to those treated at twelve weeks.

Seedlings were treated at 1, 2, 6, 8, and 12 weeks of age from date of planting. Planting date was generally 4 to 10 days after the seeds were placed in the germinator or 1 to 3 days after the hypocotyl first protruded from the seed coat. Ages of treatment were chosen after personal consultation with Smith (92) as those stages of tissue development within the hypocotyl of most interest in relation to possible resistance to heat injury. Sixty boxes of seedlings were prepared at once to permit groups of nine or twelve boxes to be tested at a specified age.

Final preparation for treatment consisted of smoothing the sand surface, applying about 3/16 inch of the surface material over the river sand, and thumbtacking the thermocouples into position.

Placement of the thermocouples was found to be an exacting procedure. The goal is to assure that the highest temperature existing at the soil-air interface is measured. Vaartaja (97) has clearly described the problem of errors resulting from conduction of heat along the thermocouple wires to the adjacent cooler layers in the soil or air. Even with full realization of the problem it was difficult to prevent recording low temperatures occasionally. The three materials were greatly different in nature. Firm contact of the thermocouple with the surface of white sand would give lower readings

than if the junction were in the film of air just above the surface. This is because the sand conducts the heat downward so well that appreciable heat was conducted from the junction if contact was made with grains below the surface. The same was true to a lesser extent with the yellow mineral soil, but seemed to be no problem with peat moss. Besides this, the junctions would shift in relation to the soil-air interface as the dissimilar metals of the two wires expanded differentially from heat. The extreme difficulties of eliminating such errors were not appreciated as fully through the course of the experiment as when the data were analyzed.

Treatments were given for the allotted time as recorded on the potentiometer chart. Lamps were turned on and off as the temperature of a particular thermocouple was recorded, providing a very exact timing. Lesions occurred at the base of the stems beginning on the heated side just as in the field. These would usually occur seedling by seedling down the gradient as the duration of exposure increased. When exceptions occurred it was usually found associated with shading from the leaves of tall seedlings, especially for treatments after six weeks of age. To avoid this some judicious clipping of leaves was done in later tests. This effectively reduced variability with no adverse effect to seedlings. After treatment the seedlings were watered and returned to the greenhouse.

Analysis and Results

Results were quite different than expected. The gradual

development of resistance to higher surface temperature with age did not occur in this experiment. By far the greatest variations in lethal temperatures arose from differences in seedbed materials. As exposure time increased mortality occurred at lower temperatures in all materials. The experiment effectively separated the individual contribution of the three factors. There was practically no interaction between them.

The range of temperatures that produced kills was remarkable in itself (Table 8). A range of 48°F. occurred between the temperature that was lethal at the shortest duration of treatment in white sand and the longest duration in peat moss. This is almost twice that indicated for field conditions. Seedlings survived in white sand at temperatures up to 176°F. for five minutes without damage, and many survived at 160°F. for short durations in the other materials. Killing temperatures at 3 and 4 hours were in the 128°-140°F. range where most killing in the field study had occurred.

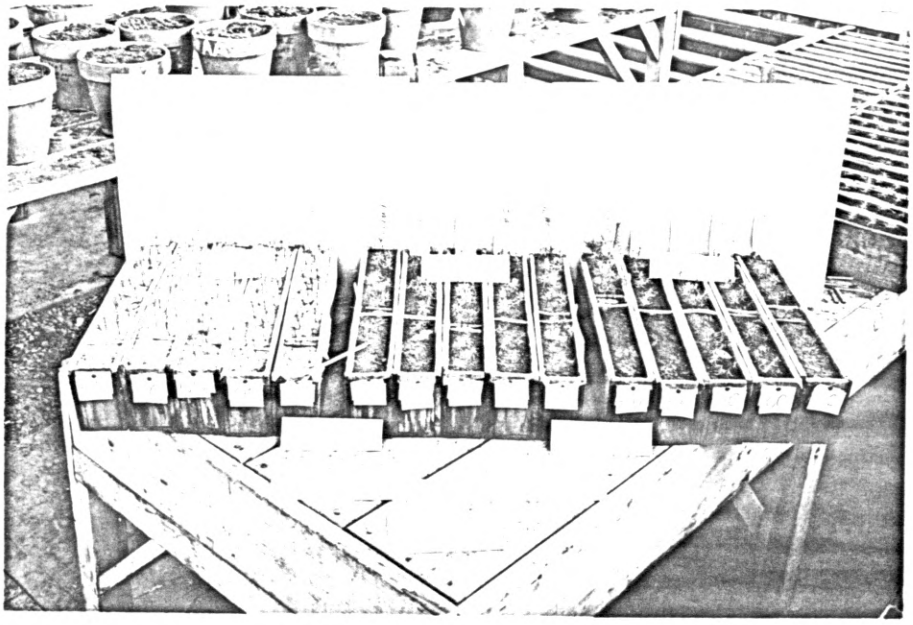
The temperatures followed certain definite patterns. The most obvious appear in the photographs taken eight to eleven months after treatment. Boxes in the study were aligned according to the three factors studied. In Figure 10, boxes containing seedlings of the five ages used which were treated for 60 minutes are grouped according to seedbed material. A white band in each box marks the seedling that died at the lowest temperature. By comparing white marks, the effect of seedbed material on mortality appears as a stairstep

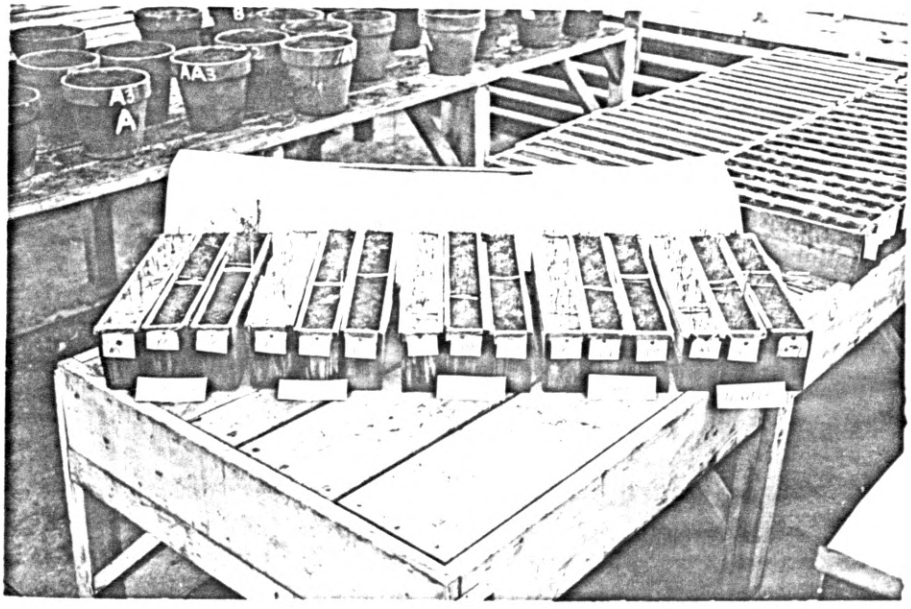
Table 8.—Lowest temperatures (°F.) at which mortality occurred in the temperature gradient study arranged by age at time of treatment, minutes of exposure, and seedbed material

Minutes of exposure	Age in weeks at time of treatment					Average all ages
	1	3	6	8	12	
Peat moss						
5	158		167	152	152	157
15	160		137	140	145	145
30	147		153	148	143	148
60	137	144	138	142	133	138
180				140		140
240					128	128
Yellow mineral soil						
5	164		ND[1/]	ND	162	163
15	165		160	157	150	158
30	161		168	150	142	155
60	138	145	155	154	146	148
180				138		138
240					137	137
White sand						
5	ND		ND	ND	ND	ND
15	158		165	172	176	168
30	172		163	158	153	162
60	158	155	170	160	147	156
180				147		147
240					142	142

1/ ND = No deaths had occurred 12 months after treatment.

Figure 10. Heat mortality of seedlings in boxes exposed for 60 minutes in the temperature gradient study. Limit of mortality, shown by white lines in each box, is about the same at all ages of treatment, but is greatly different between the white sand, yellow mineral soil, and peat moss. In the upper photograph the boxes are arranged by seedbed types. The lower photograph shows the boxes arranged by treatment date.




A3
A
AA3

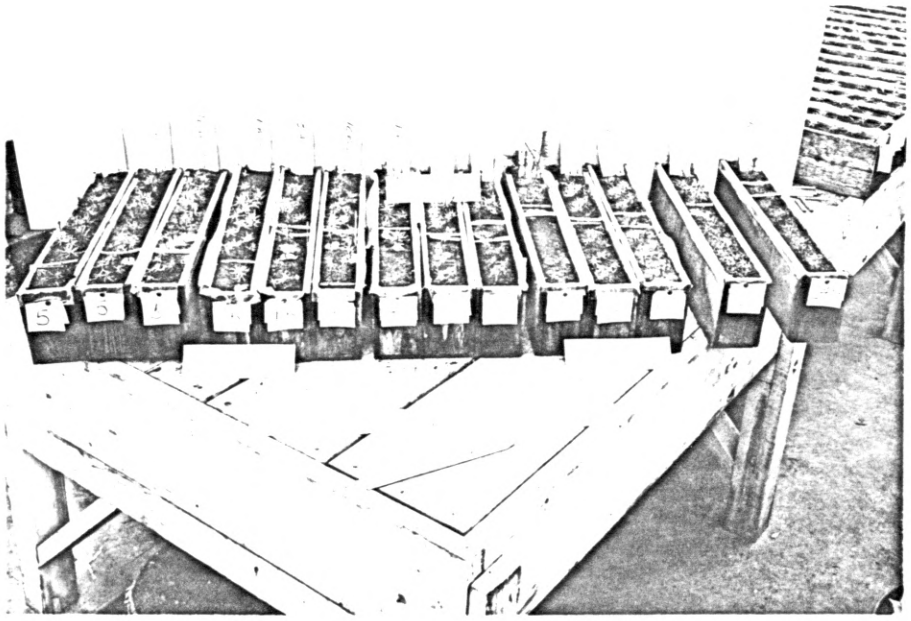
pattern. Seedlings in white sand survived at higher temperatures than in peat moss, hence were not killed as far down the temperature gradient. Seedlings in yellow mineral soil were killed for intermediate distances.

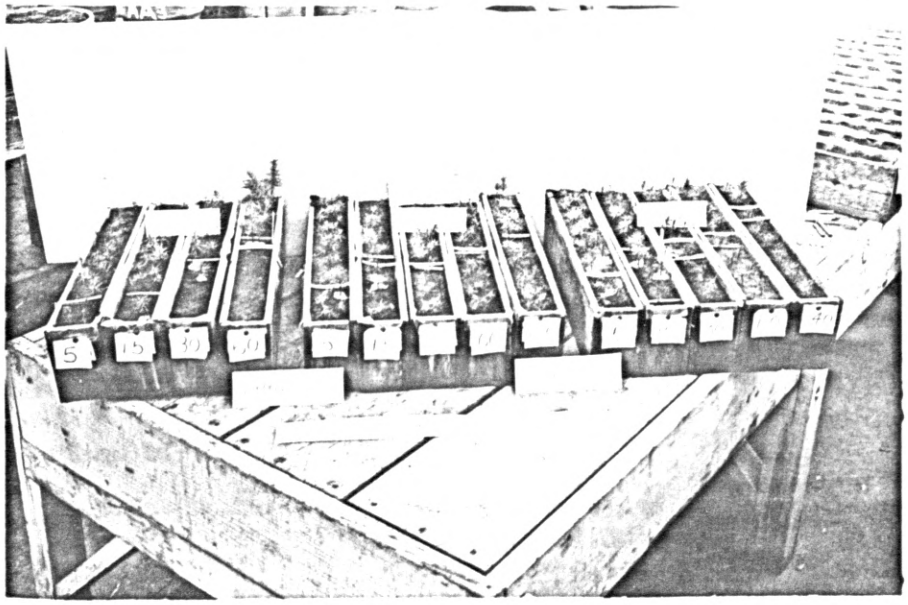
The same photograph (Figure 10) displays the lesser importance of age at time of treatment. The grouping together of boxes containing seedlings treated at ages of 1, 3, 6, 8, and 12 weeks shows about the same extent of killing for corresponding ages in a given seedbed material.

In a similar manner, Figure 11 shows increase in mortality with increasing duration of exposure, in this case by arrangement of the boxes of seedlings treated for various durations at 1, 8, and 12 weeks of age. Mortality occurred farther down the temperature gradient as treatment time was increased. Surface material shown is peat moss, but white sand and yellow mineral surfaces produced the same effect.

An analysis of variance of lowest temperature at which heat mortality occurred in each box (Table 8) provides evidence for the same conclusions. Only the 15-, 30-, and 60-minute duration and 1-, 6-, 8-, and 12-week ages are used in this partial analysis. Five-minute exposures could not be included since this duration caused no deaths in the white sand treatment. The three-week treatment was omitted because only the 60-minute duration was tested at this age.

Figure 11. Heat mortality of seedlings treated 5, 15, 30, 60, 180, and 240 minutes at three ages shows graphically the curved relationship of mortality with duration of exposure. White lines indicate the limit of mortality along the temperature gradient. Surface material is peat moss, but the same relationship was found in white sand and yellow mineral soil. Upper photograph shows boxes arranged by duration of exposure. Lower photograph shows boxes of similar exposure time arranged by treatment date. A second darker line in some boxes represents the limit of visible damage at time of treatment. For young seedlings the two lines generally correspond. For older seedlings mortality often extends beyond the limit of visible injury at treatment time.





The analysis, presented below, will be referred to again as the subject is developed:

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	Level of significance
Total	35	4556.31			
Age	3	346.97	115.66	1.88	NS
Duration	2	516.06	258.03	4.21	5%
Seedbed	2	2189.06	1094.53	17.84	1%
AXD	6	510.61	85.10	1.38	NS
AXS	6	168.95	28.16	.46	NS
DXS	4	88.44	22.11	.35	NS
Error(AXDXS)	12	736.22	61.35		

The small contribution of seedling age is indicated by the very low mean square of deviations from average mortality. Seedling age effects contributed only one-ninth the mean square of seedbed effects. Seedbed effects are highly significant, ages nonsignificant. Durations, even over so small a range, show a significant effect. The low mean squares for the interactions provide an uncomplicated comparison of the relative contribution of main effects. A comparison of the components of variance indicates that practically the only effects are from seedbeds and durations; age and interactions contribute little more variation than would be expected from experimental error.

Killing temperatures varied more than expected, considering the control over sources of variation in the study. For instance, there were many reversals in the expected descending order of temperatures with treatment time when comparisons were made within the same treatment age and seedbed material. This could be caused by variation in resistance of the individual seedling. However, a more obvious factor was evaluated first.

Seedlings at each treatment age were seen to be killed for similar distances down the temperature gradient in corresponding treatments, even if recorded temperatures varied considerably. Distance, in this case, is tied to levels of radiant energy (Figure 8).

Less variation was found when mortality was expressed in terms of calories per square centimeter per minute (Table 9). The lowest total radiant energy at which mortality occurred followed the same patterns as before. This time, however, there was only one reversal in descending order of total energy with increasing time of exposure. Data were more consistent between similar treatments. A complete analysis of variance covering this data is given below for comparison with the analysis of temperature data:

Table 9.—Lowest total radiant energy (calories per centimeter per minute) at which mortality occurred in the temperature gradient study arranged by age at time of treatment, minutes of exposure, and seedbed material

Minutes of exposure	Age in weeks at time of treatment					Average all ages
	1	3	6	8	12	
			Peat moss			
5	2.64		2.38	2.38	2.38	2.44
15	2.38		2.15	2.25	2.08	2.22
30	2.15		1.89	2.15	1.89	2.02
60	1.38	1.61	1.61	1.61	1.38	1.52
180				1.23		1.23
240					.95	.95
			Yellow mineral soil			
5	3.60		3.60+ 1/	3.60+	3.52	3.58
15	3.52		3.13	3.13	2.65	3.11
30	2.65		2.65	2.36	2.25	2.43
60	1.89	2.08	2.25	2.15	1.89	2.05
180				1.23		1.23
240					1.23	1.23
			White sand			
5	3.60+		3.60+	3.60+	3.60+	3.60+
15	3.60		3.60	3.60	3.60	3.60
30	3.60		3.13	3.13	3.13	3.25
60	2.15	2.15	3.52	3.13	2.36	2.66
180				2.15		2.15
240					1.89	1.89

1/ + = Beyond 3.60. No deaths occurred at maximum radiant energy provided in the test.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	Level of significance
Total	47	24.471			
Age	3	.046	.015	.27	NS
Duration	3	8.332	2.777	48.98	1%
Seedbed	2	12.984	4.328	76.32	1%
AXD	9	.980	.109	1.92	NS
AXS	6	.194	.032	.57	NS
DXS	6	.914	.152	2.69	5%
Error(AXDXS)	18	1.021	.057		

In this analysis the error term was extremely small, mean square of age was relatively less, and those of duration and seedbed effects were much greater than in the analysis of temperature data (page 84). This analysis confirms the observation that temperature measurements provided a less exact index of the thermal death point in these materials than measurements of total radiation. In view of the chance of an inexact thermocouple placement and of undetectable conduction errors, it is likely that a part of the greater variability lay in temperature measurement difficulties. There is little reason to believe that measurement of total radiation here is any more than an indirect, though more consistent, measure of surface temperature.

An advantage of plotting the data as total radiation rather than temperature is the comparisons possible in terms of solar radiation values. The radiation reaching the earth's atmosphere is very nearly

2.0 calories per square centimeter per minute. Energy that reaches the earth's surface is considerably less--only about 1.5 calories on horizontal surfaces on the hottest summer days. Surfaces normal to the sun's rays may receive 1.6 calories as a maximum. Pyrheliometer readings at the Horticultural Farm at Oregon State College[1] occasionally show sharp momentary peaks higher than these, but usually such peaks are associated with clouds. Calculated and empirical values are given by Geiger (32), Bryam and Jemison (17), and Turner (96) for a range of latitudes and aspects. For practical purposes, summertime maximum conditions on south slopes at this latitude would be encompassed within a range of 1.2 to 1.5 calories per square centimeter per minute.

At peak values (Figure 12A) durations of about 50 minutes were required to kill in peat moss. The corresponding killing temperature is estimated to be about 141°F. (Figure 12B). In yellow mineral soil the corresponding duration and average temperature would be about 140 minutes and 142°F. In white sand no killing occurred in four hours even at peak summertime radiation energies. Extrapolated values for white sand would be about 5 hours and 144°F.

At the other extreme the computed energy values for 40 percent north slopes on June 21 would be about 1.0 calories per square centimeter per minute (32, 96). Of the three seedbed materials, killing

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1/ These figures were furnished from records made by Oliver Compton, Horticultural Department, Oregon State College.

Figure 12A. Radiant energy values required to kill Douglas-fir seedlings at various durations of exposure on three seedbeds used in the temperature gradient test. Total radiation corresponding to maximum summertime values is shown for comparison purposes. Plotted values are averages from all ages at time of treatment.

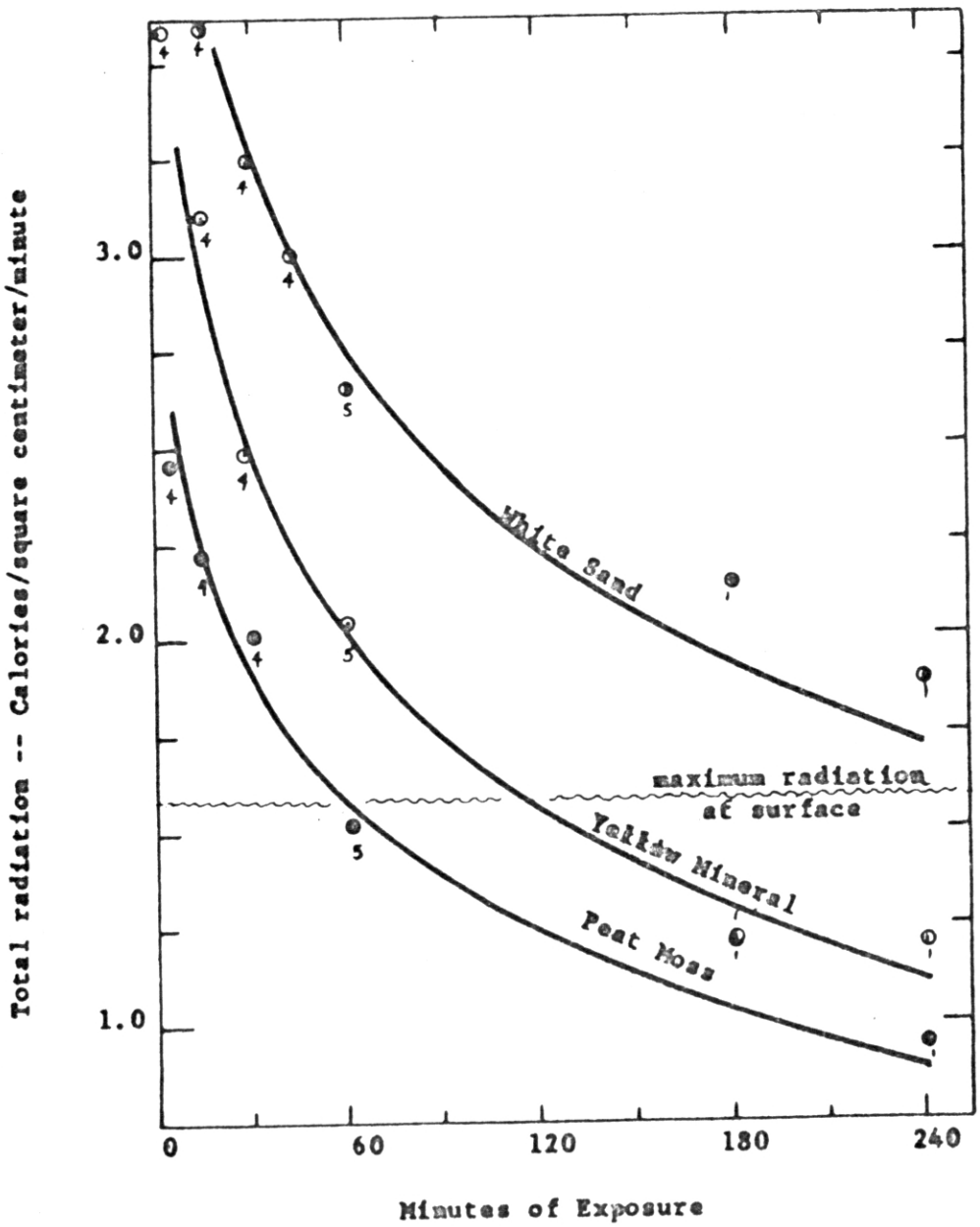
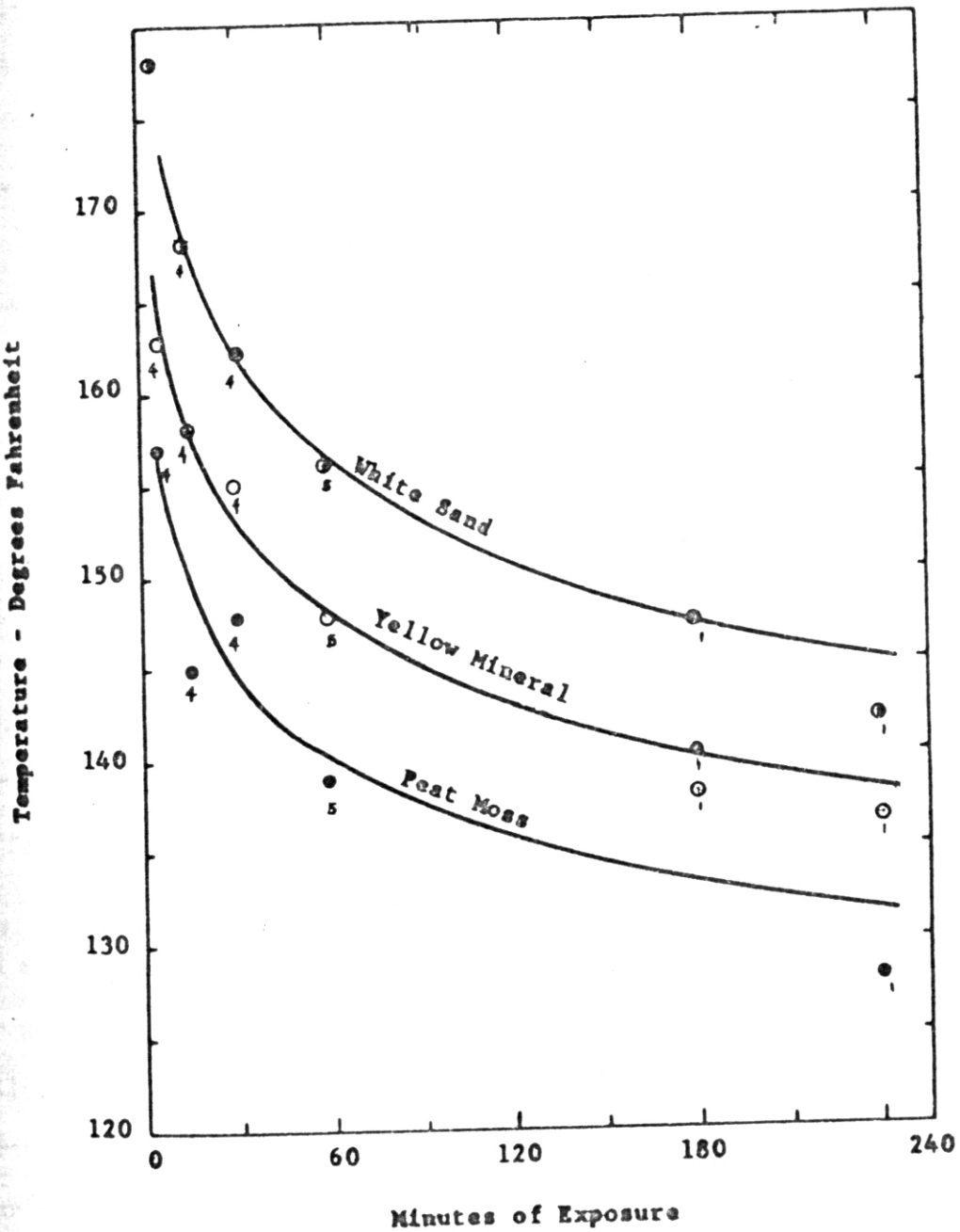

Total radiation -- Calories/square centimeter/minute
3.0
2.0
1.0
0
60
120
180
240
Minutes of Exposure
White Sand
Yellow Mineral
Peat Moss
maximum radiation
at surface

Figure 12B. Same as Figure 12A except that durations required to kill are shown in terms of temperature.


Temperature - Degrees Fahrenheit
170
160
150
140
130
120
0
60
120
180
240
Minutes of Exposure
White Sand
Yellow Mineral
Peat Moss

would occur only on peat moss at these energy values with about four hours exposure at temperatures of about 130°F. Both yellow mineral soil and white sand would not be expected to attain high enough surface temperatures with this radiant energy to kill in less than 7 to 12 hours.

The curves in Figure 12 are fitted by method of least squares after transforming minutes to logarithmic values. Correlation coefficients of the six regressions are all highly significant, ranging from .73 to .75 for the temperature data and from .85 to .96 for the radiant energy data. This confirms the greater variability of temperature measurements as well as the individuality of the curves themselves.

With this perspective on expected behavior under normal radiation levels, it is well to consider the more general meaning of the curves. A fixed temperature, for instance 150°F., required vastly different times to kill as seedbed materials were varied. About 15 minutes was required in peat moss, 50 minutes in yellow mineral soil, and about 140 minutes in white sand. At a fixed time of 60 minutes for instance, killing occurred at 138°F. in peat moss, 148°F. in yellow mineral soil and 156°F. in white sand. But the radiant energy required is vastly different. To reach these temperatures in one hour in peat moss required about 1.60 calories; in yellow mineral soil about 2.05 calories; and in white sand about 2.75 calories per square centimeter per minute. Thus a rapidly heating or "hot" material like peat moss is a double-edged sword. It kills at a lower temperature

than yellow mineral soil; it also requires less energy to reach this temperature.

The surface temperatures attained in the temperature gradient appear lower than would be expected under corresponding radiant energy levels in the field. The 12-inch mark along the temperature gradient received a total radiation of 1.6 calories per square centimeter per minute or near the maximum energy reached at this latitude. Temperatures after four hours exposure reached 151°F. in peat moss, 144°F. in yellow mineral soil and 137°F. in white sand. South slope readings on duff in the field have been reported as high as 181°F. (38), and surpass 150°F. many times each summer.

Three factors may have contributed to lower surface temperatures in the temperature gradient than expected. The first may lie in spectral differences. The spectrum of tungsten lamps peaks in the infra-red region at 10,100 Å., whereas the solar spectrum peaks in the visible region at about 5,000 Å. (101). Reflection of the ultra-violet portion by the materials tested is lower than reflection of the visible portion of the spectrum (32). Hence, these materials may be converting into heat more total energy from solar radiation than lamp radiation at corresponding energy levels. The literature on this subject is quite general and allows no direct computations to check the contribution of this factor. Measurements of differences in surface temperature under infra-red lamps operating at 2,500°K. and tungsten lamps operating at 2,960°K. revealed differences at corresponding total radiations of about 1°F. in peat moss, a

difference in the right direction but not statistically greater than measurement error. Ultra-violet radiation from the sun may cause materials to heat to slightly higher levels at corresponding total radiant energy than under lamps producing little ultra-violet light.

The second possible factor that may account for lower than expected temperatures in the temperature gradient is incidence angle. All pyrheliometer readings were taken along a horizontal surface. The sensitive thermopile is a black body hence there is practically no energy loss by reflection. However, the seedbeds may be reflecting a substantial portion of the total radiation. The solar altitude in summer is above 60° for several hours each day at this latitude, whereas the lamps were directed at about 45° angle to the surfaces of the boxes. Albedo increases as the angle of incidence decreases (32). The loss from reflection in the temperature gradient may have been enough to account for some of the difference.

This possible factor was investigated by shining a reflector spot, tungsten lamp on a yellow mineral surface at both a 20° and a 65° angle. Lamp distance was carefully adjusted so that pyrheliometer readings at the yellow mineral surface were the same at both angles. The yellow mineral surface was exposed for 15 minutes at low angle. Then with no change of surface or thermocouple placement, and after a proper period for cooling, the test was repeated at the

high incidence angle. Results at two energy levels are tabulated below:

Total radiation (cal./sq. cent./min.)	1.25	1.65
Temperature at 20° incidence angle (°F.)	109.3	117
Temperature at 65° incidence angle (°F.)	110.7	116

Higher temperature readings were expected at the high angle of incidence. Actual temperatures were no different between high and low angles than might be expected from measurement error. The possibility that the lower than expected temperatures arose from this source seems weak. The third factor involves the choice of screened peat moss as the example of an organic seedbed. As will be shown later, the screened peat moss actually attained a lower temperature than duff when checked under known total radiation.

The only practical consequence of any difference in field and laboratory surface temperatures under equal total radiation is a reduction in predicted durations needed to kill seedlings.

Evidence of differential resistance to heat by individual seedlings was weak. There were occasional seedlings that survived at least a year with definite lesions or discolorations on the stem that developed at the time of treatment. Usually, these were within an inch or two of the point on the temperature gradient where mortality had occurred at lowest temperature. In other words, there was a "twilight zone" in which damaged seedlings might occasionally recover if constantly supplied with moisture. In 28 of the 57 boxes treated

in this experiment all damaged seedlings died. In the others, seedlings survived in the zone of damage at temperatures estimated to be 3° to 15°F. higher than the minimum temperature required to kill in the same box. Whether this is evidence of resistance to heat damage, or simply reflects variations in seedbed conditions needs consideration.

A careful evaluation of these apparently resistant individuals revealed associations with extraneous factors. Some were obviously in the partial shade of other seedlings. Such shade is not so apparent when six lamps are used, but judicious clipping of leaves in the 8- and 12-week-old seedlings did markedly reduce the twilight zone over that of the 1-week and 6-week-old treated seedlings. Most of the resistant seedlings were found to be one of a pair. In many boxes two seedlings were planted in the same hole as an insurance against mortality. The intention was to clip one seedling before treatment if two survived, but they were both left in the hope of obtaining more definite information. One of the pair sometimes shaded the other.

Another extraneous factor was soil moisture. The seedlings treated at six weeks were not as well dried prior to treatment as the others. Boxes were inadverdently watered on the day scheduled for treatment. Although treatment was delayed four to six days because of this, the period was rainy and drying was slow in the greenhouse. It is noteworthy that this group of boxes had the greatest variability, showing more resistance to heat injury than earlier and later

treatments. There may have been slight variations in soil moisture from seedling to seedling within a box, or from box to box, at other treatment ages.

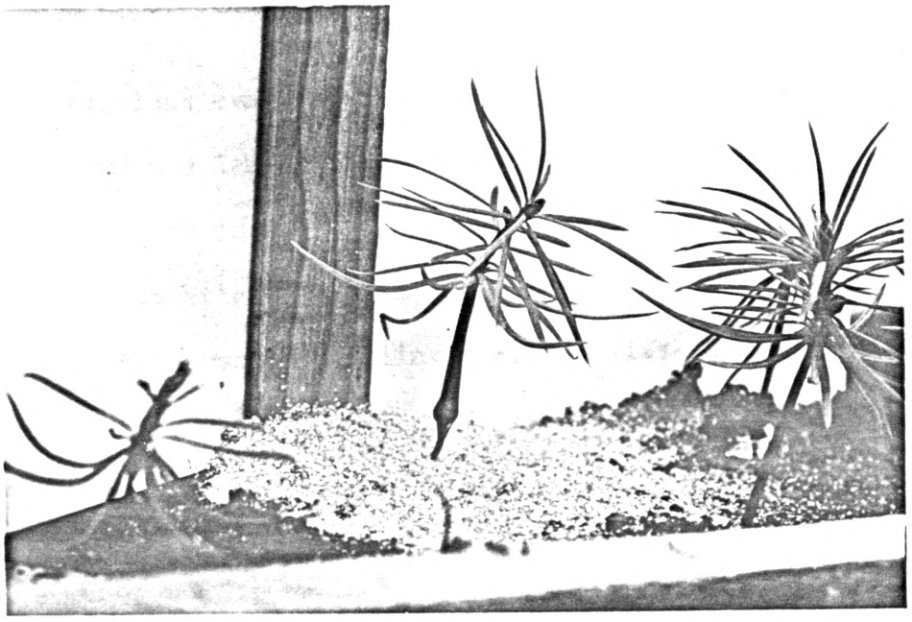
Finally, the greatest number of resistant seedlings were found associated with short durations of exposure.

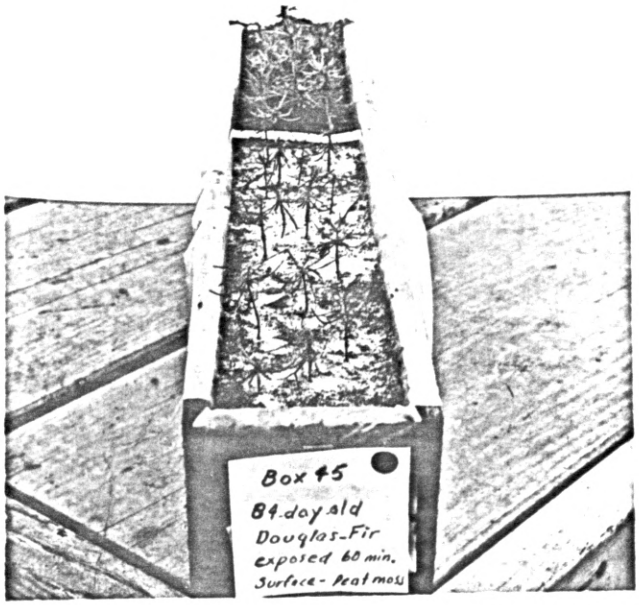
All these associations indicate that the resistant seedlings could have been favored slightly by shade or soil moisture over their neighbors. The fact that seedlings occasionally recovered from definite lesions leaves no doubt about this form of resistance. However, the instances were rare in which seedlings survived higher temperatures than their neighbors without forming a lesion.

Seedlings killed at one week of age became prostrate and disappeared without a trace in eleven months. Those killed at three weeks had sufficient cells with hardened walls (92) so they remained in upright position. At six weeks the dead seedlings remained standing, and lesions were still apparent even nine months later. Lesions became less apparent on seedlings killed at eight weeks. Seedlings treated after six weeks of age reddened in a manner resembling drought-killed seedlings in the field in late summer. Seedlings that developed lesions and lived after treatment, especially at 8 and 12 weeks of age, formed large swellings above the girdle (Figure 13). The size of the swelling depended on the length of time they lived after treatment (Figure 14). Some lived for a full year under greenhouse conditions.

Figure 13. A Douglas-fir seedling with extreme swelling of the stem above the point of heat injury. Such swellings, occurring mainly among seedlings treated at eight and twelve weeks of age, indicate that downward transport of solutes in the stem was partially or completely blocked by the injury. A few seedlings lived up to a year after treatment, but most of them showing swellings died during this period.

Figure 14. Seedlings with swellings as in Figure 13. The size of the swelling depends on length of time they lived after treatment. Those in the forward part of the box were treated with highest temperatures and have small swellings because they died soon after treatment. Those near the white band lived several months and produced large swellings.




Box #5
84 day old
Douglas-Fir
exposed 60 min.
Surface - Peat moss

Discussion of the Temperature Gradient Study

A cautious evaluation of results is needed. The small effect of heat and the large effect of seedbed materials are contrary to widely accepted ideas regarding heat injury.

Many investigators have associated increased resistance to heat injury with increased seedling age. Douglas-fir must become resistant at some time during its life, but whether this takes place during the first three months is the question here. The data would indicate not.

Could some confounding factor have erased the effect of age? With seed source, developmental stage, total energy, seedbed material, duration of exposure, room temperature, and watering schedule all under tight control there seems to be few factors left uncontrolled. However, the treatments were made at different points in time and such factors as loss of efficiency of the lamps, day length differences, and soil moisture could conceivably be considered. If anything, loss of efficiency of the lamps would magnify effects of seedling age. For these seedlings, the pattern of day length was about the same that seedlings experience in the field. The possibility that early treatments had sufficiently higher soil moisture than late treatments is not likely, but cannot be eliminated as a possible confounding factor. However, age effects must be small if differences in moisture of surface-dry soil can erase them.

Only an experiment that eliminates soil moisture as a factor could settle the question. Such an experiment is described later.

The relatively large effect of seedbed material bears scrutiny. The fact that seedlings are killed in organic materials like peat moss and survive in mineral soils is widely reported. That they die at much lower temperatures in organic material than in yellow mineral soil is a complete surprise. The pattern of the data is completely consistent with this idea. No confounding factors seem likely. Seedbed effects appear to be real ones.

There can be no doubt that killing temperatures are lower with longer durations of exposure. The data of Baker (4), Lorenz (66), Nelson (78), and Owen(79) on coniferous tissues all establish or suggest such relationships. It has not been previously shown so clearly with dry seedbed materials.

The probability that all three factors have been accurately evaluated leads to some interesting questions.

Of practical interest is the question of how much mortality attributed to drought actually results from heat injury. Three-month-old seedlings are killed at surprisingly low temperatures, and may leave little evidence of a lesion.

The logarithmic nature of the time-temperature curves suggest that the range of lethal temperatures may be wider in the field than the 48°F. variation shown in these data. All curves have appreciable slope after four hours exposure. In the field, temperatures may be

above 125°F. six hours or longer.

The time-temperature curves are statistically distinct for each of the three materials. Does this imply a distinct time and temperature at which killing occurs in every seedbed material? Of theoretical interest is the question of why a light material like peat moss having low specific heat should kill at a substantially lower surface temperature than a dense material of high specific heat like white sand.

For a starting point on these questions the effect of heat independent of seedbed material had to be known. This subject was pursued next.

The Effect of Heat Alone

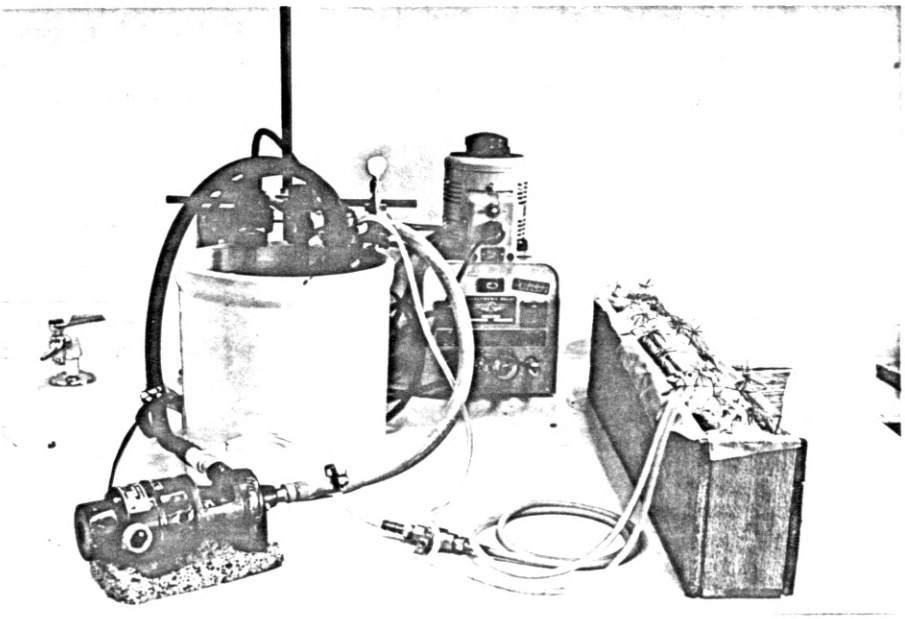
In considering the problem of treating Douglas-fir seedlings with known temperatures independent of surrounding seedbed materials, a process of elimination discarded all the techniques previously used. To be comparable with field conditions, only a narrow section of the seedling stem should be treated. This eliminated the possibilities of using ovens or water baths as such. Dry conditions should also be maintained during treatment. Apparatus employing electrical resistance or heated dry materials for surrounding the seedling stem raised insoluble questions of measuring the exact temperature at the seedling stem. A new apparatus was developed especially for the experiment. It permitted the effect of temperature variation alone on a small dry portion of the seedling stem to be assessed for seedlings of various ages.

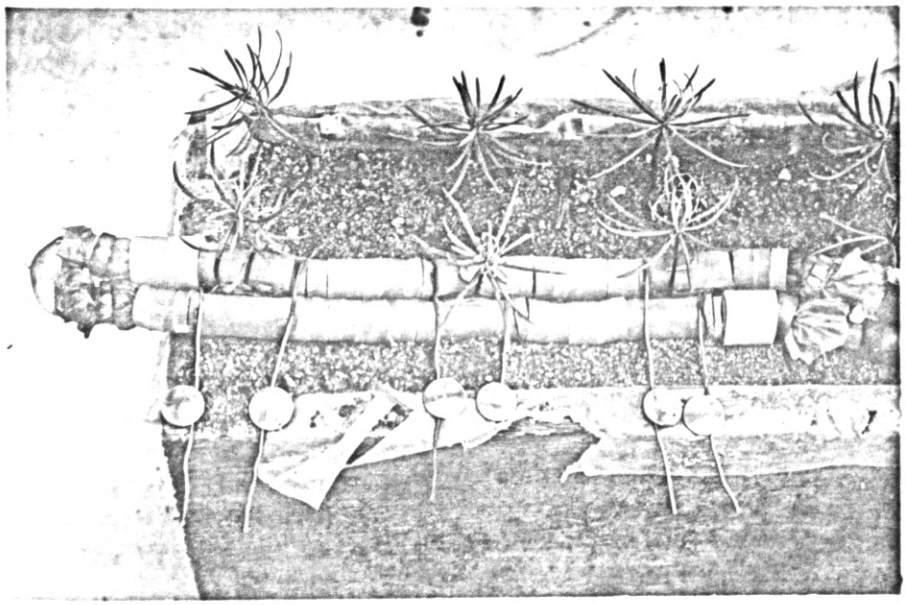
Materials and Methods

Treatment apparatus consisted of a two-gallon water bath maintained at temperatures within .1°C. by a thermoswitch and electronic relay actuating two immersion heating elements (Figure 15). A centrifugal water pump and motor circulated the water continuously. A take-off from the circulation system permitted a smaller stream of water to circulate through an apparatus that came to be known as a "dry water bath" (Figure 16). This consisted of a seven-inch-long U-shaped tubular device. Stems of three seedlings grown at two-inch

Figure 15. Water bath apparatus. Water temperature in container is maintained within .1°C. and circulated by the pump to the "dry water bath" device in the box of seedlings.

Figure 16. Dry water bath device. Water from container circulates through thin inner rubber tubing. Outer polyethelene tubing is in sections to promote flexibility. Largest sections on either side of seedlings have 3/4-inch by 1/16-inch slots through which the thin inner tubing protrudes as blisters. These surround a small spot on the seedling stem with a known temperature under dry conditions.





intervals in a box would fit between the arms of the U. Water of the desired temperature circulated past the seedlings on one side of their stems then returned along the other side. The device consisted of an inner and outer tubing. The outer tubing was 3/8-inch polyethelene, the inner was rubber of .0045-inch wall thickness. At two-inch intervals the polyethelene tube was provided with longitudinal slots about 3/4-inch long and 1/16-inch wide. The slots allowed the thin-walled inner rubber tubing to protrude as a small blister under the light pressure of the pump. Slots were on the inner face of the U in position to allow the blisters to touch the seedling from either side and mold around the stem as the arms of the U were brought together. This brought water of known temperature to a small portion of the seedling stem near ground level (Figure 16).

Temperatures of the water bath were measured with a mercury thermometer. Of more importance, thermometers were placed in 3/4-inch clear plastic tubing made part of the circulation system at points near the entrance and exit of the dry water bath device. Thus the thermometers were entirely in the circulation system at all times. A 10-power hand lens was used to read temperatures of the thermometers inside the tubing to nearest .2°F.

The dry water bath apparatus took considerable effort to perfect. The polyethelene outer tube had to be sectioned every quarter inch except at the slotted portions to permit flexibility in adjusting to the position of the seedling. Special valving was

needed to adjust the flow of water to proper velocities, as the inner tubing would stand little pressure before the blisters would enlarge beyond a useful size. A bleeder hose was needed to continuously remove air bubbles from the tubing that ran to the dry water bath apparatus. Constrictions of the inner tubing were troublesome until sections of larger polyethelene tubing were fitted at the points the constrictions usually occurred (Figure 16).

Seedlings for the study were grown in similar boxes but spaced at two-inch intervals. Before treatment, the dry water bath apparatus was placed in position near, but not touching, three seedlings. Six light copper wires were attached at one end to the six slotted portions of the apparatus and then thumbtacked lightly at the other end to the cedar wall of the box. Water was circulated through the apparatus until the temperatures of the thermometer at the exit of the apparatus was within 2°F. of the water bath temperature. Drop in temperature along the rubber tubing leading to the dry water bath apparatus was between 1° and 2°F. This prewarming period was only about 30 seconds, and was ignored for treatments over 30 minutes in duration. After prewarming, the blisters were brought into good contact with the seedling stem and the thumbtacks were pressed firmly on the wires. This required about 15 seconds. The apparatus thus held in position against the seedlings functioned without further attention until the water was shut off at end of the treatment period. Timing was by a stop watch. Seedlings were treated at 7 to 20, 38 to 42, 58 to 63 and 90 to 95 days after planting.

Results

Empirical time-temperature curves of mortality were so sharply defined, especially at temperatures above 125°F., that they did not differ to any extent from curves fitted by the method of least squares (Figure 17). Regression analysis based on temperatures and logarithms of shortest time at which at least two of the three treated seedlings were killed[1/] gave correlation coefficients of .975 and .984 for the 7- to 20-day-old and 90- to 95-day-old seedlings respectively. Such high correlation coefficients indicate less than five percent unexplained variation. Data plotted as straight lines after transformation of time to a logarithmic scale (Figure 18).

No evidence was found of development of resistance to heat injury of seedlings between one and 12 weeks of age as none of the regressions differed significantly between treatment dates. The time and temperature values were much lower than for any of the materials used in the temperature gradient test. Thus, the small effect of seedling age was verified in an independent experiment.

The experiment provided additional data on the twilight zone seen in the temperature gradient experiment. This is the interval of exposure time between the first detection of damage and the time certain death occurs to the seedling when exposed at a certain temperature. The interval was particularly easy to plot using the

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1/ For such statistical purposes many workers have preferred the point at which 50 percent of the experimental material has died (see Roeser (83)).

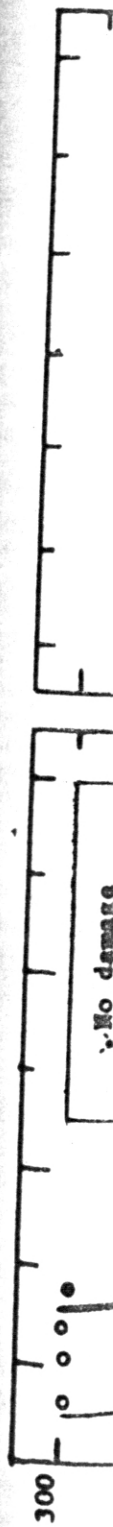
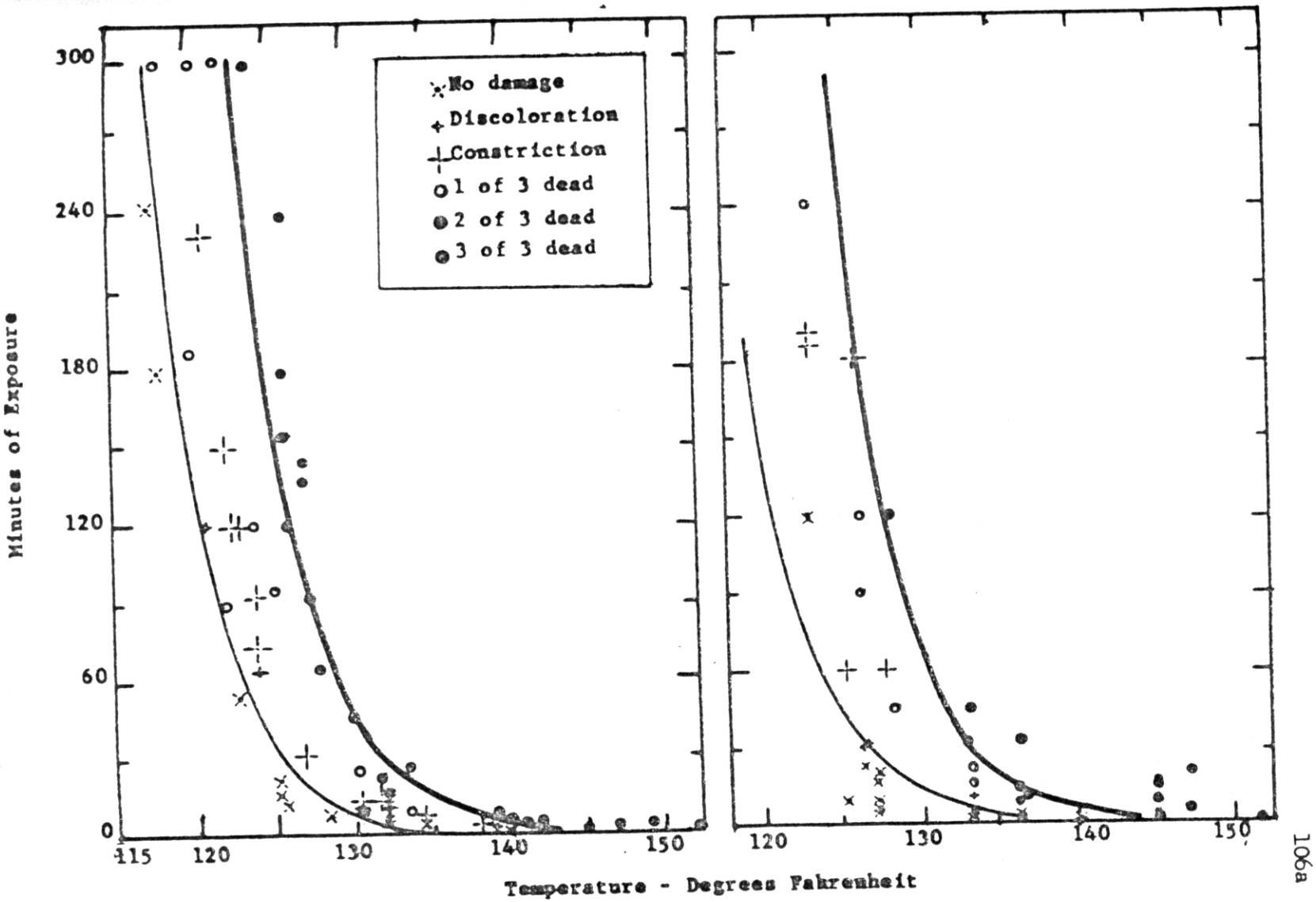
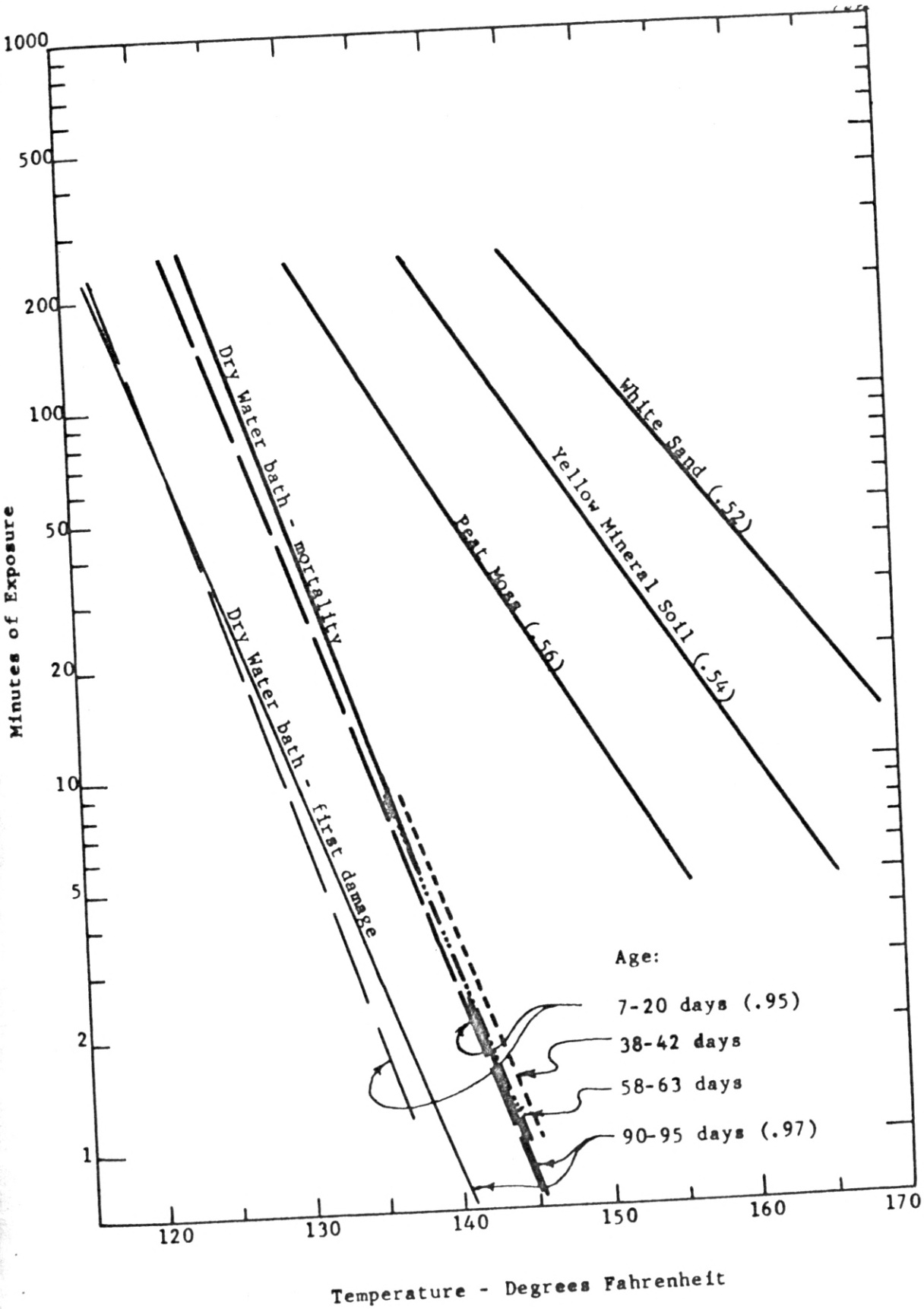


Figure 17. Minutes of exposure and temperatures causing first detectable injury or death to seedlings treated in the dry water bath apparatus. Left graph gives results from seedlings treated at 7 to 20 days. Graph on right represents seedlings treated at 90 to 95 days. Each point represents extent of damage or death from treating three seedlings. Heavy line in each graph is mathematically fitted curve indicating mortality to two or more seedlings. Light line shows time and temperature where first detectable damage occurs. No differences due to seedling age greater than chance variation are indicated.


No damage
Discoloration
Constriction
1 of 3 dead
2 of 3 dead
3 of 3 dead
Minutes of Exposure
300
240
180
120
60
0
115
120
130
140
150
120
130
140
150
Temperature - Degrees Fahrenheit

106a

Figure 18. Mathematically fitted time-temperature curves of seedling mortality plotted as straight lines on a logarithmic time scale. Lines on left are from data of the dry water bath test. Lines at right represent data covering the three seedbed materials used in the temperature gradient study. Numbers following each line label give the squared correlation coefficient, a measure of the percent of total variation explained by the regression. This is included for purposes of comparison.


1000
500
200
100
50
20
10
5
2
1
Minutes of Exposure
Dry Water bath - mortality
Dry Water bath - first damage
Peat Moss (.56)
Yellow Mineral Soil (.54)
White Sand (.52)
Age:
7-20 days (.95)
38-42 days
58-63 days
90-95 days (.97)
120
130
140
150
160
170
Temperature - Degrees Fahrenheit

7- to 20-day-old seedlings, but essentially the same curve for 90- to 95-day-old seedlings was also computed (Figure 18). Stem discolorations or lesions would show up, for instance, after eight minutes at 132°F. Seedlings treated at this temperature for longer than 23 minutes were all dead within three months. Thus, during a 15-minute interval of time at this temperature lesions may form but the seedlings might recover under greenhouse conditions. For one-week-old seedlings the time of first damage and time when at least two out of three seedlings died are given below:

Temperature	First indication of damage	Two of three seedlings died
°F.	Minutes	Minutes
140	1	4
135	4	14
130	12	60
125	40	170
120	140	610 1/

A more convenient concept of the twilight zone is in terms of temperature required to damage and to kill. The variation is only about 6°F. for any specified time. As an example, seedlings treated for 60 minutes at 123° would probably show a discoloration or lesion. Treatment of 60 minutes at 129° would probably result in death. The same interval of about six degrees would apply for shorter or longer durations of treatment up to at least five hours

1/ By extrapolation.

(see Figure 18).

Discussion of Dry Water Bath Test

Data from the dry water bath apparatus were so definite as to leave little question on the points that were covered. Seedlings up to three months of age once more showed little resistance to heat injury.

The experiment clearly shows a twilight zone. The range over which recovery from lesions may occur at specified time is about 6°F. compared with 15°F. in the previous test. This difference may be a real one but is more likely partly attributed to the less exact measure of temperature in the previous test.

The time-temperature relationship is definitely established in defining lethal temperatures for Douglas-fir as it has been for several conifers (66). This relationship proved to be of a logarithmic nature as suggested by Bigelow (11) in 1923 for bacteria and demonstrated for other organisms by Lepeschkin (64) and Cohen and Yarwood (21).

Heat alone as administered to the seedling stems in this experiment gives a time-temperature relationship with values lower by 8°F. to 16°F. than for peat moss and 22°F. to 40°F. lower than for white sand. This is not chance occurrence. Stated another way, the so called lethal temperature has been variously estimated from about 123°F. in the water bath test at four-hours duration, to 177°F. in

white sand at five-minutes duration. This 54° range is a very real one that can be demonstrated at will. This range depends only on temperature, time, and seedbed material. It is in addition to any effect of age or individual differences in resistance.

At this point, then, a question can be raised. How can a seedling that dies in three minutes under conditions of the dry water bath test at 140°F. continue to live another 50 minutes in peat moss at 140°F., or for 140 and 370 minutes in yellow mineral soil or white sand at this temperature?

The simplest explanation is the one proposed by Baker (4) that there is a lethal internal temperature for cells which he places at 131°F. as well as a time lag in reaching this temperature. Baker found that thermocouple readings inside the Douglas-fir seedling stems show lower temperatures by 8° to 21°F. than at the surface outside. The explanation already appears an over simplification in view of Lorenz's (66) water bath experiments with thin sections of conifer stems in which higher temperatures were sustained by exposed cells without damage for 20 minutes or longer. In the Lorenz study, and in the many studies at cellular level, a time-temperature relationship is well established in which high temperatures may be withstood for short intervals.

In any event, there appears to be a greater variation in killing temperatures than previously reported as they occur under dry conditions on various seedbeds. The temperature gradient and dry water

bath tests leave no doubt of this. The pattern of the variation is also clarified in terms of differences in seedbeds, duration of exposure, and seedling age. Why the variation occurs is not clear. This is the subject of subsequent tests.

The Small Role of Transpiration

The transpiration stream has been used to explain resistance to high temperatures in seedling stems and leaves (87). Leaf temperatures have been shown by Curtis (24) and Culm (22) to vary little from air temperature. They may have slightly higher temperatures than air in the sunshine, and slightly lower temperatures than air in the dark (86). Available apparatus was used to test the role of transpiration in reducing stem temperatures with a high degree of control over extraneous factors.

Materials and Methods

A combination of equipment was used consisting of the dry water bath apparatus to control temperature and lamps to control transpiration rates.

Lamps were used on half the treatments. Each of three seedlings was exposed to a different amount of light by placing a 250-watt tungsten lamp 24 inches higher than the seedling and shining on the three-seedling group at roughly a 40° angle. Radiation reaching the three seedlings at leaf level was measured with an Eppley pyrheliometer to be 2.50, 1.74, and 1.11 calories per square centimeter per minute even though they were only two inches apart. Such differences in light energy should produce different rates of transpiration, and should accordingly require a longer period to kill at

a particular temperature if the transpiration stream is an effective coolant. Lamps were turned on for five minutes before treatment to promote active transpiration.

Sets of three seedlings each were then treated at 133°F. in the dry water bath apparatus for durations of 1½, 2½, 5, 7½, and 10 minutes, some with illumination and some without. Since the lamps had no measurable effect on the stem temperature at point of treatment and the water bath apparatus had no measurable effect on leaf temperature, the two factors were manipulated independently. Two replications were made of these treatments with 45-day-old seedlings. They were inspected after treatment, 6 and 12 days later, and again 85 days after treatment.

Results

No differences due to variation in illumination were apparent. Some discoloration of stems was noted at 1½ minutes whether lamps were on or off during the exposure to 133°F. Constrictions began at five minutes whether lamps were on or off. All seedlings of the 7½- and 10-minute treatment developed lesions or constrictions. After two months, five treated seedlings had died. Three of these were among those treated under illumination, and the other two were treated without lamps. No difference is indicated. More deaths will occur but from the similar appearance of both groups no differences are expected. Also no pattern could be seen that would

indicate any differences in the amount of damage to the seedlings exposed to 2.50, 1.74, and 1.11 calories per square centimeter per minute.

In addition to the above test another will be mentioned somewhat out of turn. The experiment conducted by Baker (4) was repeated on five seedlings. The test involved implantation of fine thermocouples into the seedling stem during heat treatment, decapitation of the seedling, and sealing the cut surface. No measurable rise in temperature was noted after decapitation in any of the seedlings, thus confirming Baker's test as well as the one described here.

Discussion of Transpiration Test

If the transpiration stream has a cooling effect on the stem it could not be demonstrated. The apparatus may not be sensitive enough to measure a very small effect. However, the test should be an unconfounded one. The lamps should have no effect on the stem temperature at the treatment area. The stem temperature is raised without any appreciable change of environment in the leaves.

Temperatures Inside the Stem

It was necessary to explore internal temperatures in seedling stems to better understand why variations in killing temperatures were so great in previous tests.

Internal temperature measurements of plants have been the subject of much research. A long series of studies have been made to determine whether internal leaf temperatures were cooler than air because of cooling by transpiration (3, 90, 29, 88, 22, 24, 87, 56, 86). The conclusion is that leaf temperatures are equal or warmer than air temperatures in daytime (29, 22, 24) and cooler at night (86).

Stem temperatures in conifers have not been measured to the same extent. The small stems, especially in plants such as Douglas-fir, have little room for thermocouple implantations. In Baker's (4) extensive study on conifers, thermocouple implantations in stems at ground level were employed exclusively for the determination of lethal temperatures. He concluded that internal temperatures were always lower than surface temperatures, and that a lethal temperature near 131°F. was reached minutes later than this this temperature was attained at the soil surface. This offers a reasonable explanation for the range of temperatures required to kill in different seedbeds.

The theory was tested in various indirect ways because accurate internal temperature determinations proved impossible with available

thermocouples. Results revealed that no larger differences occur between internal temperatures and surface temperatures than could be demonstrated to occur in a column of water the size of a seedling stem. This parallels the history of research on leaf temperatures, but raises new questions.

Exploratory Procedures

This investigation proceeded from one exploratory experiment to another. Three main subjects were covered: (1) comparisons of internal and surface temperatures, (2) comparisons of internal temperatures in seedling stems and in plastic tubes of similar size filled with water, and (3) reduction in errors of measurement. Only a few of the later explorations are described, because large errors were seen in the early explorations.

Thermocouples of No. 40 copper and constantin wire (.005 inch in diameter) were made for implantations into seedling stems. By allowing the copper to melt back from the end of the constantin wire a conical point could be fashioned. This was possible because of the lower melting point of copper than of constantin. This point easily pierced the stem without need for a pilot hole made previously with a pin.

Tubes were drawn from heated 3/8-inch polyethelene tubing to produce diameters of .025 to .039 inch which corresponds to the

average diameters of six-week-old Douglas-fir seedlings. The wall thickness of this fine tubing was .007 inch. Such water filled tubes, set upright in the soil, will be referred to as "artificial seedlings" for convenience. Usually they contained one or more fine thermocouples (Figure 19).

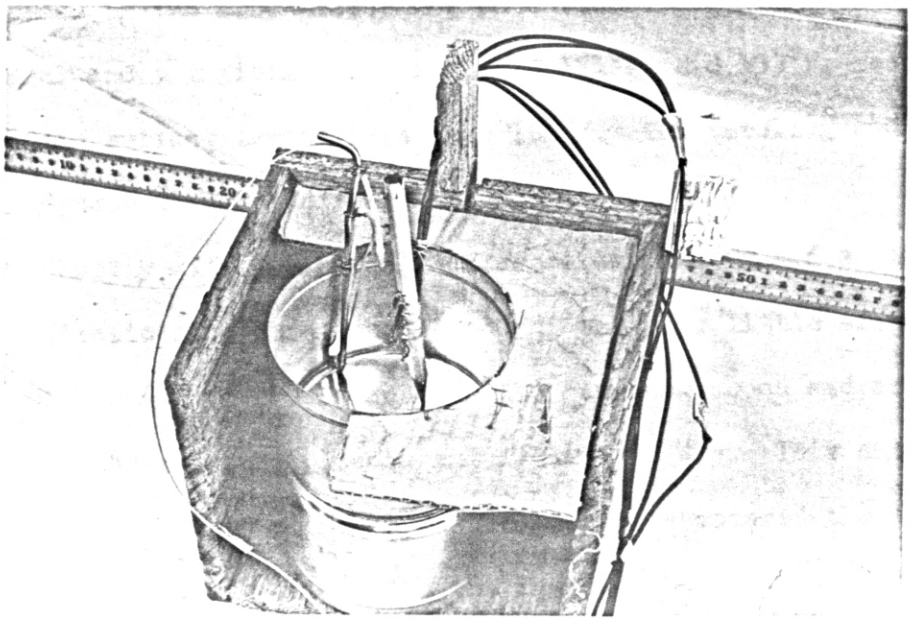
Seedlings were tested while under the lamps of the temperature gradient or under separate lamps. They were grown in the same boxes as in previous studies and the same surface materials were used.

Early tests with thermocouple implantations into seedling stems all gave lower readings for the implanted thermocouple than for the thermocouple on the soil surface. This occurred in tests with all seedbed materials. However, the following demonstration showed that thermocouples implanted in a water filled tube gave as low or lower readings.

The water filled tube or artificial seedling was sealed at one end and thrust about an inch into the soil at a point within a quarter inch of the natural seedling. The fine needle-pointed thermocouple was inserted into the seedling at a point about 1/16 inch above the surface and threaded downward so that the junction was buried in the stem at ground level. A similar thermocouple was inserted into the artificial seedling through a fine pin hole in the same manner. When lamps were turned on, both implanted thermocouples gave similar temperature readings but lower than the third thermocouple used to measure surface temperature. All temperatures were

Figure 19. Apparatus employed to measure temperature profiles of various seedbed materials. Soil can in box is filled and leveled. Thermocouples bound to slots in a pencil are positioned at surface, .5 centimeters above surface, and at .5, 1.0, and 2.0 centimeters below surface when point of pencil is touching bottom of the container. Position of thermocouples in relation to lamps (not shown) provide total radiation of 2.0 calories per square centimeter per minute for the tests.

An "artificial seedling" is also shown at right of pencil. This is a water filled polyethelene tube .037 inch in diameter containing a thermocouple, here fastened to a frame of soldering wire. Temperatures at the same levels as above were measured inside the tube of water, but proved useless because conductivity errors in thermocouple measurements could not be controlled.



recorded on the Brown recording potentiometer. As an example, the natural and artificial seedling read 131°F. and 133°F. respectively when the surface temperature read 181°F. The seedling and the water filled tube were not different in behavior.

Shortly after this the lamps were turned off and a tiny amount of a plastic pipe-threading compound, which is little affected by high temperatures, was placed on the seedling wound and around the entrance hole in the plastic and allowed to dry. This cut off any evaporation at the point where thermocouples entered the seedlings. In a similar time period with the lamps on, the surface temperature of the soil rose to 178° but both the implanted thermocouples reached 149°F. Undoubtedly some cooling of the thermocouples by evaporation from the wound was occurring. Independent tests with a thin layer of the plastic pipe-threading compound on the thermocouples showed no detectable difference from bare thermocouples in reading surface temperatures.

The next exploration indicated that large conductivity errors could arise even with these small diameter thermocouples. This time the thermocouple was implanted in a seedling at ground level, entering at a right angle to the stem so that the wires would follow the surface for several centimeters. The wound was sealed with a tiny amount of the plastic. Temperatures on the white sand surface were measured about one millimeter away from the stem with a similar fine thermocouple, the lead wires also following the surface for several

centimeters. After the lamps were turned on, each thermocouple read within 1°F. of the other minute by minute as the temperatures arose. A careful examination with a hand lens could find no fault with the implanted thermocouple. The junction was well inside the seedling stem and the plastic seal was intact.

When the temperatures leveled after 11 minutes to readings of 135°F. both inside and outside the seedling, the lead-in wires of the implanted thermocouple were raised so they slanted at about a 30° angle. Readings dropped to 125°F. or a depression of 10°F. When further elevated to about 45° they dropped to 114° or a depression of 21°F. When the lead wires were lowered parallel to the surface, readings once again became the same for both thermocouples.

This demonstration was repeated with similar results using other seedlings in peat moss and yellow mineral soil. Lower readings could be obtained with either the implanted thermocouple or the one measuring surface temperatures by either raising the wires or bringing the wires in from different directions with respect to the position of the lamp. Readings were lower when the thermocouples were brought in from the shadow side of the seedling than from the lighted side.

These many indicators of serious conductivity errors raised questions as to how small a difference could be measured between surface temperatures and temperatures inside the seedling stem. The artificial seedling provided a rough estimate of this. In the first

setup a 14-inch-long tube similar in diameter to a seedling stem was connected to a plastic squeeze bottle. The tube was looped into the soil so that a portion rose vertically from the surface. The unattached end looped into a beaker. At the soil-air interface a fine thermocouple following the surface was implanted into the tube through a pin hole and the hole sealed with plastic. The tube was filled with water and the lamps turned on. The surface temperatures and temperatures of the implanted thermocouple remained within 2° of each other and leveled off in about 15 minutes.

The squeeze bottle with water at room temperature could be pressed to allow any desired velocity to flow through the tube. When water began to flow the readings of the implanted thermocouple dropped rapidly. At maximum flows the thermocouple could be brought to read within 6°F. of room temperature while surface temperature read 144°F. Such a test is not critical because the flow of water past the thermocouple is heated by the elevated temperature of the soil. It was noted that within a minute, and sometimes within 30 seconds, after the flow was halted the implanted thermocouple rose again to equal surface temperature. Thus, the error of measurement inside the seedling stem was reduced to a fairly narrow range. In addition the demonstration showed that the time lag in reading elevated temperatures was short.

Another test using the same apparatus was conducted with the tube dipping into a beaker of water at the point where the thermocouple was implanted. Water in the beaker was 122°F. at the start

of the test and that in the squeeze bottle was 112°F. It was desired to see if a difference in water temperature of 10°F. or less could be detected. Here the thermocouple leads were conducting heat toward the junction from water which has a very high specific heat. The difference of about 10°F. was maintained during the test as temperature of the water in the beaker and in the squeeze bottle dropped at about equal rates. At maximum velocities the temperature reading of the implanted thermocouple was depressed 8°F. Cool water was next added to the beaker reducing differences between the two water temperatures. A water temperature difference as small as three degrees could be detected.

The most definitive test consisted of partially filling small plastic tubes with methanol, placing them vertically in the seedbed material, and measuring surface temperature attained under lamps as boiling began inside the tubes. The boiling point of methanol is 150°F. In white sand, yellow mineral soil, and peat moss, boiling was recorded when surface temperatures attained 149° to 153°F. Such determinations require a few precautions or greatly varying results are obtained. The column of methanol can extend only 1 or 2 millimeters above surface level and the tubes must be somewhat larger than the stems of seedlings. If smaller tubes with higher columns are used, much higher temperatures may be required before boiling begins. Such superheating may occur when no air-filled imperfections exist along the inner wall of the tube that are necessary as loci

for nucleate boiling (102). In the above determinations, tubes of .0065 inches diameter with wall thickness of .0007 inch were employed. Attempts to use tempil fragments in the tubes for such determinations proved unsuccessful.

As a final test an attempt was made to learn if lesions began at different positions on seedling stems in dry peat moss than in dry white sand or yellow mineral soil. Seedlings were carefully marked at ground line prior to exposure to high surface temperatures in these materials. Examination after a variety of durations revealed that in all these materials the lesions extend below as well as above the surface, apparently initiating at ground line. In many cases the lesions extended farther downward than in an upward direction. No lesions appeared to start above ground line on the dry surfaces. The only instance of lesions produced far above ground line occurred when seedlings were tested in damp peat moss. No lesion occurred at ground line, but a constriction appeared on a stem at a higher point where a bit of damp peat moss had been packed to the stem. It dried several hours in advance of the surface material to create elevated temperatures at that point on the stem.

Discussions of Internal Temperatures

The natural tendency, with the stems as small as those of Douglas-fir, is to implant thermocouples at an angle when measuring internal temperatures. Otherwise, little more than the junction can

be lodged into the tissue. It was demonstrated that much lower temperatures are invariably recorded with this kind of placement. Both conductivity errors and the cooling by evaporation from the wound must be controlled before internal temperatures can be measured. Evaporation was probably controlled by the lead plastic compound used here, but no way was devised to overcome conductivity error. Hence, internal temperatures were not measured. It is doubtful if anyone has done so directly with thermocouples in stems as small as those of Douglas-fir.

The measurements that were best controlled gave readings with implanted thermocouples that were little different from surface temperatures. Likewise, readings inside a column of water in plastic tubes the size of seedling stems approached surface temperatures as errors were eliminated. Checks on minimum temperature differences that might be detected under the condition of measurement indicated that differences larger than 4°F. would probably have been measured. Finally the boiling point of methanol (150°F.) was reached inside plastic tubes when surface temperatures ranged between 149° and 153°F. in all three seedbed materials. Because every measurement made in seedling stems gave approximately the same temperatures as that of a tube of water of similar size, there is no indication of a biological mechanism within the seedling that reduces its temperature.

All these explorations and checks were not direct, and different conclusions may be shown with a superior technique. But if it is true that internal and external temperatures are essentially the same then we must revise our views on lethal temperatures. Such revisions are considered in the general discussion.

The finding that lesions extend below as well as above ground line in all materials tested probably reflects difficulties in making good field observations. Lesions are sometimes described as beginning slightly above the surface (4), although the original descriptions by Hartley (35) show them as extending above and below the soil-air interface. The author has observed lesions in the field associated with dead needles touching the stem high above ground line. This was duplicated in the laboratory. But the general case seems to be that the lesion is initiated at the soil-air interface.

Temperatures of Various Materials Exposed to Known Total Radiation

The practical purpose of checking relative surface temperatures of various substances under known total radiation is to provide a basis for comparing them with temperatures attained on white sand, yellow mineral soil, and peat moss. From this, the time and temperature at which mortality probably would occur can be estimated for each material. The estimate would not be expected to be exact, but well in line with the accuracy to which such descriptive words as peat moss, yellow mineral soil, and white sand can be specified.

The subject matter also leads into the more basic fields of micrometeorology and soil physics. For the most part, these fields will be avoided. So many variations in surface temperature arise as materials vary in moisture content, compaction, surface texture and composition, or their microclimate varies in air circulation, humidity, quality of light, and latent heat that the subject already fills several volumes (32).

Investigations were made under simple environmental conditions. In most tests the materials were oven-dry and tested under lamps in still, dry conditions of an air-conditioned laboratory. Such conditions were considered best for the desired qualitative comparisons since lethal temperatures are generally attained in the field under dry conditions on clear, still days. Some materials were tested at field capacity, however.

Three tests of the seedbed materials were made. The first was a preliminary screening of 40 materials, both natural and artificial, to determine which materials to use in the temperature gradient study. The second test measured temperatures near the soil-air interface on 20 natural materials occurring on Douglas-fir clearcuts. The third test explored the effect of moisture on surface temperatures using peat moss, duff, yellow mineral soil, and white sand.

Test I

A screening of 40 materials was accomplished under a 250-watt infra-red reflector lamp clamped on a ring stand so that the silver line on the bulb was nine inches above the base of the ring stand. Dry materials to be tested were placed in the lid of a paper Dixie cup which is about one-inch deep and four-inches across. The surface was smoothed and excess material removed by running the edge of a spatula across the top. Temperature pellets melting at 138°F. were fragmented into grains less than .05 inch and were sprinkled sparingly on the surface. A few fragments of pellets that melted at 125°F. were added to provide a warning for timing the melting of the 138°F. pellets. Fragments of 150°F. pellets were sometimes added to serve as a check on timing when very easily heated materials were being tested. Timing by stop watch was started when lamps were turned on and stopped when the first 138°F. pellet fragment was seen to melt. This procedure assured added uniformity between trials because the hottest spot in each sample was being tested.

A portion of the materials screened in this way were also tested at field capacity with surfaces moist. To assure comparable conditions between trials the lids were first punctured for drainage, filled with the materials, and soaked from below by placing them in a shallow pan having about ½ inch of water. After this, the filled lids were allowed to drain four hours in a tight wooden box under moist cheesecloth to maintain high humidity before they were removed one by one for testing.

In addition to this treatment, the surfaces of some dry materials in the lids were sprayed with a light, uniform coat of aluminum paint or black lacquer to change the surface color.

The natural materials were more consistent in behavior than artificial materials, hence are considered separately.

The fifteen dry natural materials fell into two widely differing groups according to exposure time required to reach 138°F. (Table 10). The organic materials (grass, peat, needles, and charred bark) attained 138°F. in less than 11 seconds. The mineral group (sand, clay, loam, and subsoil) ranged between 21 seconds and 47 seconds. Sand seedbeds attained this temperature in the least interval of time (Tuchie fine sand) as well as the longest (Boardman onyx sand). Yellow mineral soil reached 138°F. the slowest of those materials widely encountered on clearcuts.

Both the mineral and organic surfaces sprayed with aluminum paint required about one-third longer time to reach 138°F.

Table 10.—Test I. Time in seconds required for natural and artificial materials to attain 138°F. under a 250-watt infra-red lamp

Seedbed materials	Volume weight: gr. per cu. cm.	Surface condition: Dry	Moist	sprayed with aluminum paint	sprayed with black lacquer
Natural materials					
Cheatgrass	0.07	8	83	13	6
DF needles, new	0.08	9	36	18	
DF needles, old	0.09	10	39	15	
Peat moss	0.09	11	115	13	
Charred bark	0.32	10	58	13	
Aiken loam	0.84	22	202	33	22
Yellow mineral subsoil	0.95	36	220	44	
Willamette loam	0.97	22	215	34	
Palouse loam	1.09	24	250	32	
Clarno clay	1.09	29	205	44	
Pumice (Miliken)	1.18	26	225	39	
Tuchie fine sand	1.32	21	245	28	16
Dark sand	1.38	22			
Willamette River sand	1.52	37	208	48	
Boardman onyx sand	1.54	47	254	56	
Artificial materials					
Vermiculite	0.16	10	195	11	8
Sawdust (coarse)	0.18	26	105	30	
Soil conditioner	0.20	7	187	10	
Perlite	0.37	53			
Fuller earth < 1mm	0.49	29			
Fuller earth > 1mm	0.59	32			
Chalk > 1mm	0.68	48			
Talc < 1mm	1.15	119			
Talc > 1mm	1.25	116			
Rock salt	1.09	205			
Fine salt	1.24	240			

Table 10.—Test I. Time in seconds required for natural and artificial materials to attain 138°F. under a 250-watt infra-red lamp

Continued

Seedbed materials	Volume weight: gr. per cu. cm.	Surface condition: Dry	Moist	sprayed with aluminum paint	sprayed with black lacquer
Gravel, ½" minus	1.25	69	90	147	
Quartz < 1mm	1.27	155			
Quartz > 1mm	1.42	165			
Rogue River silica	1.35	250			
Coarse sand > 1mm	1.44	64			
Beach sand < 1mm	1.50	39			
White sand	1.54	156			
Apatite > 1mm	1.53	71			
Apatite < 1mm	1.87	77			
Ottawa sand	1.65	232			
Aluminum oxide > 1mm	1.72	58			
Barite > 1mm	2.46	165			
Barite < 1mm	2.32	160			
Magnetite (black)	2.50	23			
Zircon sand	2.70	275			

Conversely, surfaces sprayed with black paint reached 138°F. in a somewhat shorter time. The effect was roughly proportional to the time requirement for the particular material when dry. In either case, no "hot" seedbed (one reaching 138°F. very quickly) was changed to a "cool" one, or vice versa, by a change of color. Addition of moisture increased the time required to reach 138°F. from 4 to 27 times, but still in rough proportion to the time requirement for heating dry material.

The 26 artificial materials were much more variable in the time required to reach 138°F., ranging from 6 seconds for soil conditioner to 275 seconds for zircon sand (Table 10). Since the search was directed toward finding a material that might remain below lethal temperatures in full sunlight, the list includes mostly white materials or very dense ones. The fact that both the slowest and fastest heating materials were white emphasizes that color alone is an unreliable index of surface heating properties. Of special interest as possible artificial seedbeds are the dense sands of quartz and silica that rank amongst the slowest materials to attain 138°F. of those tested. An extreme example of a very dense material that heats very quickly is magnetite (Fe_3O_4). Although this black material weighs 2.50 grams per cubic centimeter, it reached 138°F. in 23 seconds!

A few materials were tested moist as well as with surfaces coated with aluminum paint or black lacquer. The results again were much more variable than with natural materials.

Test II

Samples of materials were collected on clearcuts of various ages and on the surface and at several depths under an old-growth stand on the H. J. Andrews Experimental Forest. These materials were tested for surface temperature, as well as temperatures at .5 centimeter above and below the surface, and at depths of 1 and 2 centimeters. Samples were placed in a 400 gram soil tin set in a frame to provide accurate positioning of each tested sample (Figure 19).

The tests were made under two 150-watt tungsten spot reflector lamps adjusted to give a total radiant energy of 2.0 calories per square centimeter per minute. This radiant energy level was chosen because it produced temperatures in 30 minutes that were near maximum temperatures attained in the field. Temperature measurements were made with copper-constantin thermocouples of No. 24 wire. These were set ridgidly in a frame with the wires running for at least three centimeters parallel to the surface at the four positions to minimize possible conductivity errors. Once the surface thermocouple was properly adjusted to the surface level all the thermocouples above and below the surface would be positioned automatically. A

continuous record of the temperatures was kept with a Brown recording potentiometer. Materials were exposed at the 2.0 calorie radiation level for 30 minutes.

Temperature measurements near the soil-air interface of 20 natural materials from clearcuts and from under old-growth stands (Table 11) confirms essential features of the screening tests. Organic surfaces attain a certain temperature more quickly under equivalent radiation than mineral soils without appreciable organic material. It is seen that several natural materials, notably duff, moss, and charcoal rate above the screened peat moss used in the temperature gradient study. White sand is by far the slowest to attain high temperatures.

Some other features are of interest in Table 11. Effects of burning on surface materials are indicated in the listing of similar burned and unburned materials along with temperatures reached when exposed to 2.0 calories per square centimeter per minute for a 30-minute period.

Table 11.—Test II. Temperature (°F.) reached in 30 minutes at 2.00 cal./sq.cm./min. exposure 0.5 centimeter above surface, on surface, and 0.5, 1.0, and 2.0 centimeters below surface of 20 materials associated with Douglas-fir clearcuts

Seedbed materials	Point of measurement				
	.5 cm. above surface	at surface	.5 cm. below surface	1 cm. below surface	2 cm. below surface
Freshly burned duff, under stand	145	174	161	148	134
Fresh moss, under stand	145	168	167	156	144
Fresh unburned duff, under stand	151	165	158	145	130
Charcoal	131	165	147	140	118
A_2 horizon, under stand	145	163	149	130	117
Weathered burned duff, 3 years old	138	158	151	135	118
Weathered unburned duff, 3 years old	144	158	150	135	118
Dark sand from creek	133	154	144	133	116
Upper B horizon, under stand	135	153	138	124	109
Aiken loam	133	153	137	122	108
Fresh bark slivers	138	151	133	127	114
Old bark slivers	132	149	133	124	112
Sawdust, 3 years old	138	149	138	135	120
Sawdust, fresh	136	149	133	122	110
Lower B horizon, virgin stand	131	149	130	122	108
Cubical rotten wood	131	149	131	126	116
Lower B horizon, burned area, 3 years old	129	147	129	120	108
Hard burn, fresh	133	147	131	118	108
Peat moss, screened	140	160	144	133	122
Yellow mineral subsoil	132	147	131	123	114
White sand	133	138	118	112	102

Material	Temperature
Fresh duff - unburned	165°F.
Fresh duff - burned	174°F.
Weathered duff (3 yrs.)-unburned	158°F.
Weathered duff (3 yrs.)-burned	158°F.
Shot loam (3 yrs.) - unburned	151°F.
Shot loam (3 yrs.) - burned	147°F.
Yellow mineral soil - unburned	147°F.
Hard red burn - burned	147°F.

Burning of surface organic material appears to result in higher surface temperatures; once the organic material is consumed the differences in surface temperature between comparable burned and unburned soils is minor. Weathering also tends to erase the differences between burned and unburned surfaces.

Test III

Boxes of seedlings were tested in the temperature gradient after being soaked to field capacity. The purpose of this was to estimate roughly the amount of total energy that may be required to reach killing temperatures after a rain. Surfaces of peat moss, yellow mineral soil, white sand, and duff were employed in this test. The boxes of seedlings were prepared with the four surface materials, then carefully soaked from below and sprayed from above. The boxes were allowed to drain overnight but were covered with polyethelene

to maintain high humidities and moist surfaces. Seedlings were exposed under the lamps for five-hour intervals each day and then placed under plastic to simulate the high humidities of night. Treatment was stopped when all the surface material in a box became thoroughly dry. As drying progressed down the box, records were made of the extent and depth of drying after each five-hour period. Mortality records were also kept so that corresponding duration of exposures in dry materials could be estimated.

Trials with moist surfaces under lamps of the temperature gradient gave striking results. No stem lesions occurred on seedlings in any box until the surface became dry. This is of considerable importance since it shows that radiant energy at levels of nearly twice the solar constant was unable to produce stem lesions if surfaces were kept moist. This demonstrated that radiant energy alone was not producing injury under conditions of this experiment. Approximately 1,680 minutes, or over 5 days of treatment were required to completely dry the white sand surface over the entire box; approximately 1,350 minutes, or over 4 days were required for the peat moss; 920 minutes, or nearly 3½ days were needed for yellow mineral soil. A loose duff surface was completely dry in 39 minutes!

At the end of these treatments there was a residual cooling effect from the moisture in the soil just below the surface. Killing in moist white sand after 1,680 minutes was equivalent to that obtained after only about 60 minutes of treatment starting with dry

surfaces. With moist peat moss, 1,350 minutes were equivalent to 30-minute treatment in dry material. In yellow mineral soil after 930 minutes killing was equivalent to 180 minutes of treatment. In the duff treated only an hour the killing was equivalent to about 15 minutes treatment when dry.

These equivalent times only serve to show that variation in subsurface moisture is a very important factor in lethal temperature determination. Even after these long exposures, moisture was still near the surface and surface conditions did not resemble the dry surfaces employed in the temperature gradient study. Damp sand was found at the end of the treatment within 3/4 inch of the surface even at the hottest point of the temperature gradient. The soil was usually damp just below the surface at the cool end of the gradient. Temperature on a soil in a surface-dry condition was considerably lowered and killing was delayed by the presence of moisture a fraction of an inch below. This was especially true with the mineral soils but was less of a factor with organic materials. Loose duff reached very high surface temperatures even when the moist sand could be seen $\frac{1}{2}$ inch below through open spaces between needles.

Discussion of Seedbed Temperatures

Ranking of seedbed materials for their surface heating properties was more effectively accomplished with Test II than with Test I. This is because the time-temperature curve has a characteristic shape with all materials tested, as well as at all levels of energy (Figure 7). The most rapid rise is during the first minute. After eight minutes the rise is very slow.

In Test I most organic surfaces passed 138°F. so quickly that all determinations fell between 8 and 11 seconds. With mineral seedbeds requiring a longer time interval to reach 138°F., the time-temperature curve was beginning to flatten, and differences were greater. Thus, Test I was useful in ranking materials, but useless in drawing further comparisons between materials, such as their relative temperatures at a given time.

Test II, in which comparisons were made after 30 minutes, takes advantage of the portion of the time-temperature curve where little change is occurring. Thus, it both ranks materials and provides comparisons at a given time, but is a much more time-consuming test. In Test II seedbeds could be more clearly separated on the basis of surface heating properties.

Attempts were made to find general relationships between characteristics of materials and surface temperatures. Obviously, this was not the original purpose in collection of the data, and the

analysis does not give strong conclusions. Nonetheless, such treatment will be of interest to many workers in this field.

Geiger (32) attributes differences in heating properties of materials to differences in air space within them. Because the solid portion of most surface materials on clearcuts would have a narrow range in specific gravity, the weight in grams per cubic centimeter (the volume weight) would largely reflect differences in air space. Volume weight of the 40 materials in Test I (Table 10) ranges between 0.07 and 2.70. For the 15 natural materials, volume weight is highly related ($r = .85$) to time required to attain 138°F. (Figure 20). But with the 26 artificial materials this relationship though statistically significant is poorer ($r = .62$) as seen by the scatter of points when plotted (Figure 21). Thus, the data for the natural materials follows closely the pattern described by Geiger. Temperature attained on artificial materials may also relate to air space, but the solid portions of these materials range so greatly in specific gravity that volume weight is probably a poor expression of air space. An example is black, rapidly heating magnetite with volume weight of 2.50, but having a large air space.

Color differences alone do not drastically change surface temperature characteristics as indicated by performance of tested materials after reflective and nonreflective paints were added to the surface. The result was a shifting either toward slower or quicker heating of all materials much as if the lamp were moved further from

Figure 20. Relationships of time to attain 138°F. under infra-red lamps and volume weight of 15 natural materials. The organic materials, which have low volume weights, heat more quickly than those in the mineral group. Moistening, or spraying with reflective aluminum paint, increases time requirement in proportion to heating properties of dry materials.

NATURAL MATERIALS

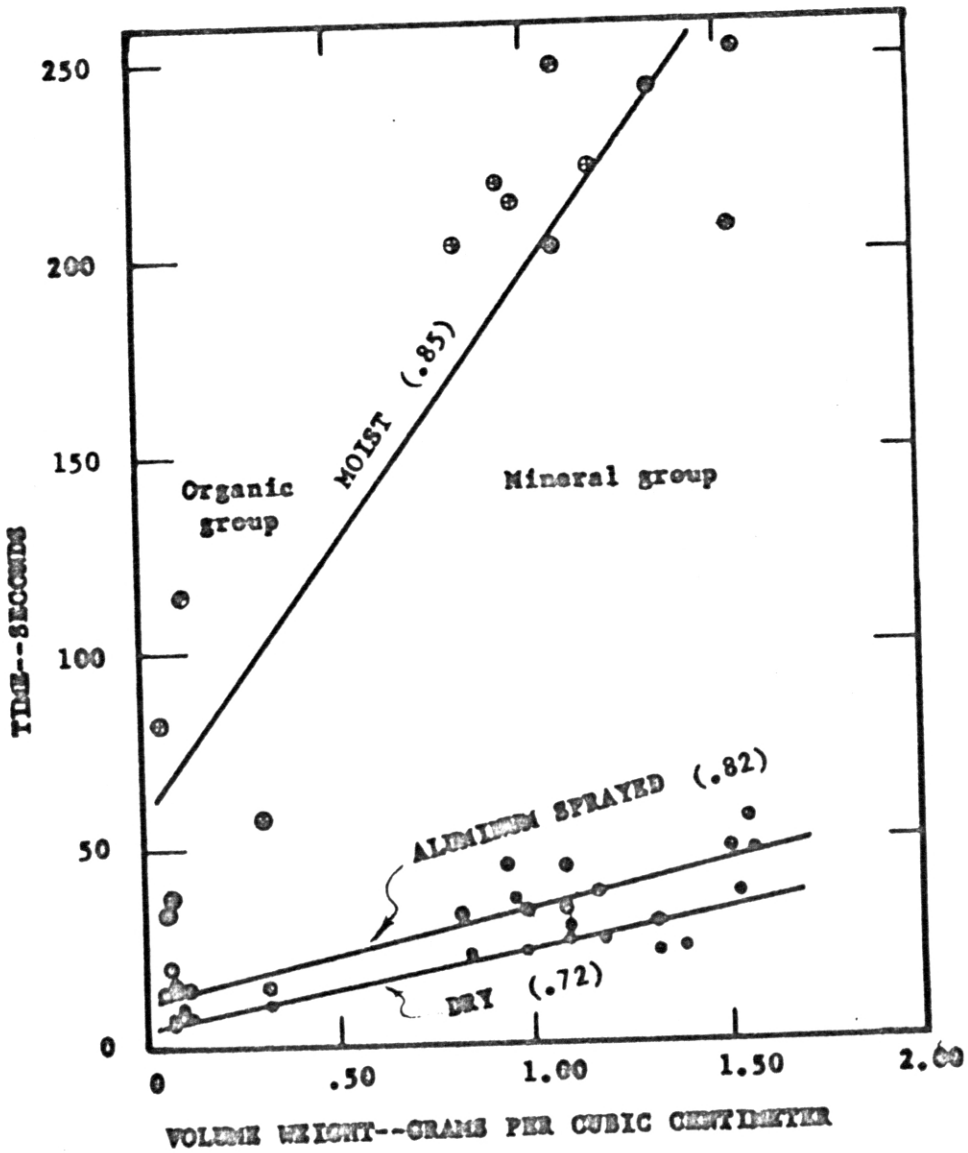
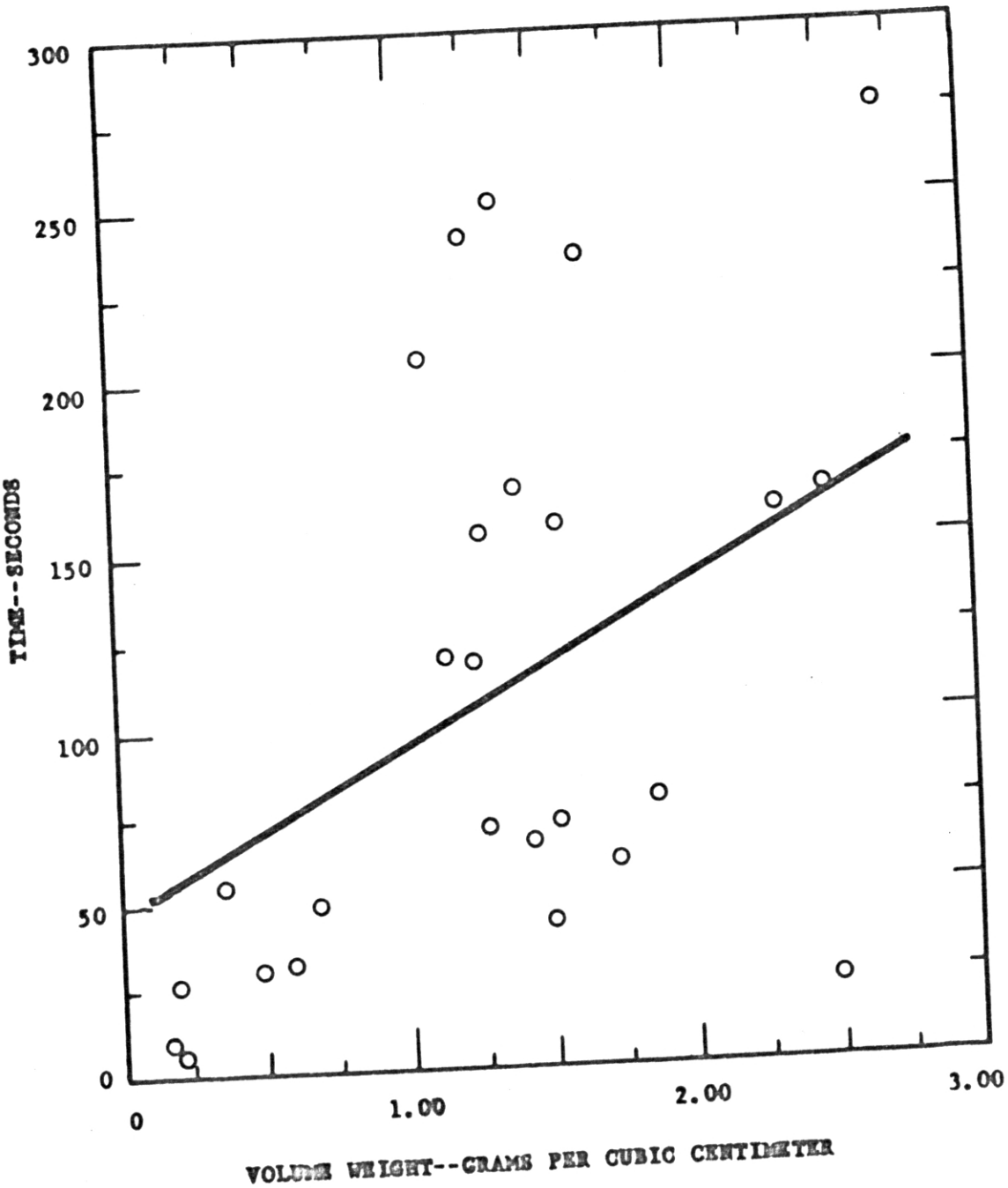


Figure 21. Relationship of time to attain 138°F. under infra-red lamps and volume weight of 26 artificial materials.

ARTIFICIAL MATERIALS



or nearer to the surface. It is difficult to assess the magnitude of this effect from Test I, but it was apparent that the heating properties of the material overrode the effect of surface color. Relative ranking was seldom changed. Among artificial materials, both the fastest and slowest to reach 138°F. were white. On the other hand, on natural seedbeds the effect of color may be very important as is seen from Test II. A sample of duff that attained a surface temperature of 165°F., when exposed for 30 minutes at 2.00 calories per square centimeter per minute, attained 174°F. with the same exposure after it had been scorched with a flame from a Bunsen burner (Table 11).

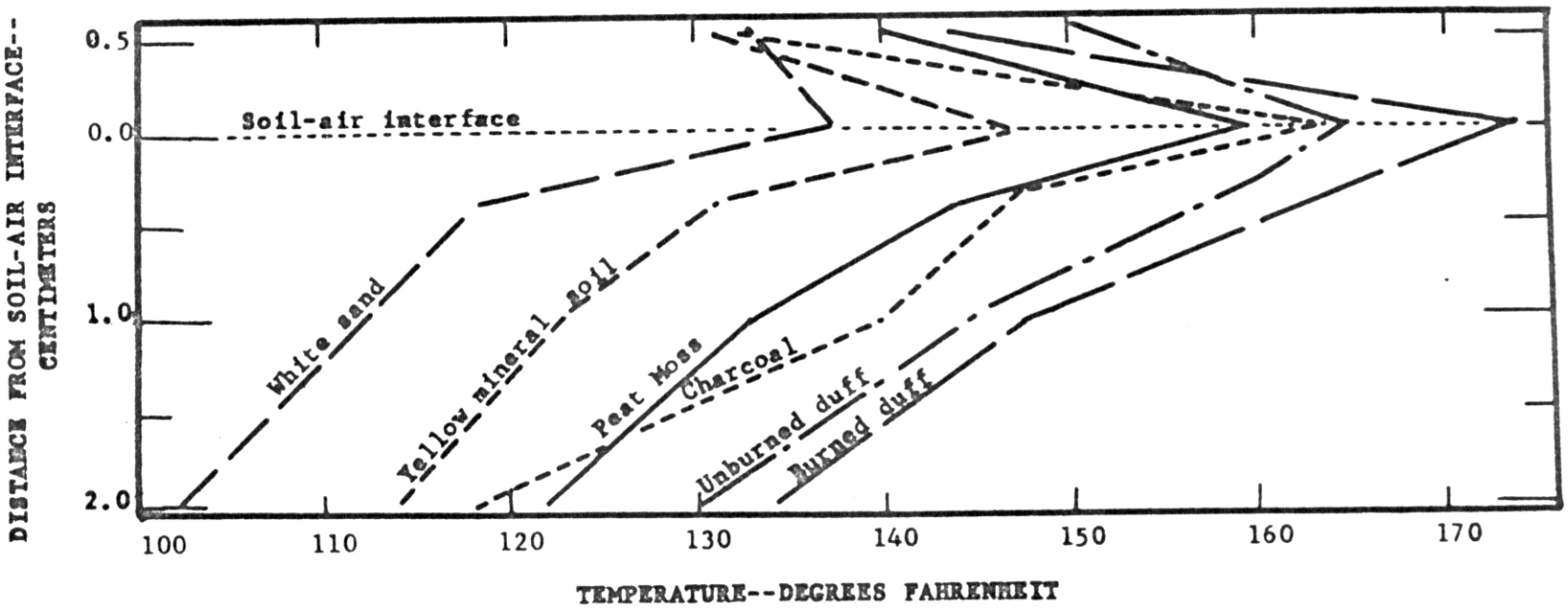
The importance of variation in surface moisture may be greater in these laboratory experiments than in the field. Exposed seedbeds usually become thoroughly dry sometime during the summer in the Pacific Northwest. But a seedbed material that is capable of holding much water near the surface may be protected from high surface temperatures for considerable periods during drying weather. Dew may also aid in prolonging this protection. This would be especially true of the partially shaded mineral seedbeds and perhaps of compacted organic ones that resemble screened peat moss. This additional moisture would certainly provide for better germination of seed as reported for such seedbeds by Smith (91). But the loose organic materials generally found exposed on clearcuts would be expected to dry rapidly on the surface and reach killing temperatures

just as damp duff performed in Test III. Moisture appears to multiply the surface temperature differences already established between materials. It also adds to the complexity of interpreting the meaning of surface temperatures if top soil layers are not thoroughly dry.

From Test II, temperatures of various materials through the profile near the soil-air interface (Figure 22 and Table 11) clearly indicate the influence of color. Reflective materials result in temperatures at 0.5 centimeters above the surface that are more nearly equal to surface temperatures than do nonreflective materials. For example, the surface and air temperatures at 0.5 centimeters for the highly reflective white sand are 138°F. and 133°F. respectively, a drop of only 5°F. For nonreflective charcoal, corresponding temperatures are 165°F. and 131°F. a drop of 34°F. Corresponding temperatures for unburned duff are 165°F. and 151°F., a drop of 14°F., and for freshly burned duff the drop is 29° with a surface temperature of 174°F. and air temperature of 145°F. Here the only change was a blakening of the surface by burning. The behavior of all the 29 materials with regard to surface and air temperatures follows a pattern related to absorption of radiation.

In the same data, effectiveness in downward conduction of heat is indicated by the steepness of the downward temperature gradient. The very effective downward conduction of yellow mineral soil is indicated by a difference of only 33°F. between surface temperature and temperature at 2.0 centimeters below the surface. Poor

Figure 22. Temperatures of various seedbed materials above, at, and below the soil-air interface.


DISTANCE FROM SOIL-AIR INTERFACE--
CENTIMETERS
0.5
0.0
1.0
2.0
Soil-air interface
White sand
Yellow mineral soil
Peat moss
Charcoal
Unburned duff
Burned duff
100
110
120
130
140
150
160
170
TEMPERATURE--DEGREES FAHRENHEIT

conduction in charcoal is indicated by a difference of 47°F. In general, organic seedbeds show wide temperature differences that indicate slow downward conduction, whereas mineral seedbeds show narrower differences.

White sand and yellow mineral soil are about equal in downward conduction, the cooler properties of the white sand being attributed to its lower absorption of radiation. Peat moss shows a high capacity for absorption of energy and a poorer capacity for downward conduction, but in neither regard is it extreme. About half the organic materials tested are more extreme.

This intermediate position of screened peat moss in Test II indicates perhaps the most reasonable explanation for the low temperatures experienced on peat moss at normal summertime energy levels of the temperature gradient study. Duff, both burned and unburned, attained 8° to 14° hotter temperatures in Test II than did peat moss. The screening of the peat moss used probably increased the proportion of heavier dirt in the finer fraction. In a test of the two fractions the unscreened portion attained a surface temperature of 165°F. as compared to 160°F. for the screened peat moss.

GENERAL DISCUSSION

The original aim of the study was to substitute direct measurements of physical factors for more gross evaluations presently used in deciding if a Douglas-fir clearcut area might restock naturally without planting. Surface temperature was considered to be the physical factor showing greatest promise of correlation with restocking, hence was considered first. A simple field method was found to measure surface temperature by means of temperature pellets of known melting points. Correlation between seedling mortality and melting of 138°F. pellets was found to be quite good. Most surviving seedlings had some shade at ground line. However, an appreciable proportion of the seedlings survived in the field at temperatures apparently above 138°F. Some even survived temperatures in excess of 150°F. Laboratory studies proved that this perplexing range of lethal temperatures was a real one.

These laboratory studies both simplified and complicated the interpretation of temperature data. To simplify matters, there was no evidence that seedlings became more resistant to heat injury after a few weeks as was commonly supposed, but eventually died after treatment at about the same temperatures up to three months of age. Nor was the temperature at which injury first appeared appreciably different between individual seedlings, even if a small proportion did undoubtedly recover from lesions both in the field and in laboratory studies. The range of this twilight zone in which seedlings may

recover was found to be about 6°F. in the water bath study at all durations of exposure up to four hours. The range may be a little greater under greenhouse conditions with ample water following treatment, but may be greatly reduced in the field under rigorous drying conditions. The interpretations of the effects of age and resistance of individual seedlings to heat damage were simplified to the point where they might be disregarded for practical purposes. The possibility that some hardening process may occur with field seedlings was not tested, hence cannot be completely discounted.

On the other hand, the effects of seedbed materials and duration of exposure on lethal temperature were found to complicate interpretations of surface temperature data. Together these factors can account for differences in lethal temperatures ranging over 50°F. The 138°F. pellet correlated best with seedling mortality in the field trial because the range of seedbed materials and exposure times happened to give an array of killing temperatures that averaged closest to this figure. Obviously, if all the seedlings tested had been on yellow mineral soil the 150°F. pellet would have correlated more closely with mortality. This actually was the case with the field plots on the mineral soil of road fills at the H. J. Andrews Experimental Forest and the Siskiyou-Cascade Research Center (Figures 5A and 5C). Had seedlings all been on duff, the 125°F. pellet would probably have correlated more closely with mortality.

The exclosure samples (Figure 5D) represented a mixture of mineral and organic seedbed types. In this case the percent of melted 138°F. pellets closely followed the curve of cumulative mortality through the entire summer.

Average killing temperature, then, is dependent on average seedbed conditions and average exposure time on a clearcut. The question again arises as to how well the 138°F. pellet correlates with seedling mortality on the eight clearcuts of the field study. On these clearcuts are average seedbed (Table 5c) and exposure (Table 5d) conditions simular or quite different from those in the study that compared seedling mortality with melting of pellets (Figures 5A to 5D)? A tally of hours of exposure and seedbed conditions was possible only with the H. J. Andrews Experimental Forest data from the two exclosures. Hours of exposure averaged 3.9 on the eight clearcuts and 3.7 in the exclosure sample. This small difference contributed very little effect to average killing temperature because the curve values change slowly at such long exposures. In comparing seedbed types between the exclosure sample and the eight clearcuts, only the yellow mineral types and the burned and unburned organic types were considered extreme enough to effect results. Other types would be intermediate in heating or killing properties. Yellow mineral types averaged 18 percent and duff types (duff, charred duff, broadleafs, and moss) averaged 30 percent of the microsites on the eight clearcuts. For the exclosure sample, yellow mineral types

averaged 28 percent of the microsites and corresponding duff types averaged only 12 percent. These percentages suggest that a pellet melting at a temperature a degree or two higher than 138°F. would have correlated very closely with mortality on the clearcuts. Clearcuts in other parts of the Pacific Northwest, on which seedbed types depart widely from these average proportions of mineral and organic microsites, might require an adjustment in estimating percentage of seedling mortality from the percentage of melted 138°F. pellets.

Does surface temperature sampling of a fresh clearcut correlate well enough with the pattern of restocking to be useful? The answer to this question would depend on how well effects of many other factors such as seed supply, animal damage, and plant competition averaged out between clearcut areas. This should be separately tested by sampling a number of fresh clearcuts for surface temperatures and following the restocking pattern. The present series of clearcuts is confounded in this regard by difference in time of measurement, difference in seed years, and planting of some of them. Such a study should follow logically from this one.

But whether the original aim of the study bears any fruit it has suggested some new approaches to forestall heat injury. One approach might exploit the time required to kill. Perhaps seed trees on clearcuts may be more important for their shade than their seed if spaced to break up the day into short periods of exposure. Another approach, the use of artificial seedbeds, is suggested by the white sand that did not attain killing conditions even under prolonged exposure.

The study has also provided an array of new information about Douglas-fir cutovers; it has explained much of the variability that is encountered in the field; and it has also provided some new interpretations of thermal death points for seedlings in dry seedbeds.

Field evaluation of microsites has provided the figures needed to evaluate the relative importance of problems associated with the staggered-setting system of clearcutting in old-growth forests. The amount of disturbed and undisturbed area, the proportion of burned and unburned surfaces, the extent of nonseedbed surfaces and many other figures describing surfaces of clearcuts are now available for such evaluation.

Knowledge of the proportions of clearcut surfaces that exceed certain temperature levels is of some importance even if no further measurements are made. The fact that 99 percent of the stations on one clearcut exceeded 125°F. during the summer of 1954 is not to be lightly dismissed. Only four south slope clearcuts were sampled, and on three of the four 95 percent or more of the stations reached 125°F. In terms of microaspects, only those in perpetual shade would be expected to remain below this level unless they faced in a northerly direction. Even northerly microaspects reached elevated temperatures if fully exposed, but shade was more plentiful on them. The knowledge of a few measurements of this kind is sobering to those faced with the scientific management of Douglas-fir lands.

One source of variability on which the study touches is the

value of vegetation as shade for regeneration. Other than the low plants and very dense plants—those already being questioned as serious competitors for seedlings—few plants giving intermittent shade protected surfaces from high temperatures. Perhaps the delay in disappearance of moisture may be of value in promoting germination (91) or in protecting the seedling. Perhaps the high temperatures may be of short enough durations in the intermittent shade of plants to prevent killing. But the fact that most of the seedbeds under plants are of organic debris makes even short durations of exposure dangerous for Douglas-fir seedlings. It would appear that the only kind of a seedbed that is unquestionably safe is one that is shaded all day.

Seedbed temperatures are not dangerous until surfaces are dry. The presence of moisture near the surface also was shown to furnish a measure of protection, probably by providing better conduction of heat downward (32) and also from cooling by evaporation. However, surfaces are almost certain to dry down several inches on most Douglas-fir clearcuts at sometime during dry summers. In areas where rains occur regularly, soil moisture may be an overriding factor in preventing heat damage, especially on mineral soils.

Special emphasis should be given the possibility that heat losses may be important with regard to older seedlings. Such injury in other coniferous species has been reported by Hartley (35), Korstian and Fetherolf (58), Rudolph (84), and Paelinck (80).

Studies of heat injury to older Douglas-fir seedlings are indicated. Also, damage from heat injury late in the first season may not produce killing until several months have passed as was demonstrated in this study. An instance where this probably occurred was reported by Hartley (35). This could occur on seedbeds which are protected by moisture early in the season. Mortality would be difficult to distinguish from drought in late summer or from frost in over-winter losses.

Proof that seedling mortality followed widely different time-temperature relationships on three seedbed materials raises several questions concerning the interpretation of thermal death points. The first is whether every dry seedbed material has a distinct time and surface temperature at which killing occurs. Each material tested was found to reach a given temperature in a certain order at each level of radiant energy. Judging from the almost unvarying order in which killing occurred with successively lower temperatures in white sand, yellow mineral soil and peat moss, one could scarcely interpret the data in any other way. We may picture seedbeds encountered on Douglas-fir clearcuts as a spectrum of time-temperature relationships of the kind shown in Figure 12B. All the curves probably plot as straight lines when time is transformed to a logarithmic scale. This seems to be a characteristic of heat mortality curves for all organisms (11). The curve of yellow mineral soil would be near the slowly heating or cool end of the spectrum and peat moss would be

near the rapidly heating or hot end of this family of curves.

The picture of a spectrum of curves needs a further modification. With each material there is some latitude between damage and killing. The curve of first detectable damage appears to be roughly 6°F. lower than the curve of mortality in seedlings up to three months old in the three seedbeds tested. Hence, each of the curves is in reality a band of killing temperatures. The band may be narrow or wide depending upon the seedling environment after damage occurs.

Another such curve or band in the spectrum was produced from the dry water bath study (Figures 17 and 18). This was lower in temperature at all durations than the other curves, and may well represent a lower limit of the family of heat-mortality curves—a "basic" time-temperature relationship.

The band of killing temperatures from the dry water bath study compares well with results of other water bath studies. The curve of first detectable damage (Figure 18) is almost identical with the time-temperature curves at which pronounced yellowing of pine needles occurred in a study by Nelson (78). The mortality curve (Figure 18) is not greatly different from curves produced by Lorenz (66) for killing of cortical cells in thin sections of eastern United States conifers. They correspond also to some of the mortality curves reported by Bigelow (11) for non-spore-bearing organisms. The thermal death points reported for particular times and temperatures by Baker (4), Shirley (87) and Sachs (85) fall near the values reported

here. From a theoretical viewpoint, even the killing of pea roots by Leitch (62) at temperatures between 35°C. and 45°C. after exposures of long durations falls along an extrapolation of this basic time-temperature curve. Thus, the time-temperature relationship of heat injury could be interpreted as no more than an upward extension of the growth curves found in plant physiological studies (73, 74). Note that the common denominator of all these death-point determinations is that the organisms were immersed in water baths.

A second question now arises. If the concept of a spectrum of curves is the correct one, some explanations must be proposed as to why dry materials produce curves that differ from this basic curve found in water bath studies. Underlying all previous work was the concept that there was a specific internal temperature for a given period of time at which killing occurred within the cells for any organism like Douglas-fir. This view is expressed by Baker (4) who felt that differences in surface temperatures at which killing occurred were due to different time lags in reaching a particular internal temperature. It may still be the correct one, but the evidence from the explorations of internal temperatures given here open this view to question.

At least two sources of error in measuring temperatures inside of stems as small as those of Douglas-fir were demonstrated to be serious. These sources are evaporation at the wound, and conduction of heat down the thermocouple wires to cooler zones. As these

errors were brought under better control there was consistently less difference between temperature at soil surface and temperature as measured inside the seedling. Measurements from implanted thermocouples differed little from similar measurements inside a plastic tube filled with water used to simulate a seedling stem. Methanol inside plastic tubes began to boil as soon as the soil surface attained the temperature at which methanol should boil. The transpiration stream was demonstrated to contribute little as a coolant. The evidence for some other biological mechanism that might reduce internal temperatures in a seedling was not found. It appears that temperatures inside a seedling stem at ground level are about the same as outside. The time lag in reaching high temperatures would be very short, probably less than a minute, if no biological mechanism exists to reduce internal temperatures.

All these demonstrations force the undesired conclusion that seedlings may tolerate very high internal temperatures for considerable periods without damage. The field data reveal examples of some seedlings that probably withstood internal temperatures of over 150°F. and many that withstood 138°F. for an hour or more daily. In laboratory tests this conclusion would mean that the interior of a Douglas-fir stem may be at 140°F. for only about three minutes before death occurs under conditions of the dry water bath study. It would also mean that seedlings survive 140°F. internal temperatures up to

50 minutes in peat moss, 120 minutes or more in yellow mineral soil and for four hours or more in white sand without damage. These high internal temperatures at first seem absurd.

If, however, support is sought for such an idea it can be found in the literature. Lorenz (66), for instance, indicates tolerances for such high temperatures over many minutes in cortical cells of several conifers from his vital staining techniques of heat treated thin sections. But results of other studies with water baths place thermal death points lower than those given by Lorenz. In cactus MacDougal (70) even recorded appreciable growth during one and one-half hours exposure to 131°F.

A comparison between results of water bath, ovens, and other methods of determining thermal death points is very revealing. Lowest killing temperatures are seen in water bath studies of roots (85, 62, 87). Immersion of tops (4, 87) and needles (78) show a consistently higher thermal death point at corresponding times. In oven studies, death points are even higher (85, 87), with dry ovens showing higher death points at corresponding times than when high humidities are maintained. Studies using lamps on dry soil show highest temperatures at which killing occurs (4, 25, 79). Similarly, dry heated sand in contact with the seedling stem required equally high temperatures to kill (83). Very high temperatures are withstood by dry seeds (42). The pattern from the literature is not contradictory to the general idea that the measured temperature at which

death occurs changes with each dry material that surrounds the seedling. Thus, the existence of a spectrum of time-temperature relationships is indicated.

If such a range of thermal death points is considered not in terms of temperature, but of calories of heat transferred, the pattern is more consistent. Heat transfer into the seedling immersed in water baths is at maximum rates, and killing occurs at lowest temperatures at a given time interval, following the basic time-temperature curve (Figure 18). Higher water temperatures were required to kill when bark that could restrict the transfer of heat was present on the stems, however (87). In moist ovens, the heat transfer was probably at higher rates than in dry ovens and killing was at lower temperatures, although not as low as in the water bath studies. Studies with dry soils of various kinds, probably involving the slowest heat transfer per unit of environment, extends this same pattern. These required the highest temperatures of all to kill.

But here we run into an anomaly. White sand and yellow mineral soil in the present study had better heat transfer characteristics than peat moss, yet seedlings in peat moss were killed at lower temperatures. At present the reason for this is not definitely established. At best we can speculate that somehow more heat is transferred into or trapped within the seedling at the same surface temperature in peat moss than in white sand. How might this happen?

In all comparisons of temperature the seedling stem behaved in much the same manner as a plastic tube filled with water. If we consider the relative thermal conductivity of a column of water (0.0015 calories per degree across one centimeter per second) it is relatively high compared with peaty soil (0.00015). It is also somewhat higher than thermal conductivity of dry sand (0.0004 to 0.0010) and much higher than motionless air (0.00005). While the above figures from Geiger (32) would only approximate thermal conductivity values for soils used here they do indicate that the seedling stem, acting like a water column, probably furnished an alternative pathway for dissipation of surface heat to cooler layers of air above or to the soil below. In all dry seedbeds, the seedling would be a better pathway than the air in an upward direction or the surface material in a downward direction. In the case of peat moss it should be substantially better than for mineral seedbeds.

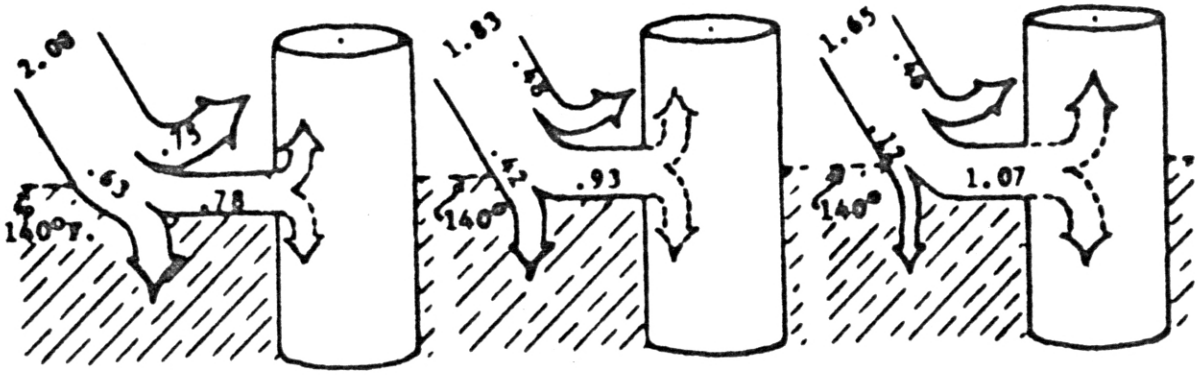
The pattern of heat dissipation upward, whatever the relative proportion of total energy transferred through the seedling stem rather than dissipated through the air, would not be expected to differ greatly from one material to the next. Figure 22 indicates that temperature gradients upward are influenced by the amount of total radiation that is reflected. This may slightly influence the height through the stem that heat is dissipated upward. But since upward dissipation involves air in every case, one would not look in this direction to explain the great differences in killing temperatures between seedbed materials.

In a downward direction, the dissipation of heat from the seedling stem may be greatly different between materials due to relative differences in conduction. In mineral soils heat may be easily lost into cooler layers just below the surface. On the other hand, the insulating qualities of organic materials, because of their high proportions of air space may impede the rapid dissipation of heat. Thus organic seedbeds may either dissipate more heat into the seedling stem, or the stem may retain it for longer distances, or both.

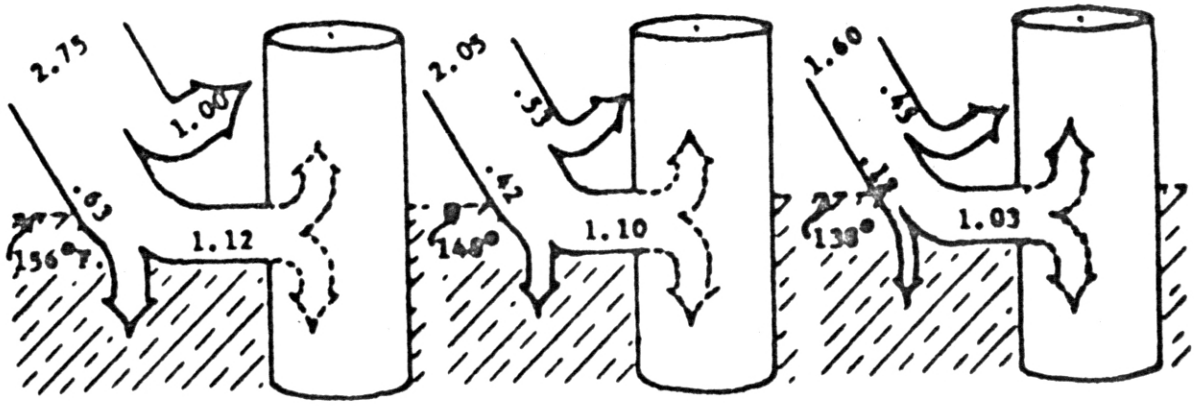
Tested with available caloric values the results seem to confirm this hypothesis. Figures 23 and 24 show schematically the various pathways by which the total radiation is dissipated from the surface of the three materials. In Figure 23, total radiation values are shown that in each case give a surface temperature of 140°F. for the three materials. These are 2.08, 1.83, and 1.65 calories/sq. cm./ min. respectively for white sand, yellow mineral soil and peat moss. The percent of total radiation that is reflected was measured with an inverted pyrheliometer in the temperature gradient. Total radiation reflected was determined to be 36, 26, and 28 percent for white sand, yellow mineral soil, and peat moss, respectively. These percentages were used to compute the total radiation reflected, giving values of .75, .48, and .46 calories/sq. cm./min. Conduction downward was computed using thermal conductivity values of 0.0007, 0.0005, and 0.00015 calories for white sand, yellow mineral soil and peat moss,

Figure 23. Proposed heat transfer pattern for seedlings in three materials at 140°F. surface temperature. Arrows show dissipation of total radiation as reflection, downward conduction, and the amount that could enter the seedling. Under equal surface temperature, peat moss could provide more heat to the seedling than the other materials.

Figure 24. Same as Figure 23 except that surface temperatures and total radiation values are those that are lethal to seedlings after 60 minutes exposure. Under these conditions each seedbed would seem to provide about equal heat to the seedling, even though temperatures and radiation values are greatly different.



WHITE SAND | YELLOW MINERAL SOIL | PEAT MOSS



WHITE SAND | YELLOW MINERAL SOIL | PEAT MOSS

respectively. After consultation of conductivity values from numerous sources the values given for white sand and yellow mineral soil were judged as reasonable and probably conservative values. The value for peat moss is from Geiger (32). Differences between surface temperature and temperature at the depth of one centimeter were estimated from Table 11 as 15°, 14°, and 13°C., respectively. Hence downward conduction calculations gave .63, .42, and .12 calories/sq. cm./min. as values for white sand, yellow mineral soil and peat moss, respectively. Subtraction of energy loss by reflection and conduction leaves calorie values of .78 for white sand, .93 for yellow mineral soil, and 1.07 for peat moss. This represents energy that must be dissipated by convection or through the seedling stem and the highest values are indicated for peat moss when surface temperatures are equal.

In Figure 24 another case is considered. Here the assumption is that energy values at which killing occurs at a given time should be similar. In 60 minutes, seedlings were killed at about 2.75 calories total radiation in white sand. The corresponding value for yellow mineral soil is 2.05 and for peat moss 1.60. A computation similar to the one above indicates that following subtraction of calculated values for reflection and conduction the surface energy caloric value for white sand is 1.12; for yellow mineral soil, 1.10; and for peat moss, 1.03.

Considering the assumptions involved in all these calculations, the values given here are close enough for purposes of illustration.

Where equal surface temperatures are considered, the calculations show higher energies available at the surface in peat moss. When total radiation values correspond to those where killing occurs, the surface energy values are roughly the same in the three materials.

The proof of such an hypothesis depends upon measurements of internal temperatures of seedling stems under conditions of high surface temperature. Until better means of measuring internal temperatures are devised this hypothesis cannot be tested directly.

But even without this detail, it is now clear that a particular surface temperature such as 138°F. means little by itself. It is lethal for Douglas-fir seedlings only if exposed at a certain total radiation for a specified duration, in a particular material of a definite particle size range, at a given moisture content, and arranged or compacted in a certain way. There may be a dozen more qualifications as yet unexplored. Change any factor and 138°F. may or may not be lethal. Thus heat injury is obviously a complex subject—far more so than was envisioned.

With such complexity, studies of individual factors will no doubt eventually lead to an understanding of what occurs in the field. But they are not likely to lead to the goal of so exactly describing the millions of microsites on a clearcut area as to allow accurate prediction of heat losses. For this practical forestry goal the average killing temperature, plus a statistical treatment of the wide

variations from the average, offers the only satisfactory approach. Field sampling of temperature at the microsite level promises to become a useful means of predicting this mortality as our understanding of this variability improves.

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