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Overstory Removal and Residue Treatments Affect Soil Surface, Air, and Soil Temperature: Implications for Seedling Survival

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RESEARCH SUMMARY

Timber harvesting and residue reduction practices that alter shade, surface thermal properties, and moisture influence energy balance and heat transfer on the site, significantly influencing temperatures. Because the problems of mortality to seedlings due to high temperature and insufficient moisture are potentially widespread and expensive, it is crucial to be able to identify problem sites during the planning process.

Following alternative overstory removal and residue reduction treatments at three locations, ground surface temperature maximums increased and minimums declined significantly as the amount of overstory removal increased. Potentially lethal high temperatures (>133 °F) occurred frequently on all sites, while potentially lethal minimum temperatures (<25 °F) occurred on two sites. Potentially lethal temperatures occurred more frequently under treatments involving greater overstory removal. Similar relationships between treatment intensity and maximum and minimum temperatures were observed among alternative surface conditions resulting from residue treatments. In general, maximum and minimum temperatures of burned and litter surfaces in clearcuts were not different, but mineral soil surfaces were significantly different from the litter surfaces under a shelterwood cutting. Temperatures of a chip surface included maximums significantly cooler than that of burned and litter surfaces. Observed mortality of planted seedlings on study sites was consistent with the pattern of potentially lethal temperatures measured on the units.

Clearcutting significantly increased soil temperatures at depths to 16 inches compared to the uncut treatment. Humus temperatures in a shelterwood were intermediate between the clearcut and uncut treatments. Surface condition also significantly altered temperatures at 2 to 16 inches deep. Average temperatures under burned, litter, and chip surfaces were all different; those under burned surfaces were warmest and those under chips were coolest. In general, the pattern of treatment differences in the soil is the same as at the surface. Overstory treatment did not influence air temperature.

If high temperatures or frosts are expected on a site, varying the amount of overstory removal or providing shade by leaving more residues on the surface may reduce the potential for seedling mortality. Scarification of the surface to provide for a mineral soil seedbed will also reduce the potential for high temperatures and, thus, seedling mortality. It is important to be aware of the thermal properties of the surface materials and understand the consequences of leaving plant litter, branches, charcoal, loosened soil, and other materials on the surface. Where the potential for frost pockets exists, cutting units should be laid out so cold drainage is not blocked. Overstory canopies can be effective in reducing the occurrence of midsummer frosts.

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INTRODUCTION

Logging results in microclimate changes that influence seedling regeneration and subsequent forest development. The most significant and immediate microclimate changes are temperature, light, and moisture. Of the many plant processes that are influenced by temperature, light, and moisture (Kramer and Kozlowski 1979; Gates 1980), seedling establishment is one of the most crucial in the early life of a forest stand.

Temperatures from 120 to 140 °F (Hare 1961) may be lethal for first-year conifer seedlings, depending on species (Baker 1929; Silen 1960) and exposure time (Baker 1929; Levitt 1980). Condition of the protoplasm, internal water relations, and tissue mass also influence mortality (Levitt 1980). Baker (1929) stated that the limit of safety was 122 °F for 2 hours. Maximum surface temperatures on south-facing and west-facing slopes in western Montana frequently exceed 138 °F and often 149 °F (Shearer 1967), with maximums reaching 174 °F (Shearer 1981). Lotan (1964) found soil surface temperatures often reached 149 to 167 °F on gentle slopes at high-elevation sites in southwestern Montana and eastern Idaho. Surface temperatures on slash-burned clearcuts in Oregon exceed lethal levels on 69 to 97 percent of the south slopes and nearly 50 percent of the north slopes (Silen 1960; Hallin 1968). The extent (spatially and temporally) of temperatures exceeding lethal levels on sites in the Northern Rockies is not known other than for point-in-time measurements.

High temperatures on exposed soil surfaces cause significant mortality of conifer seedlings (Baker 1929; Silen 1960; Cochran 1969). Shearer (1967) reported that high temperature was the major cause of mortality of first-year western larch (*Larix occidentalis* Nutt.) seedlings on south-facing and west-facing slopes in Montana. In some cases, however, seedlings of lodgepole pine (*Pinus contorta* Dougl.) have survived temperatures of 149 to 167 °F (Lotan 1964). High heat loads created by opening the forest also cause drying of the surface through increased evaporation. As the surface dries, maximum temperatures increase (van Wijk and DeVries 1966; Cochran 1969).

Low temperatures also cause significant mortality of conifer seedlings during the growing season (Cochran and Bernsten 1973; Lotan and Perry 1983). Topography, moisture conditions, and surface thermal properties contribute to the occurrence of frosts (Cochran 1969; Fowler 1974). Lethal low temperatures vary by species from 30 to 14 °F (Cochran and Bernsten 1973; Levitt 1980).

Temperature variation at the surface and in the air layer surrounding seedlings is a function of the heat flux density at the surface and the thermal properties of the seedbed material. Expected temperature variations are described by the amount of heat energy incident upon the surface and how the heat energy is distributed at the surface. The components of heat amount and distribution are described by the equation (Rose 1966; Cochran 1969):

$$G = Rn - H - LE$$

where

G = the heat flux density at the surface
Rn = the net radiation flux density (measure of energy available at the surface)
H = the sensible heat flux density into the atmosphere, including heat dissipated by air currents
LE = heat used in latent heat of vaporization and used in evaporation and transpiration

How G influences temperature variation at the surface and in the soil depends on the volumetric heat capacity (C) and thermal conductivity (K) of the surface and lower soil horizons. A factor ($\sqrt{KC}$) called the thermal contact coefficient (Cochran 1969) integrates these two factors. Temperature variations are inversely proportional to $\sqrt{KC}$. The nature of the material, moisture content, and amount of air space (thus, compaction, texture, and soil type) influence these thermal properties. Temperatures are more extreme on organic surfaces than on mineral soil (Cochran 1969; Fowler 1974). The thermal properties of the seedbed are critically important (Cochran 1969; Fowler 1974). The equation predicts that those practices providing shade (decreasing Rn), allowing for increasing air circulation (increasing H), or decreasing surface evaporation will lower the temperature variation by reducing the amount of heat at the surface or by dissipating the heat before it raises the temperature to lethal levels.

Some degree of shading is helpful in reducing seedling mortality due to high and low temperatures (Shearer 1967; Ryker and Potter 1970; Strothman 1972; Cochran 1975).

Logging residues and vegetation provide shade, which reduces temperature extremes, thus increasing survival (Edgren and Stein 1974).

This paper reports postharvest temperatures at the soil surface (surface-air interface), in the air (to 4.5 ft), and in the soil (to 16 inches) following several levels of overstory removal and for four surface conditions resulting from several residue treatments. Temperatures are compared with adjacent uncut stands and with expected responses based on heat fluxes and thermal properties of the surfaces. Consistency of treatment response is examined by looking at results from three stands in different habitat types. Measured temperatures represent the period immediately following treatment to 8 years later. The potential for seedling mortality, based on high and low temperature data, is compared with actual seedling survival data.

STUDY AREAS AND METHODS

We had two study sites in the Flathead Range of Montana and one in the Gros Ventre Mountains of Wyoming. These sites represent a range of climatic conditions that occur in the Northern Rocky Mountains. May through September precipitation ranges from 25 to 45 percent of the annual amount and varies considerably with topography. Average temperatures also vary considerably throughout the region. Ordination of these three sites along moisture and temperature gradients (fig. 1) is based on growing season May through September precipitation totals and July temperatures. Climax forest series (Pfister and others 1977) are Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.).

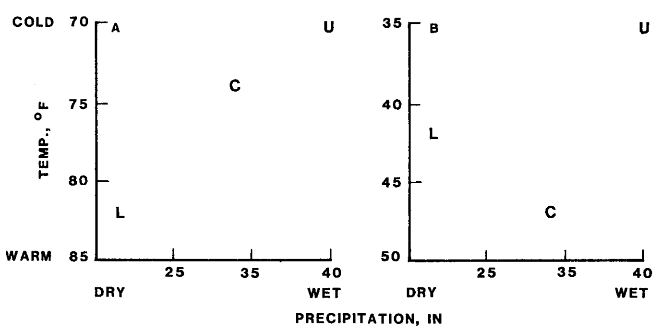


Figure 1—Ordination of study areas—Coram (C), Lubrecht (L), and Union Pass (U)—along a moisture (annual) and temperature gradient based on July average maximum temperature (A) and July average minimum temperature (B).

Treatments

Treatments on the study sites included: (1) a silvicultural prescription requiring overstory removal that varied from none through thinnings, selection cuts, and shelterwoods to clearcutting; and (2) a postharvest residue treatment varying from none to treatments of complete removal, piling, chipping, and burning. Surface conditions of litter, burned, mineral soil, and chips resulting from residue treatments were evaluated (fig. 2). This study is superimposed on a larger study. A description of specific treatments used for each study area follows.

Lubrecht Experimental Forest—This site is about 35 miles northeast of Missoula, MT, at an elevation of 4,000 ft. The terrain is gently rolling (slopes 0 to 5 percent), with west to northwest aspects. Climatic data, taken at the forest headquarters since 1956 (Montana Forest and Conservation Experiment Station 1983), indicate an average annual precipitation of 18 inches. Maximum July air temperatures average 81.6 °F, and minimum July air temperatures average 42.5 °F.

Tree cover prior to treatment was a mixed size and age class Douglas-fir forest. Western larch and ponderosa pine (*Pinus ponderosa* Laws.) were significant components of the stand. This area has a long history of selective logging where merchantable trees were periodically removed from the stands. Habitat type (Pfister and others 1977) is *Pseudotsuga menziesii/Vaccinium caespitosum* (PSME/VACA).

Logging was done in 1977 with ground skidding equipment. The following overstory treatments were compared to the uncut stand:

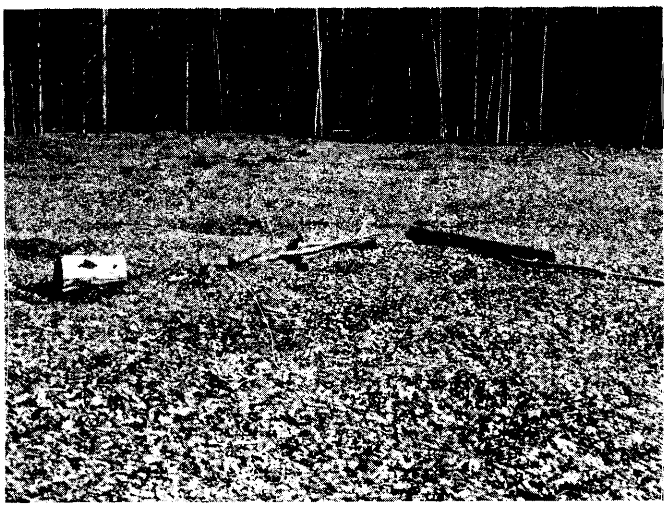
1. **Clearcut**. All merchantable trees were removed on a 15-acre clearcut and the rest of the material was felled, leaving 29 tons per acre of residue.
2. **Understory removal**. Treatment removed about 40 percent of the merchantable volume by cutting the smaller diameter material and leaving the better sawtimber and large pole stems as an overstory. About 18 tons per acre of residue was left on the surface. The residual overstory transmitted about 50 percent of full sunlight.
3. **Shelterwood**. About half of the merchantable volume was removed, leaving an overstory of small sawtimber and pole stems. Dense clumps of saplings and poles were selectively thinned. The residual overstory transmitted about 60 percent of full sunlight. This was a common treatment in this type of stand in 1977.
4. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments on the study units included the following:

1. To simulate close utilization, all residues down to 1 inch in diameter were removed. The small material was bunched by hand prior to skidding. The surface was quite uniform looking after treatment (fig. 2B). Except for skid trails, the understory vegetation was essentially undisturbed. The surface condition used for temperature measurement was a litter surface, made up of small twigs, leaf and needle litter, and duff. About 10 percent of the surface was exposed mineral soil.
2. A pile-and-burn treatment in the shelterwood overstory treatment left most of the surface (except under the piles) in the litter and mineral soil surface conditions with an appearance like the close utilization treatment. The litter and mineral soil surface conditions were used for temperature measurement.
3. Broadcast burning in the clearcut resulted in a 64 percent reduction of slash (Steele 1980) creating a completely blackened area with some mineral soil exposed

(A)

(B)



(C)

Figure 2—Postharvest residue treatments for providing different surface conditions used for temperature measurement: (A) broadcast burning provided the burned surface; (B) close utilization provided the litter surface; (C) residues chipped and spread back on the site provided the chip surface of Union Pass.

(fig. 2A). The surface condition on this treatment used for temperature measurements consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided.

Surface conditions evaluated on each of the overstory and residue reduction treatments are shown in the following tabulation:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization	Burned, litter
2. Understory removal	Close utilization	Litter
3. Shelterwood	Pile and burn	Litter mineral
4. Uncut	—	Litter

Small containerized seedlings of ponderosa pine, Douglas-fir, and western larch were planted each year following treatment (1979 to 1982). In the spring of each year, 23 seedlings were planted in each residue subtreatment within each overstory treatment. A 2- by 2-ft area was scarified around each seedling at the time of planting.

Coram Experimental Forest—This site is 5 miles south of West Glacier, MT, at an elevation of 5,000 ft. All treatments are on east-facing aspects with slopes from 40 to 60 percent. The climatic information for the area (Hungerford and Schlieter 1984) indicates an average annual precipitation of 33 inches at the treatment units. Maximum July air temperatures average 74 °F, and minimum July air temperatures average 47 °F.

Tree cover prior to treatment was a 320-year-old Douglas-fir/western larch forest. The predominant species were Douglas-fir and western larch. Subalpine fir and Engelmann spruce (*Picea engelmannii* Parry) were common, with some western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), western white pine (*Pinus monticola* Dougl.), and paper birch (*Betula papyrifera* Marsh.) present. Habitat type (Pfister and others 1977) is *Abies lasiocarpa/Clintonia uniflora* (ABLA/CLUN), *Clintonia uniflora* phase or *Xerophyllum tenax* phase. At the upper elevations the *Menziesia ferruginea* phase was evident.

Overstory treatments on this study site were:

1. **Clearcut**. Clearcuts ranged from 2 to 17 acres. Logging was completed during 1974 using a running skyline yarder. Prebunched residues were also removed with the skyline yarder. Mechanical scarification was essentially limited to the skyline corridors.

2. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments on the clearcut included the following:

1. Broadcast burning resulted in a 20 percent duff reduction (Artley and others 1978). High water content in the duff layer was responsible for not reaching prescription levels of 50 percent mineral soil exposed. The surface condition used for temperature measurement consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided. Burning was done in early September 1975.

2. To simulate close utilization, all residues down to 1 inch in diameter were removed. Except for skyline corridors, the understory vegetation was essentially undisturbed. The surface was a mosaic of vegetation and exposed litter surfaces. The surface condition used for temperature measurement was a litter surface made up of small twigs, leaf and needle litter, and duff. Little mineral soil was exposed. The following tabulation shows the surface conditions evaluated for each overstory and residue reduction treatment:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization	Burned, litter
2. Uncut	—	Litter

Annually for 4 years following both treatments, 25 bare root (2-0) seedlings of Douglas-fir and Engelmann spruce were spring planted. Survival and growth measurements were made periodically.

Union Pass—This site is 40 miles southwest of Dubois, WY, on the Bridger-Teton National Forest at an elevation of 9,200 ft. Slope ranges from 5 to 20 percent on an east aspect. Climatic data for this area are not available, and the nearest stations are considerably lower in elevation. Correcting for elevation and slope, annual precipitation is estimated to be 35 to 40 inches. Mean July maximum air temperature is about 70 °F, and mean July minimum air temperatures are 35 to 40 °F.

Tree cover prior to treatment was overmature lodgepole pine (160 years old) with small amounts of Engelmann spruce, subalpine fir, and limber pine (*Pinus flexilis* James). Habitat type (Steele and others 1983) is *Abies lasiocarpa/Vaccinium scoparium* (ABLA/VASC). Understory vegetation was sparse.

Overstory treatments on this study site were:

1. **Clearcut**. Clearcutting was done in 1971 using a feller buncher and ground skidding (Benson 1982).

2. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments within the clearcut included the following:

1. Broadcast burning, done 2 years after logging (spring 1973), resulted in 30 percent mineral soil exposed and reduction in litter depth from 1 inch to 0.71 inch (Benson 1982). The surface condition used for temperature measurement consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided.

2. To simulate close utilization, all residues down to 1 inch in diameter were removed. This treatment exposed mineral soil on 42 percent of the surface and reduced the understory vegetation cover considerably. After treatment, 19 tons per acre of woody material remained. The surface condition used for temperature measurement was a litter surface made up of small twigs, leaf and needle litter, and duff.

3. On half of the close-utilization treatment area, an amount of residue equivalent to that removed was chipped and spread back on the site (fig. 2C). The average depth of the chips was about 4 inches. No mineral soil or vegetation was exposed. The surface of the chips was used as the surface condition for temperature measurement.

Surface conditions evaluated on each of the overstory and residue reduction treatments are shown in the following tabulation:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization, chips spread	Burned, litter, chips
2. Uncut	—	Litter

Bare root (2-0) seedlings of lodgepole pine were planted in the spring the first year after treatment on all treatments. Spot seeding was also done. At the time of planting and seeding, 18-inch square areas were scarified around each spot or seedling.

Measurements

Surface, air, and soil temperature were monitored for the overstory treatment and surface conditions described for each study area. Specific temperature measurements taken for each study site and treatment combination are shown in the tabulation for each study area and in table 1. The time and duration of measurements by site are shown in table 2. The term "surface" is used to indicate the surface exposed to the atmosphere, whether the exposed material is litter, ash (from burning), mineral soil, or chips. Measured surface temperatures are actually 0.04 to 0.08 inch below the true surface. Temperature sensors were installed close to the surface by covering with one layer of the surface material—for example, one leaf, one thickness of needles, one layer of soil (enough to cover the metal), or one layer of chips. It was necessary to frequently visit the sensors and reset them if they were uncovered. Air temperature sensors at 4.5 ft above the surface at Lubrecht and Coram were placed in standard Cotton Region type shelters.

At Union Pass, air temperatures were measured at 8 inches and 4.5 ft above the surface. Sensors were placed in specially constructed shielded tubes. Soil temperatures in the humus layer at 0.4 to 1.2 inches below the surface were measured at Lubrecht and Coram. Temperatures in mineral soil at 2, 8, and 15.7 inches deep were measured at Union Pass. Sensors at Union Pass were pushed horizontally into the undisturbed soil of the wall of a hole dug to the proper depth, which was then backfilled.

Table 1—Temperature measurements taken by study site, overstory, and surface condition

Measurement location	Study site								
	Lubrecht			Coram			Union Pass		
	Surface	Air	Soil	Surface	Air	Soil	Surface	Air	Soil
Overstory treatment:									
Uncut	x	x	x	x	x	x	x	x	x
Clearcut	x	x	x	x	x	x	x	x	x
Shelterwood	x	—	x	—	—	—	—	—	—
Understory removal	x	—	—	—	—	—	—	—	—
Surface condition:									
Litter	x	—	—	x	—	—	x	x	x
Mineral soil	x	—	—	—	—	—	—	—	—
Burned	x	—	—	x	—	—	x	x	x
Chips	—	—	—	—	—	—	x	x	x

Table 2—Length of time following treatment that temperatures were measured by study site

Study site	Years following treatment						
	1	2	3	4	5	6	7
Lubrecht	x	x	x				
Coram	x	x	x	x	x	x	x
Union Pass[1]						x	

[1]Temperatures were measured for only 1 year.

Temperatures were measured using small, 0.064-inch diameter, thermistor beads inserted in 0.094-inch diameter by 0.5-inch long stainless steel tubing. Shielded 30-gauge wire attached to the thermistor ran 6 to 10 ft to a junction box. Multiconductor cables (18-gauge) up to 2,500 ft long were connected from the junction box to a recording data acquisition system. Each data acquisition system handled from 16 to 40 temperature sensors. Temperatures were recorded hourly on a 12-month basis for varying lengths of time (table 2).

Net radiation was measured on all sites for some of the treatments. Continuous monitoring of net radiation was done for the clearcut and uncut treatments at Coram for 4 years and at Lubrecht for 3 years. Net radiation measurements were also made over each of the surface treatments at noon on a clear day at Lubrecht and Union Pass. These data are used in the discussion to help explain how treatments affect temperature.

Analysis

Analysis of research results involved: (1) evaluating effects of overstory removal treatment on surface, air, and soil temperatures; and (2) evaluating effects of surface condition, resulting from residue treatments on surface, air, and soil temperatures. The discussion of results is presented in that order. Because treatment effects are influenced by the elevation, terrain, and climatic characteristics of the specific locations studied, results are also generally presented separately for the three study sites. As discussed earlier, the range of overstory treatments and surface conditions, as well as temperature observations, also varies by site. Consequently, between-site comparisons are necessarily limited.

To evaluate treatment effect on surface temperature, we used two types of summaries: (1) monthly average maximum and minimum temperatures were calculated, and (2) the occurrence of potentially lethal temperatures—referred to as hot events and cold events—was tabulated. Statistical tests (to be described later) determined treatment differences for maximum and minimum temperature by month for May through October. The percentage of months, over the measurement period, that differences were significant was then compared for the overstory treatments and surface conditions.

We calculated the number of hot events and cold events based on surface temperatures, then used these to indicate the hazard for seedling mortality. A hot event (HE) is defined as 2 or more consecutive hours of temperatures that are greater than 122 °F or 1 hour at 133 °F or higher. A cold event (CE) is an occurrence of minimum temperature of 23 °F or colder. These thresholds—122, 133, and 23 °F—were picked to represent average lethal levels for several tree species (Baker 1929; Hare 1961; Levitt 1980). The HE's and CE's are summed over the growing season, then used to calculate the percentage of days that they occurred within the period. Neither the HE nor the CE is intended to suggest that seedling mortality will invariably result from these events, but they do represent a significant hazard to survival. We then compared HE and CE data with measured seedling survival on the study areas.

To evaluate treatment effect on air temperatures, we used daily maximum and minimum values and average day and night temperatures. We used the day and night average temperatures because they influenced growth of tree seedlings (Cleary and Waring 1969; Hellmers and others 1970).

Because soil temperatures are much more stable than surface or air temperatures, daily averages were used to compare treatments at depths below 2 inches. Temperatures in the humus layer (0.4 to 2.0 inches deep) are included in the results as soil temperatures. Analysis of the humus layer includes maximum and minimum temperatures and HE's and CE's. Temperatures in the root zone are discussed relative to their effects on seedling growth and root development.

Tests for significant treatment effects on surface temperature were made using one-way analysis of variance to determine if treatments were different for maximum and minimum temperatures (by month). Also, tests of treatment differences in air and soil temperatures were evaluated using one-way analysis of variance. Analyses were run only for data from May through October. Duncan's multiple range test was used to test for individual treatment differences. If variances were not homogeneous, we used approximate *t*-tests. All tests were done at the 0.05 significance level. Differences in the overstory removal treatments were compared using temperatures measured on the litter surface condition of each treatment. Differences between the surface conditions were compared using a common overstory removal treatment (usually the clearcut). Mineral soil and litter surface conditions at Lubrecht, however, were compared in the shelterwood treatment.

OVERSTORY REMOVAL AND TEMPERATURE

Surface, air, and soil temperature data accumulated from treated units were analyzed first to evaluate the effects of level of overstory removal on temperature. To compare overstory treatments on a common basis, data from the litter surface condition were used.

Surface Temperature

Lubrecht—The amount of overstory removal significantly influenced maximum surface temperatures, mean monthly maximum surface temperatures being significantly warmer where all or most of the canopy was removed (table 3). From May through October of the first 3 years after harvesting, temperatures on the clearcut surface were significantly warmer than those on the shelterwood surface 40 percent of the months, were equal for 40 percent of the months, and were significantly lower for the other months. Over the 3 years, surface temperatures on the clearcut and shelterwood treatments were significantly warmer for 80 percent of the months than were surface temperatures on the understory removal or uncut treatments. Surface temperatures on the understory removal for some months were up to 11 °F warmer than on the uncut, but for 60 percent of the months differences were not significant.

Maximum surface temperatures were observed as high as 165 °F and often exceeded 133 °F (fig. 3) for the clearcut and shelterwood treatments. Temperatures of 122 °F

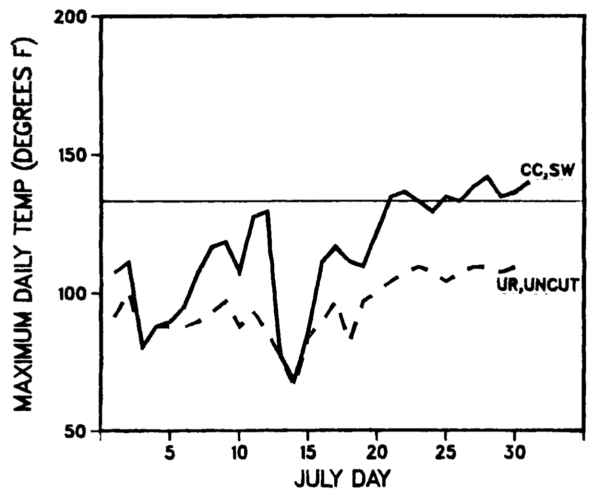


Figure 3—Maximum daily ground surface temperatures in July 1980 at Lubrecht for the clearcut (cc), shelterwood (sw), understory removal (ur), and uncut treatments. Surface condition is litter. The horizontal line through the graph is 133 °F, a seedling survival threshold.

Table 3—Average maximum surface temperatures (°F) by month for 1978, 1979, and 1980 for the overstory treatments at the Lubrecht study site. Data from the litter surface were used for all treatments. Values for a month (months are not compared) having different letters are significantly different at the 0.05 level.

Overstory treatment	May	June	July	Aug.	Sept.	Oct.
		1978				
Uncut	61a	90a	102a	95a	75a	75b
Understory removal	72b	100b	106a	86a	77a	61a
Shelterwood	72b	106b	126b	117b	93b	79b
Clearcut	93c	126c	138c	118b	97b	93c
		1979				
Uncut	66a	75a	—	—	93a	68a
Understory removal	77b	86a	—	—	91a	70a
Shelterwood	82b	100b	—	—	126c	84b
Clearcut	104c	126c	—	—	113b	81b
		1980				
Uncut	—	86a	104a	99a	70a	61a
Understory removal	—	88a	95a	102a	81b	64a
Shelterwood	—	93ab	115b	127c	100c	79b
Clearcut	—	97b	115b	118b	82b	70ab

Table 4—Average minimum surface temperatures (°F) by month for 1978, 1979, and 1980 for the overstory removal treatments at the Lubrecht study site. Data from the litter surface were used for all treatments. Values for a month (months are not compared) having different letters are significantly different at the 0.05 level.

Overstory treatment	May	June	July	Aug.	Sept.	Oct.
			1978			
Uncut	34b	39b	43b	41b	37b	27b
Understory removal	35b	38b	41b	39b	36b	24b
Shelterwood	36b	40b	44b	41b	38b	26b
Clearcut	26a	30a	35a	34a	28a	12a
			1979			
Uncut	34b	37b	—	—	37c	36c
Understory removal	34b	36b	—	—	33b	26b
Shelterwood	34b	36b	—	—	36bc	28bc
Clearcut	25a	29a	—	—	25a	17a
			1980			
Uncut	—	44b	45c	40c	38b	30b
Understory removal	—	47b	45cd	38b	39b	28b
Shelterwood	—	47b	47d	40bc	39b	31b
Clearcut	—	40a	38b	32a	33a	23a

or greater were measured from April (12 days after snowmelt) into October. Maximums on the understory and uncut treatments rarely exceeded 122 °F. Figure 3 is representative of the patterns observed for most summer months over the 3 years.

The degree of overstory removal also significantly affected minimum surface temperature (table 4). Removal of up to about 50 percent of the overstory (understory removal and shelterwood) did not cause minimum temperatures to fall lower than in the uncut stand. However, removal of all the overstory caused minimum temperatures to be significantly lower than on the shelterwood, understory removal, or uncut treatments for all months.

Minimum temperatures on the clearcut in 1978 were as low as 18 °F in June, 25 °F in July, and 21 °F in August. By September nearly every night was below 32 °F, with a low of 10 °F. Temperatures below 32 °F were not observed on the shelterwood or uncut treatments, and only occasionally on the understory removal treatment in June, July, or August (fig. 4).

The same pattern seemed to exist in 1979, but instrument failure precluded records in July and August. The summer of 1980 was warmer; no temperature below 32 °F was recorded in July.

Hot event days, when the temperature exceeded the lethal threshold, occurred on the clearcut and shelterwood treatments from May through October on 14 to 37 percent of the days (table 5). The probability of an HE was greater on the clearcut, but the difference is not significant. No HE's occurred on the understory removal treatment, and only three were measured on the uncut control over the 3 years. These results suggest that the potential for seedling mortality due to high temperatures is quite high on the clearcut and shelterwood treatments, but almost nonexistent in the uncut stand and on the understory removal treatments.

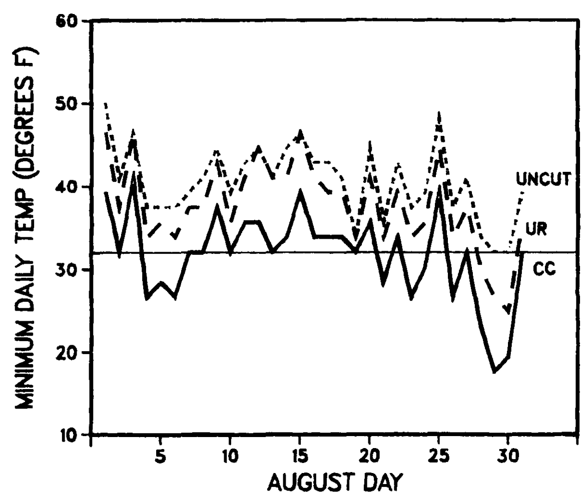


Figure 4—Minimum daily ground surface temperatures in August 1980 at Lubrecht for the uncut, understory removal (ur), and clearcut (cc) treatments. Temperatures in the shelterwood (sw) were the same as the understory removal. The surface condition was litter.

On the surface of the clearcut, cold event days—when the temperature dropped to the lethal threshold of 23 °F or below—occurred on 16 to 26 percent of the days in May through September the first 2 years after treatment. During the third year none occurred on the clearcut. During the 3 years following treatment, only one CE occurred on the uncut and understory removal treatments and none on the shelterwood treatment. Most of the CE's occurred in May and September (75 to 80 percent), but a significant number occurred in June, July, and August. Like the HE's, the results show that a potential for seedling mortality due to low temperatures exists on the clearcut treatment.

Table 5—Hot events (percentage of possible days) for the overstory treatments at several study sites. Data represent the May through October period for 1 to 7 years after treatment. Data for the litter surfaces on the clearcut were used when they were available. If not, data from the burned surface were used.

Study site	Overstory treatment	Years after treatment						
		1	2	3	4	5	6	7
		Percentage of possible days						
Lubrecht	Uncut	1	0	2	—	—	—	—
	Understory removal	0	0	0	—	—	—	—
	Shelterwood	14	16	25	—	—	—	—
	Clearcut	28	37	23	—	—	—	—
Coram	Uncut	2	0	0	—	—	—	—
	Clearcut	36	27	23	29	29	6	1
Union Pass	Uncut						0	
	Clearcut						65	

In summary, the clearcut treatment on the Lubrecht site creates conditions with a high potential for seedling mortality due to high and low temperatures. The shelterwood treatment had a high potential due to high temperatures but not to low temperatures. The residual stand canopy in the shelterwood is open enough to let incident radiation warm the surface, yet it is dense enough to hold heat in at night, slowing radiational cooling. Maximum and minimum temperatures in the understory and uncut treatments typically are not high enough or low enough for potential seedling mortality. Figure 5 shows the maximum and minimum temperature relationships for each treatment on a typical summer day.

Other Sites—Only data for the clearcut and uncut treatments are available on the other two sites. Data from the Coram and Union Pass study sites also demonstrate that clearcutting results in significantly warmer and colder surface temperatures. Data on HE's at Coram and Union Pass (table 5) are comparable to the results observed at Lubrecht. The potential for seedling mortality (due to high temperatures) is quite high on the clearcut and low in the uncut stand. The frequency of HE's is high (65 percent) at Union Pass; only data for the month of July are available. Logging significantly increased the potential for seedling mortality at Coram and Union Pass.

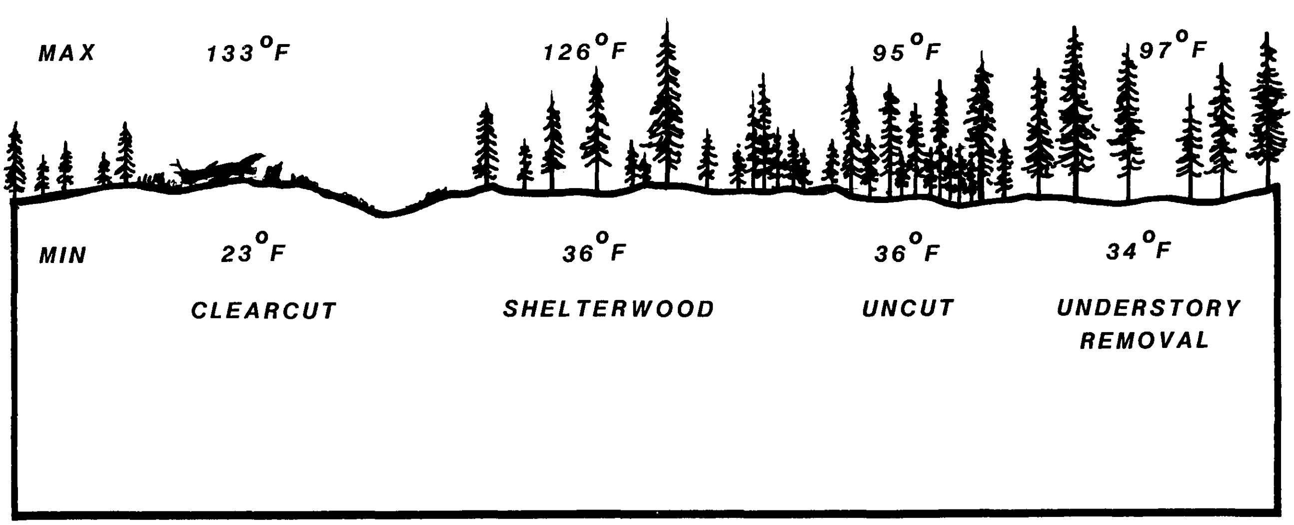


Figure 5—Daily maximum and minimum surface temperatures (°F) by overstory treatment at Lubrecht, August 29, 1978.

Minimum surface temperatures at Coram and Union Pass were significantly colder on the clearcut treatment. Results for these two sites between the clearcut and uncut follow the same pattern as at Lubrecht. Average minimum temperatures are warmer for Coram than for Lubrecht. This appears to be a result of topographic differences.

At Coram the CE's following clearcutting were not as frequent as at Union Pass. The frequency of CE's was low at Coram, and they occurred only in May or September—none in June, July, or August. The frequency of CE's varied from 0 to 45 percent of the nights in July at Union Pass. The effect of surface condition is discussed later.

Comparison With Expected Results—The results reported here are consistent with and explained well by the energy balance equation. The major effect of the overstory removal treatments was to increase energy incident upon the surface (*Rn*) (fig. 6). Increased *Rn* causes an increase in the heat flux density at the surface (*G*). Changes in convective heat loss (*H*) and latent heat loss by evaporation and transpiration (*LE*) are not able to dissipate the added heat, which results in increased temperature variation at the surface. Although the temperature differences were not significant for all treatments for all months, the trend of increasing growing season surface temperatures with increasing levels of canopy removal was observed (table 3 and fig. 3). The effects of vegetation influence on shade will be discussed under the surface condition section.

Because the surface condition of all treatments for the overstory removal comparisons is the same (litter), the thermal properties did not significantly influence the temperature differences. Higher surface temperatures on the clearcut and shelterwood treatments not only increase the potential for seedling mortality due to high temperatures, but also are effective in drying the surface layers, which creates additional moisture stress. The drier surface conditions in turn lower volumetric heat capacity and thermal conductivity, which further increases temperature variation.

Minimum surface temperatures for the treatments are also explained well by the same factors (table 4 and fig. 4). The more exposed surfaces, where more of the canopy has been removed, are subject to greater radiational cooling and thus lower temperatures. On the shelterwood treatment that admits about 60 percent of full sun, the canopy is sufficient enough to limit radiational cooling, which explains the absence of CE's, and to reduce the potential mortality due to low temperatures. In addition to the effect of the *Rn* term, topographic conditions at Lubrecht and Union Pass are such that cold air can accumulate, creating frost pockets. In these cases the *H* term is affected. More will be said about this in the discussion of the surface conditions.

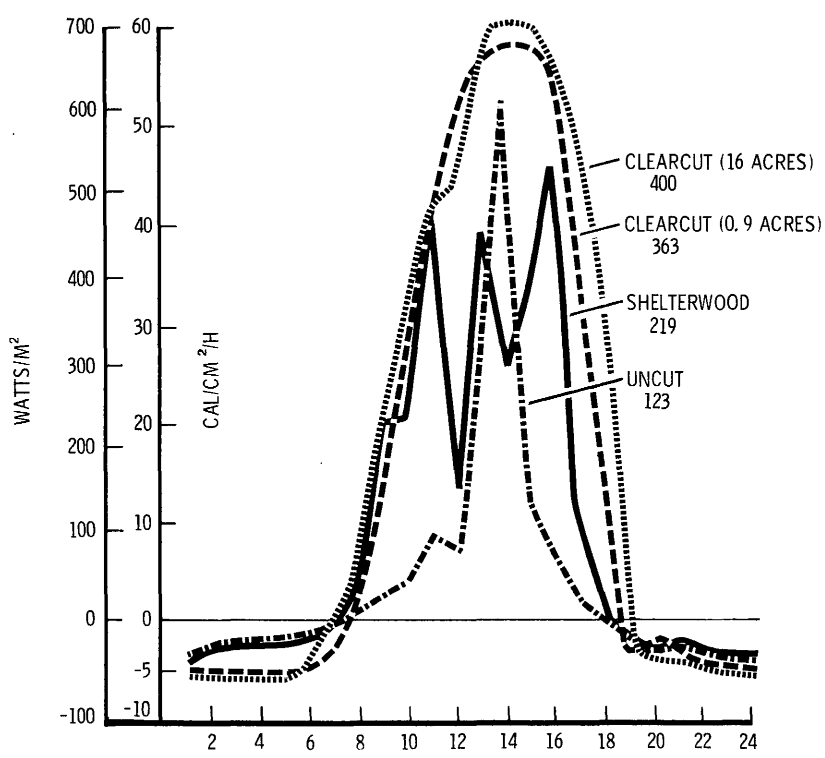


Figure 6—Diurnal variation in net radiation by cutting method on June 18, 1976, Coram Experimental Forest. Daily totals are given for each treatment in cal cm^{-2}.

Air Temperature

Air temperatures at 4.5 ft above the surface in clearcut units were not significantly warmer than above the surface in uncut units at any of the sites. Comparison using accumulative degree days over the May through October season did not reveal significant differences either. Data from Coram and Union Pass show that topographic position influences air temperature much more than clearcutting. Monthly average minimum temperatures in openings at the toe of a slope were 5 to 12 °F cooler than openings a few hundred feet up the slope (fig. 7). Monthly average maximum temperatures were at least as warm at the toe of the slope as in openings on the slope.

Soil Temperature

Lubrecht—Daylight average and maximum temperatures in the humus (O_2) layer 0.4 to 1.2 inches deep at Lubrecht over the 3 years were significantly warmer on the clearcut than in either the shelterwood or uncut treatments (fig. 8). Humus in the shelterwood was significantly warmer than in the uncut. Maximum humus temperatures were as high as 136 °F on the clearcut, and July average maximum was about 115 °F. The HE's occurred, but were not frequent (10 during the 3 years). Maximums on the shelterwood were nearly as high at 131 °F, with a July average maximum of 111 °F in 1978. Temperatures were much colder in 1979 and 1980, with a July average of about 86 °F. Only three HE's occurred in the shelterwood, all in 1978. The maximum humus temperatures on the uncut site were 91 °F.

Minimum and night average humus temperatures were significantly colder on the clearcut than in the shelterwood or uncut treatments. Minimum humus temperatures observed (May through September) were 18 °F in the clearcut and 21 °F in the shelterwood. Average July minimums were 43 °F in the clearcut and 50 °F in the shelterwood and uncut treatments.

Other Sites—Humus or upper level soil temperatures at Coram and Union Pass were measured at depths from 1.2 to 2.0 inches. Absolute maximum temperatures ranged from 73 to 90 °F in the clearcut and were significantly warmer than in the uncut treatments. Night minimums at Coram in the clearcut were not significantly colder than in the uncut. The clearcut at Union Pass was significantly warmer at night than the uncut for the short measurement period. We do not know the reason for this reversal, yet the 24-hour cumulative number of degree hours—those greater than 32 °F—is 80 percent higher in the clearcut than in the uncut.

Soil temperatures at depths from 2 to 16 inches were only measured on clearcut and uncut treatments at Union Pass. Temperatures at these depths were significantly warmer in the clearcut than in the uncut. Temperatures at 2 inches deep averaged nearly 12 °F warmer in the clearcut broadcast burn than in the uncut, 11 °F at the 8-inch depth, and almost 10 °F more at the 16-inch depth (fig. 9).

Summary

Temperatures increased from the ground surface to depths of 16 inches as a result of clearcutting. Site location has little or no effect on the treatment differences, though the maximums and average temperatures are higher at some locations. The magnitude of differences decreases with increasing depth, yet the differences remain statistically significant.

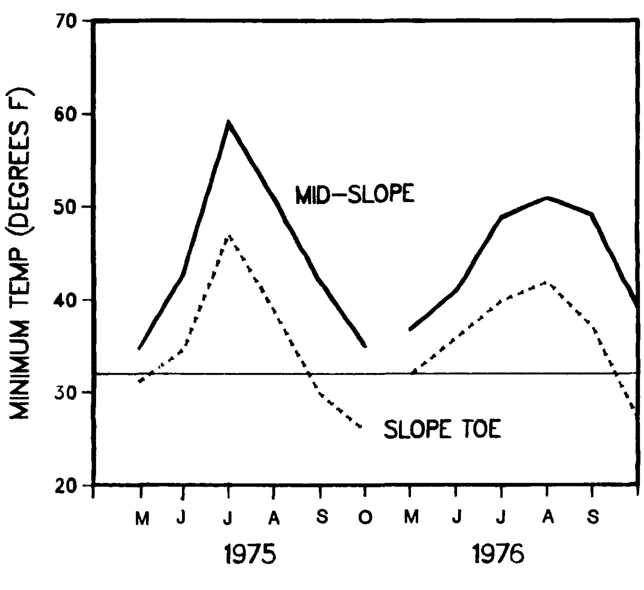


Figure 7—Mean monthly minimum air temperatures at the toe of a slope and at midslope on the Coram Experimental Forest. Temperatures are for May through October of 1975 and 1976.

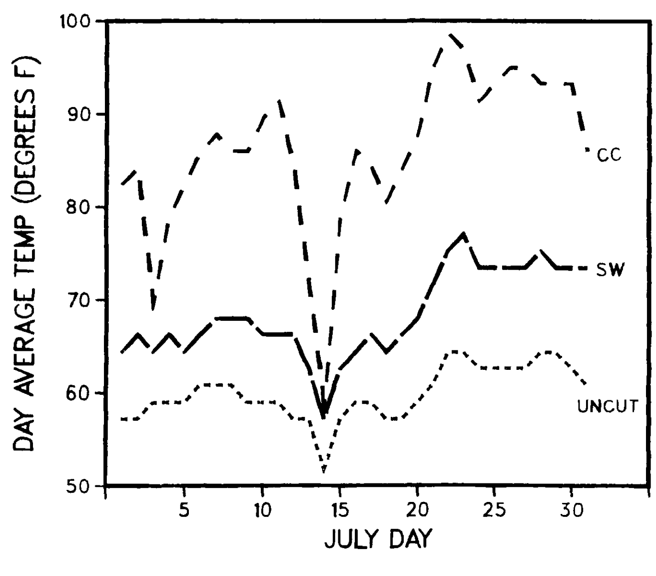


Figure 8—Daylight average temperatures of the humus (O_2) layer (0.4 to 1.2 inches depth) on the clearcut (cc), shelterwood (sw), and uncut treatments at Lubrecht in July 1980. Surface condition was litter.

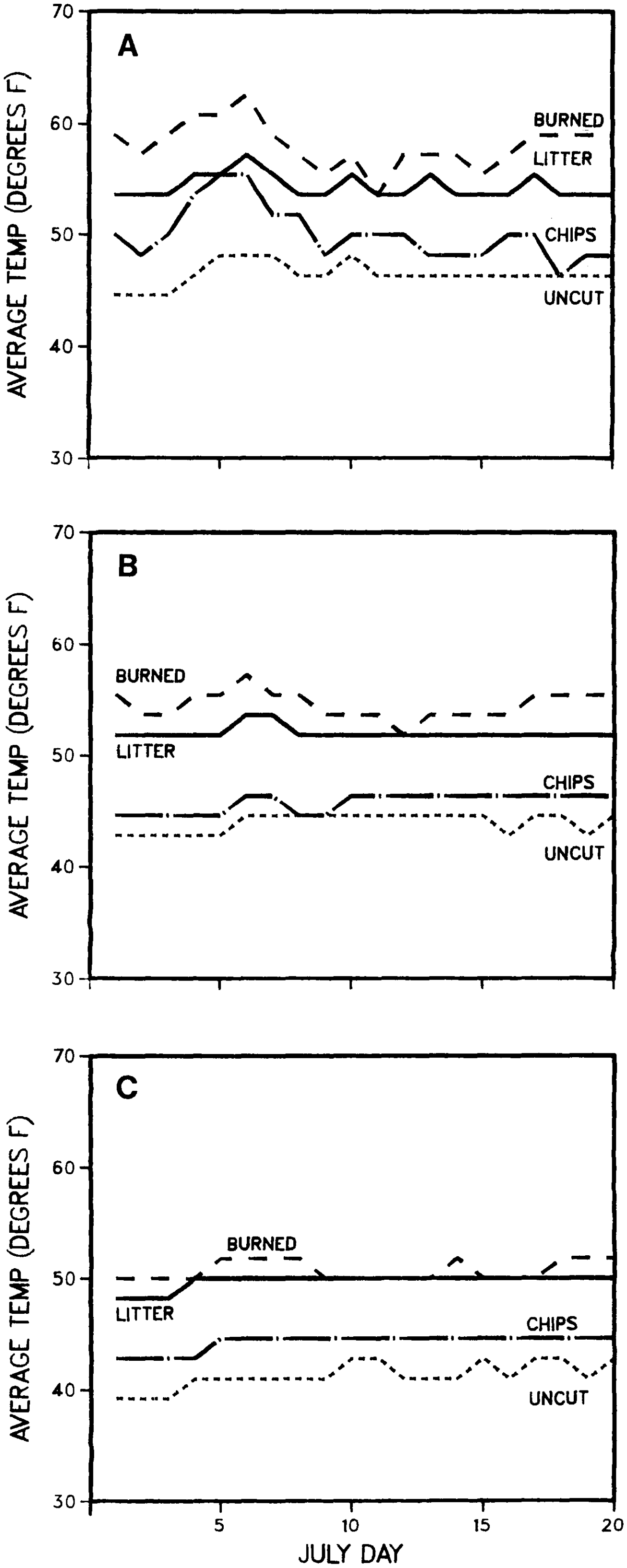


Figure 9—Average soil temperatures at depths of 2 inches (A), 8 inches (B), and 16 inches (C) for burned, litter, and chip surface conditions in clearcut and uncut treatment units. Data are from Union Pass in July 1979.

These results for soil temperature seem to be explained well by the effects of Rn as influenced by overstory removal. Although $\sqrt{KC}$ affects the rate of conduction and associated temperature changes, this factor was overwhelmed by the differences in Rn at the surface of the treatments. These effects will be discussed in more detail for the surface conditions.

SURFACE CONDITION AND TEMPERATURE

Surface conditions resulting from residue treatment included litter, burned, mineral soil, and chips. The effect of surface condition on surface, air, and soil temperatures is examined by comparing temperatures for the different surface conditions under the same overstory treatments. The clearcut was used for all but one comparison. The shelterwood treatment is used in that one.

Surface Temperature

Lubrecht—Maximum surface temperatures on both the burned and litter surfaces in the clearcut were greater than 133 °F during midsummer (fig. 10). For the first 2 years after burning, average maximum (monthly) temperature on the burned surface was 9 to 16 °F greater than on the litter surface. For 57 percent of the months for May through October, these differences were significant. After 2 years, a heavy stand of bull thistle and its thistledown on the burned treatment provided enough shade to decrease surface temperatures below those on the litter surface.

Hot events occurred on the burned and litter surfaces from 17 to 37 percent of the days from May through October (table 6). The HE's were observed for more than 30 days each year after burning on both litter and burned surfaces, even though instrument difficulties resulted in 45 days when temperatures could not be measured.

Minimum temperatures were not significantly different for the burned and the litter surfaces for most months. After the thistle crop developed on the burned treatment, minimum temperatures were significantly warmer on the burned surface than on the litter surface. Both the litter and burned surfaces had significant numbers of CE's in 1979—the first year after burning. Cold events were observed on 42 percent of the days on the litter surface and 26 percent of the days on the burned surface from May through September. Only two CE's were observed on the litter surface in 1980 and none on the burned surface. Climatic conditions and vegetation regrowth were the likely causes of reduced CE's in 1980.

In the shelterwood, average maximum surface temperatures of exposed mineral soil were significantly lower—5 to 34 °F—than temperatures of the litter for 75 percent of the months over the 3 years. Average maximum temperatures on the mineral soil surface never exceeded 100 °F. Difference between the litter and mineral surfaces was least in May and October and greatest in July (fig. 10). Hot events on the litter occurred from 14 to 25 percent of the days, but no HE's occurred on the mineral soil surface during the measurement period. Average minimum temperatures were 1 to 4.5 °F colder on the litter surface

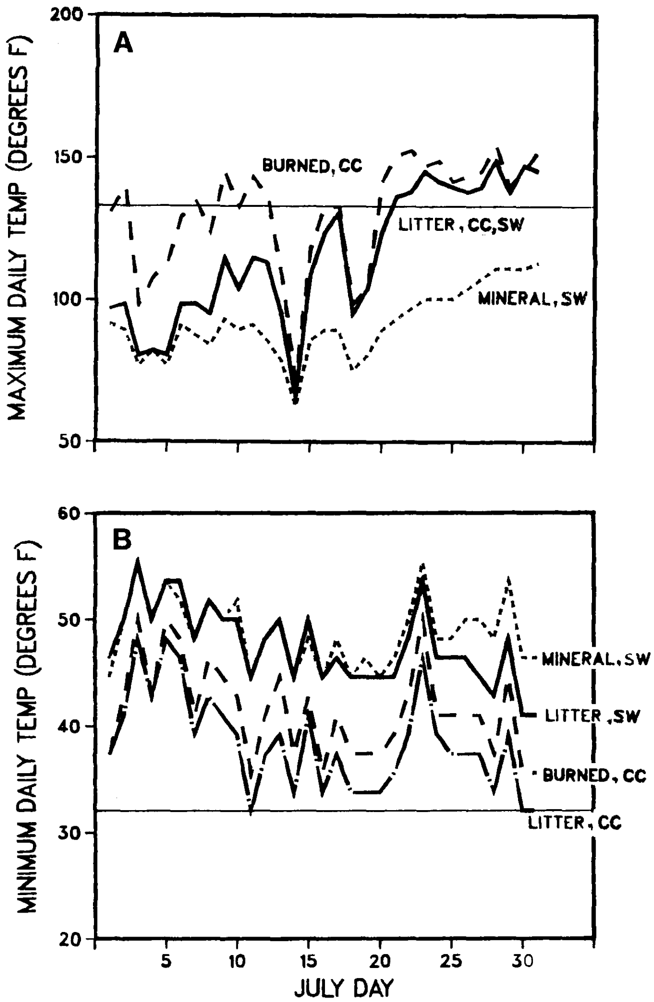


Figure 10—Maximum (A) and minimum (B) daily temperatures of burned, litter, and mineral soil surfaces at Lubrecht in July 1980. Burned surface was measured in the clearcut (cc) and mineral in the shelterwood (sw). Maximum litter temperatures were the same in clearcut and shelterwood. Horizontal line for maximum temperatures (A) is at 133 °F—a seedling survival threshold.

Table 6—Hot events (percentage of possible days) by surface condition at the Lubrecht site. Data are for the months of May through October.

Residue treatment	Years after logging 1	2	3
	--- *Percentage of possible days* ---		
Burned surface (clearcut)	—	[1]37	[2]23
Litter surface (clearcut)	27	19	17
Litter surface (shelterwood)	14	16	25
Mineral soil (shelterwood)	0	0	0

[1]First year after burning.
[2]Second year after burning.

than on the mineral soil surface. These differences were significant for only 33 percent of the months. No CE's were observed on the mineral soil or litter surfaces in the shelterwood treatment, mostly because of the overstory canopy. Because the mineral soil surface measured was in the shelterwood treatment, it could not be directly compared to the burned surface in the clearcut; minimums were much warmer in the shelterwood than on the clearcut.

These results indicate a definite contrast between temperatures on organic (burned and litter) surfaces and mineral soil. Because the maximum and minimum temperatures of litter and burned surfaces are similar, the probability of temperature-related seedling mortality may be similar. Lower maximum and higher minimum temperatures on the mineral surface suggest that temperature-related seedling mortality would be lower than on the litter surfaces.

Coram—Only litter and burned surfaces in the clearcut are compared here. From the first through the fourth years after burning, average maximum temperatures on the litter surface were significantly warmer than on the burned surface for 79 percent of the months (May through October). During the fifth and sixth years after burning there were no differences between treatments. Data from another clearcut at Coram, for a shorter period, showed the same results.

Hot events were observed mostly in the first year on the burned surface, and then only on 5 percent of the possible days. The litter surface had 24 to 42 percent of the days with HE's from the first through fourth years. After the fourth year HE's were rare—4 percent or less on the litter surface and only 1 percent on the burned surface.

Minimum temperatures on the burned and litter surfaces at Coram varied from being equal to being 10 °F colder on the litter during the first 4 years after burning. Mean monthly minimum litter surface temperatures were significantly colder for 86 percent of the months by 2.7 to 5.4 °F. Cold events were not observed on either surface for any year.

Union Pass—Burned, litter, and chip surface conditions are compared on the clearcut. Average maximum temperatures were not significantly different between the burned and litter surfaces 6 years after treatment. Hot events were observed on 62 percent of the days for both treatments in July. Maximum temperatures measured on the chip surface were significantly cooler—13 °F—than on the litter or burned surfaces (fig. 11). The HE's were observed 10 percent of the July days on the chip surface.

Average minimum temperature for July was significantly colder on the litter surface than on the burned surface and colder on the chip surface than on either the litter or burned surfaces (fig. 11). Cold events in July were observed on the litter surface 10 percent of the nights, on the chip surface 43 percent, and not at all on the burned surface. These differences in minimum temperatures and CE's are due more to slope position, which demonstrates the effect of cold air drainage (fig. 12).

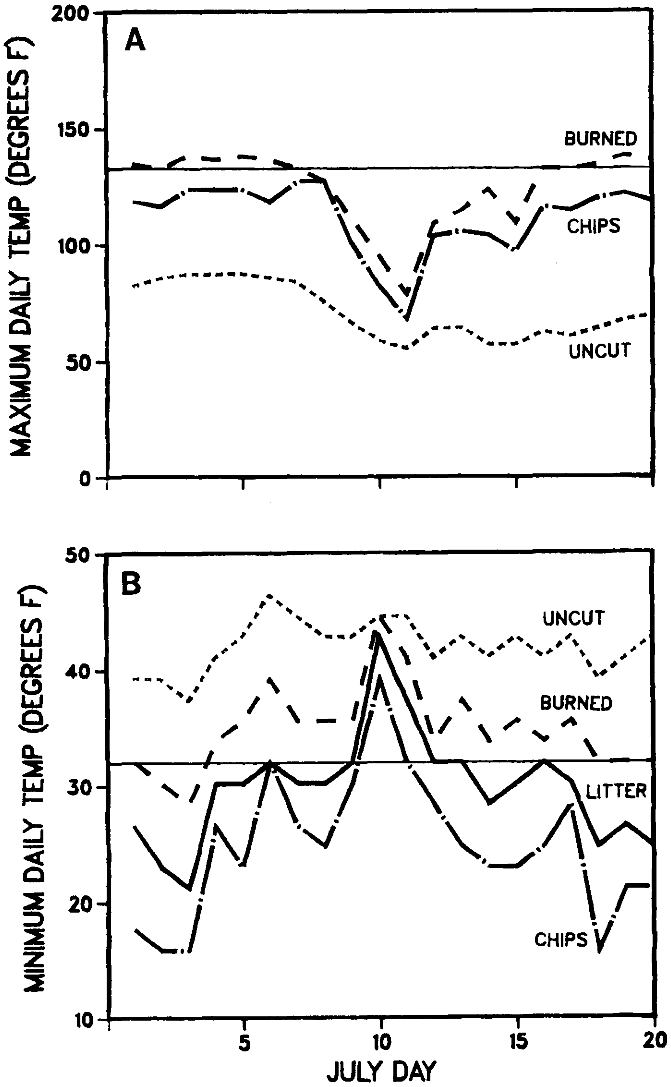


Figure 11—(A) Maximum daily temperatures on burned, chips, and untreated surfaces. Litter surface is same as burned. (B) Minimum daily temperatures on untreated, burned, litter, and chip surfaces. Data are from Union Pass in July 1979. Burned, litter, and chip surfaces are in the clearcut. Horizontal line for maximum temperatures (A) is at 133 °F, a seedling survival threshold.

In summary, the results for Union Pass are consistent with those at Lubrecht for the burned and litter surfaces. Vegetation development for the two treatments is also similar to that at Lubrecht, except slower. Even after 6 years, ground coverage of vegetation was low (less than 25 percent) on both treatments.

The difference in results for maximum temperatures on the burned and litter surfaces between Coram and Lubrecht can be explained by observations about the pretreatment vegetation, subsequent vegetation development, and severity of the burns. At Coram the burn was not as hot as the burn at Lubrecht because of the differences in duff moisture (Artley and others 1978; Steele 1980). This situation, coupled with habitat type differences, promoted rapid postburn vegetation development at Coram. By midsummer of the first year after burning at Coram, a good ground cover of grasses and forbs existed that was quite effective in shading the surface. At Lubrecht the litter surface of the close utilization treatment was disturbed more by ground skidding, which stimulated resprouting and provided conditions for colonization of weeds. At Coram, where a skyline yarder was used, understory vegetation was disturbed differently on the close utilization treatment where the litter surface was measured. Branches and tops of shrubs and herbs were broken and mashed but not severely damaged. As a result, resprouting and regrowth were not stimulated enough to cause rapid growth response, yet coverage was enough to provide a significant number of shaded spots for seedlings.

Comparison With Expected Results—Other published results reveal some inconsistencies between burned and unburned surfaces. Fowler and Helvey (1981) did not find any differences between temperatures on the burned pile, broadcast-burned scarified surfaces, and the unburned surfaces on a clearcut in northeastern Oregon. Ahlgren (1981) reports that burned surfaces were warmer for the first 7 years than were unburned surfaces. After 8 years burned surfaces became cooler, a trend that was attributed to gradual development of shrubs. Our results seem to be consistent with Ahlgren's observation of vegetation development. Temperatures of burned and litter surfaces were similar (both maximums and minimums), yet the amount of vegetation cover and the rate at which it developed significantly modified the differences.

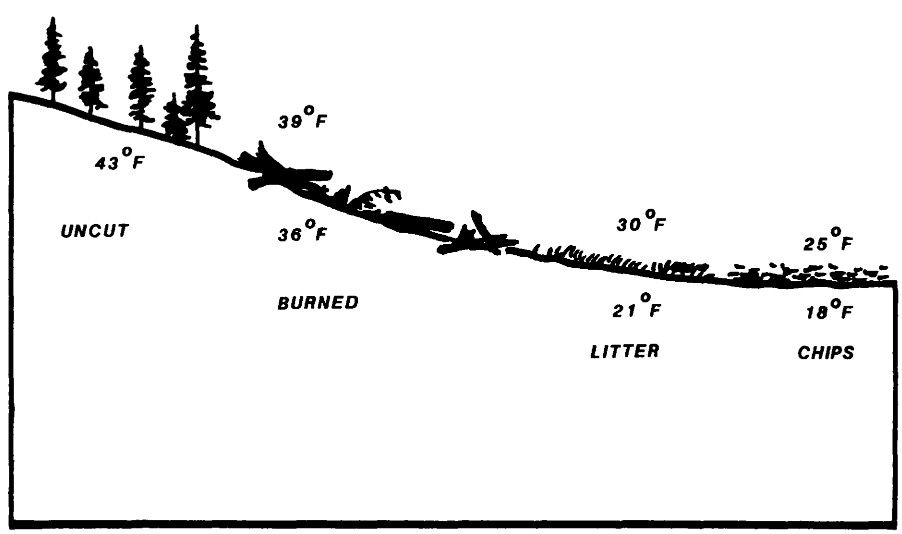


Figure 12—Minimum temperatures at Union Pass on July 10, 1979. The lower row of numbers represents surface temperatures; the upper row represents temperatures at 2 inches above the surface.

Temperatures on the litter and burned surfaces are expected to be similar (under full sunlight), based on the energy balance equation, and the thermal contact coefficient ($\sqrt{KC}$) (table 7) that influences *G*. This situation applies if we assume that (1) both surfaces are dry, thus the *H* and *LE* terms should be equal; and (2) increased *Rn* contribution to burned surfaces as compared to litter surfaces is offset by a lower $\sqrt{KC}$ value for the litter. This shows that if $\sqrt{KC}$ were different for either surface, because of moisture, compaction, and so forth, the *LE* term would be different, causing the surfaces to have different temperatures.

The study results reported here, and those published, tend to support the expectation that burned and litter surfaces will be similar. At Coram, however, where maximums on the litter surface were warmer and minimums colder on the burned surface, *Rn* on the burned surface was apparently reduced by the rapid vegetation growth that provided shade and reduced the temperature variation.

The energy balance equation and thermal properties of $\sqrt{KC}$ (table 7) cause us to expect that temperatures on the burned or litter surfaces will be considerably more variable (higher and lower) than for the mineral soil surface. Lubrecht data are consistent with this expectation. The major factors influencing this difference are $\sqrt{KC}$ and *Rn*. Net radiation is less on the mineral soil (fig. 13) and $\sqrt{KC}$ is considerably greater for mineral soil than for litter, which means that less heat to the surface is conducted away more quickly than for a litter surface. This keeps the surface temperature from rising as much. The same factors allow heat from the soil to warm the surface at night, which keeps minimum temperatures of mineral soil warmer than litter or burned surfaces. Although mineral soil surfaces in the clearcut were not compared with litter or burned surfaces, the differences should be greater than in the shelterwood. If mineral soil were more moist, the differences would be accentuated even more. *LE* and $\sqrt{KC}$ would increase for the mineral soil, which would further reduce the temperature variation at the mineral surface in comparison to litter or burned surfaces.

Compared to litter and burned surfaces, the chip surface is expected to have less temperature variation (lower maximums and higher minimums). The data at Union Pass are consistent with this expectation. Chips have a higher albedo, reducing *Rn* when compared to a litter or burned surface (fig. 13). This lower heat flux density at the surface, coupled with a higher $\sqrt{KC}$ (table 7) than litter or burned surfaces, explains the reduced temperature variation. If the moisture content of the litter surface were higher (relative to the chips), the temperature differences would be reduced because of increased *LE*, which would lower *G*.

Figure 14 shows maximum temperatures for four surface conditions compared to air and humus temperatures. The temperatures shown are for a hypothetical site adjusted to a common set of conditions. These are typical maximum summer surface temperatures on a clearcut for a clear day in full sun. Burned and litter surfaces are much warmer than all other surfaces and the humus at a 1-inch depth. All surface conditions are much warmer than air temperature at 4.5 ft.

At Union Pass, minimum temperatures and CE departed from the expected pattern. Litter surfaces were colder than burned surfaces, which should be similar, as at Lubrecht, and the chip surface was colder than either, where it should be warmer (fig. 11B). The basic explanation for these reversals in minimum temperatures lies in the topographic positions of the treatments. The close utilization treatment, where litter surface temperatures were measured, and the chip spread treatment were in a

Table 7—Average values of albedo or reflectivity and the thermal contact coefficient ($\sqrt{KC}$) for typical surfaces. Values are from Fowler (1974).

Surface	Albedo	$\sqrt{KC}$[1]
	Percent	*cal cm^{-2} sec$^{-1/2}$ °C^{-1}*
Burned	2	0.0018
Litter		
(dry needles)	6-10	.0013
Bark (dry)	20	.0031
Chips	36	.0026
Soil	20-35	.0111
Air	—	.0001
Water	—	.0361

[1]*K* = thermal conductivity; *C* = volumetric heat capacity.

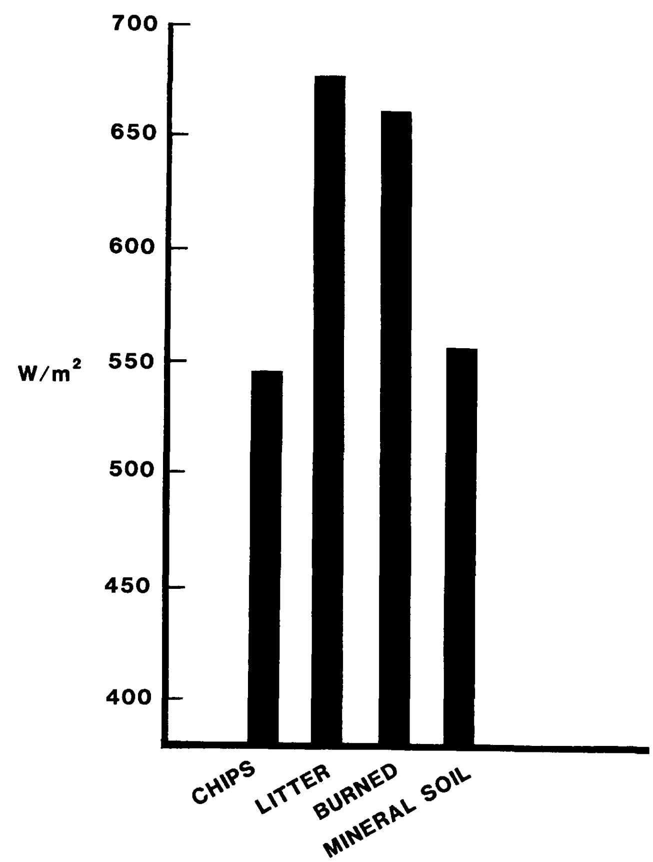


Figure 13—Net radiation over several surface conditions in a clearcut at Union Pass at noon on July 12, 1979. The differences between burned and litter surfaces and between mineral soil and chip surfaces probably are not significant.

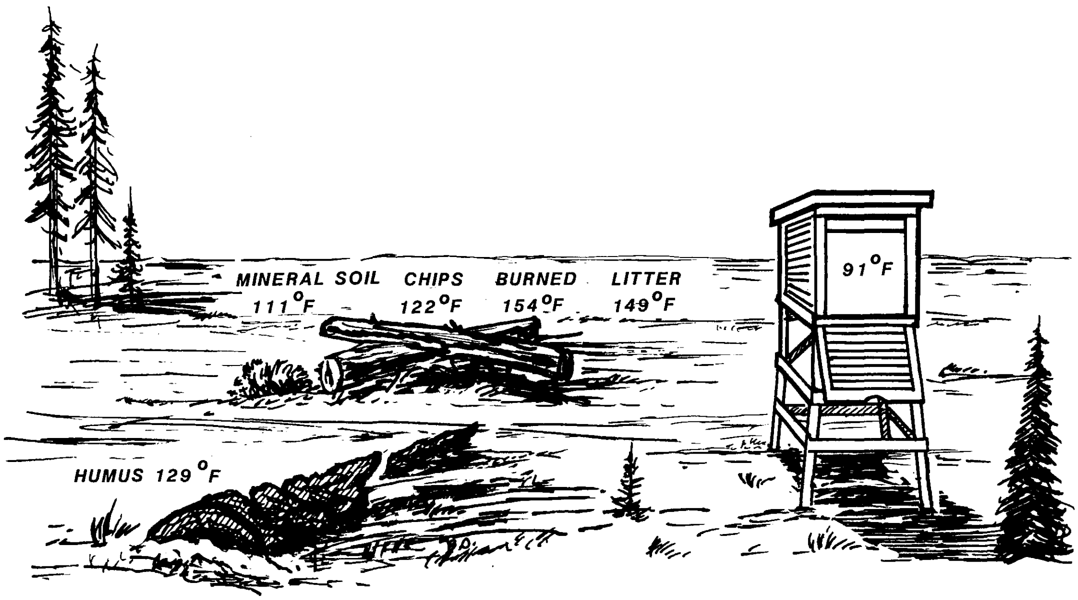


Figure 14—Maximum temperatures expected in a clearcut of a hypothetical site for four surface conditions—burned, litter, mineral soil, and chips—humus at 1-inch depth and air temperature at 4.5 ft.

relatively flat area where cold air accumulates at the toe of a slope that is below the burned surface (fig. 12). The chips treatment is the lowest. In this case *H* was reduced because of restricted airflow and colder, more dense air accumulated in pockets. This aided radiational cooling, thus lowering the surface temperatures. Additionally, where chips were spread, basins were created in the chips to allow seedlings to be planted. These additional depressions trapped more cold air. Surfaces with lower $\sqrt{KC}$ values are more susceptible to lower temperatures and frosts, particularly in frost-pocket situations.

Air Temperature

Air temperatures above the surface conditions were measured only at Union Pass. Surface condition did not have any effect on maximum air temperature at 4.5 ft or 8 inches above the surface. Because surface temperatures were higher on burned and litter surfaces than on chip surfaces, we expected that air temperatures above these surfaces might be different. However, prevailing winds and upslope thermals likely caused enough mixing that surface differences did not significantly influence maximum temperature at these levels.

Minimum air temperatures were significantly different at both 4.5 ft and 8 inches. Temperatures above the chip surface were significantly colder than above the litter or burned surfaces at both heights. At 8 inches above the litter surface, temperatures were also significantly colder than above the burned surfaces. As with the overstory treatments, these differences are due, at least partially, to cold air drainage caused by slope differences.

Soil Temperature

Temperatures at depths of 2 inches and greater were measured only at Union Pass. Higher surface temperatures of some surface conditions at Union Pass caused greater soil temperatures at depths of 2, 8, and 16 inches. Mean temperatures (at all depths) were significantly warmer below the burned surface than below the litter and chip surfaces (fig. 9). Root zone (2- and 8-inch depths) temperatures ranged from 58.1 to 54.5 °F under the burned surface, 54.3 to 51.8 °F under the litter surface, and 50.1 to 45.5 °F under the chips. Temperatures under the burned and litter surfaces are probably not different enough to cause differences in root growth, plant development, or microorganism activity. The colder temperatures under the chips are likely to decrease root growth, transpiration, and microorganism activity. Temperatures under the chips increase much more slowly in the growing season than under the other surfaces. Near-freezing temperatures and frost were often observed in June under the chips. Spreading the chips shortened an already short growing season at this high elevation.

Summary

Temperatures at the ground surface, to depths of 16 inches, are warmer for burned and litter surface conditions than for mineral and chip surface conditions. The results are explained rather well by the energy balance equation and the thermal properties of the surfaces. Differences in temperature between the burned and litter surfaces seem to be influenced by the rate of vegetation recovery. This is consistent with other published results. Minimum temperature differences departed from the expected pattern due to slope position that affects cold air drainage. Differences in the soil mimic the differences at the surface for the surface conditions studied.

Surface condition does not appear to influence air temperature. Wind movement likely caused enough mixing to mask any differences in maximum temperature. Differences in minimum air temperatures are apparently caused by differences in slope position.

REGENERATION RESPONSE

Assuming that HE's and CE's are events with a potential for causing seedling mortality, there should be a relationship between these events and actual seedling survival. For the sites in this study, the relationship between HE's and CE's and regeneration success does seem to be strong and consistent.

Lubrecht

At Lubrecht, the frequency of HE's and CE's (table 8) suggests that first-year survival should be lower on the clearcut than on the understory removal for the first 2 years. Douglas-fir and western larch survival (first year) for the 1979 planting was from 0 to 8 percent (table 8) on the clearcut treatment, and greater than 64 percent on the understory removal treatment where no HE's or CE's were measured (Schmidt 1984).

Survival for ponderosa pine was greater than for Douglas-fir or western larch at about 50 percent on the clearcut and 96 percent on the understory removal treatment. Even though the survival was higher for ponderosa pine, the pattern of survival for all species was consistent with the expected pattern, based on HE's and CE's.

First-year survival for seedlings of all species planted in 1980 was higher than for the 1979 planting, which might be expected because the number of HE's and CE's was lower than for 1979. The clearcut had the highest frequency of HE's and CE's and much lower survival for western larch than for the understory removal. Survival differences were not as dramatic as the previous year for Douglas-fir. Survival of ponderosa pine was not much different for any of the treatments except the close utilization surface in the clearcut. Overall, for all species in both years, survival was not different between the broadcast burn and close utilization treatment, which is consistent with the pattern of HE's and CE's.

The frequency of HE's during the growing season seems to better explain the pattern of survival for western larch than do the CE's. For ponderosa pine, CE's seem to better explain the pattern of survival than the HE's. For Douglas-fir, HE's and CE's seem to be about equal in explaining the survival pattern. These results are consistent with our ideas about the adaptability of these three species. Ponderosa pine is known to be more adapted to hot-dry sites and thus may survive the HE's better than the CE's. Douglas-fir, the intermediate of these species, is better adapted to drier sites than is western larch but not as well as ponderosa pine, thus possibly being equally susceptible to HE's and CE's at Lubrecht. Western larch would be expected to be more sensitive to hot-dry sites. Thus, the mortality would likely be the result of the HE's and related moisture stress before the CE's occurred.

Table 8—First-year plantation survival data from Lubrecht for ponderosa pine, Douglas-fir, and western larch container stock planted on clearcut and understory removal treatments. Broadcast burn and close utilization treatments were used in the clearcut. Hot events and cold events for these treatments are shown by year.

	Clearcut		
	Broadcast burn[1]	Residue removed[2]	Understory removal[2]
	1979		
Species (percentage survival)			
Ponderosa pine	48	28	96
Douglas-fir	4	8	76
Western larch	4	0	64
Temperature (percentage days)			
Hot events	37	19	0
Cold events	26	42	0
	1980		
Species (percentage survival)			
Ponderosa pine	100	60	84
Douglas-fir	52	56	72
Western larch	8	16	68
Temperature (percentage days)			
Hot events	23	17	0
Cold events	0	3	0

[1]Surface condition was burned.
[2]Surface condition was mostly litter.

Coram

The only two comparisons at Coram that can be made are between the burned surface of the broadcast burn treatment and the litter surface of the close utilization treatment within the clearcut. Seedling survival was high (90 percent) on both treatments for all plantings (Shearer 1980) of Douglas-fir and Engelmann spruce even though HE's were more frequent on the litter surface. Hot events on the litter surface were nearly as frequent as at Lubrecht, but they were rare on the burned surface after the first year. In both treatments at Coram there was more vegetation and debris to provide protection for seedlings than at Lubrecht. Germination and survival on the seeded spots were higher on the burned surface than on the litter surface. The HE's likely had minimal effect on survival of germinating seedlings, but insufficient moisture was the major cause of mortality (Shearer 1980). However, moisture was less of a limiting factor at Coram than at Lubrecht. The absence of CE's seems to have benefited seedling survival at Coram.

Union Pass

At Union Pass, seedling survival after 5 years was 92 percent on the broadcast burn treatment, 46 percent on the close utilization treatment, and 26 percent on the chip spread treatment in the clearcut (Schmidt 1982). Survival for each of these treatments is more closely related to CE's (table 9). The HE's apparently did not influence survival. The CE's and survival seem to be related to the topographic position of the treatments in a frost pocket rather than to the surface conditions themselves. Stocking on the seed spots and natural regeneration spots also decreased as the frequency of CE's increased.

Summary

In general, probability of seedling survival increased whenever the frequency of HE's and CE's decreased. It appears likely that CE's caused freezing of plant tissue, which contributed to seedling mortality. For HE's, the damage may have been a direct heat injury that caused death, but it is just as likely that the high temperatures caused dessication of the soil, creating moisture stress conditions that led to seedling mortality. Higher radiation loads on the seedlings in the clearcut and above some surface treatments, such as the chips, caused the elevated surface and soil temperatures and also greater vapor pressure deficits (increased *LE*) and thus greater moisture stress in the seedlings.

Table 9—Plantation survival data after 5 years (1982) for lodgepole pine at Union Pass, WY, on a clearcut with three residue treatments. Hot and cold events are given for July 1979.

	Clearcut		
	Broadcast burn[1]	**Close utilization**	**Chips**
Species (percentage survival)			
Lodgepole pine	96	46	26
Temperature (percentage days)			
Hot events	62	62	10
Cold events	0	10	43

[1]Temperatures were measured on the burned surface on the broadcast burn, litter surface on the residue removed, and the chip surface on the chips.

Imposing treatment practices to reduce temperature variation must be used with caution. Treatments that have been shown to reduce temperature variation (exposing mineral soil) also increase evaporation and can create a moisture deficiency problem. On sites where high temperature is not a problem but moisture is, leaving a mulch (litter) or providing one may reduce moisture losses (Cochran 1969). Another major factor is the condition of planting stock. At Lubrecht, condition of the containerized seedlings was quite variable (Shearer 1985). Seedlings that are already stressed may be more likely to succumb when planted in more stressful situations. Thus, these results do not provide proof of the relationship between temperature and mortality. But they do provide strong evidence that the effects of treatment on site energy balance and thermal properties should be evaluated in relationship to the potential for seedling survival.

CONCLUSIONS AND IMPLICATIONS FOR MANAGERS

Several points from this and other studies have a bearing on surface temperature modification and successful regeneration of stands.

1. It is crucial to be able to identify potential mortality problems due to temperature and moisture at the time silvicultural prescriptions are prepared. If problems are expected, steps can be taken to avoid problems by altering silvicultural and subsequent reforestation practices.

2. Current reforestation guides indicate that high temperatures are a problem on south and west aspects on slopes over 30 percent at lower elevations. In this study, potentially lethal high temperatures were also observed on level ground, on east-facing slopes, and at high elevations on clearcuts in Douglas-fir and subalpine fir habitat types. Potentially lethal cold temperatures were measured on level sites at high and low elevations in both habitat series. The pattern of seedling survival on these sites indicates that mortality was in fact related to the hot and cold temperature events.

3. Results of this study show that shelterwood or partial cuttings with 50 percent or less sunlight transmission to the forest floor significantly reduce the occurrence of high temperatures and low temperatures. Seedling survival was higher in these stands.

4. Seedbed preparation and residue treatments for slash reduction significantly influence the occurrence of potentially lethal seedbed surface temperatures by altering the thermal properties of the surface. In general, practices that increase the thermal conductivity and volumetric heat capacity (thus, $\sqrt{KC}$—thermal contact coefficient) of the surface materials will decrease maximum temperatures and increase minimum temperatures. Treatments that expose mineral soil reduce surface temperature variation (decrease maximum and increase minimum) compared to natural litter-covered surfaces. Burned and natural litter-covered surfaces on clearcuts may be equally susceptible to high temperatures, based on results reported here. However, this may vary depending on the thermal properties of the surface materials.

5. Where it is not practical to alter the surface materials (thermal properties), excessively high and low temperatures can be reduced by providing shade. Leaving enough residues onsite to provide adequate shade protection will reduce temperatures and increase seedling survival. Residues can also conserve moisture at the surface by reducing evaporation. Allowing some vegetation growth (provided moisture is not limiting) will also provide adequate shade and thus temperature modification. Seedlings planted on these sites should be positioned to take advantage of the modified microsites—on the north or east sides of logs, stumps, branches, rocks, etc.

6. On sites where soil moisture is more of a problem than is high temperature, mulches (plant litter, artificial materials; dry, loosened soil; etc.) left on the surface can help retard evaporation and thus increase survival. However, these practices must be planned carefully because they will increase surface temperatures.

7. Frost-pocket problems can be aggravated by overstory and residue treatment. The ability to identify potential frost pockets while developing the silvicultural prescription is important. Subalpine fir in drainages or flat areas or *Vaccinium caespitosum* in the understory are often good indicators of potential frost pockets.

8. Shade from partial overstories, residue, or understory vegetation can provide varying degrees of protection for seedlings in frost pockets. Only the most frost-resistant species should be used in frost-pocket areas.

9. Clearcuts and other cutting units should be laid out to provide for adequate air drainage through a cutting unit, if it is not the lowest depression. This will minimize cutting-related frost pockets. Smaller cutting units (group selections) will reduce radiational cooling and frost problems on sites that may have potential problems. To be effective, widths of strips or patches should be less than two tree (border tree) heights wide.

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Hungerford, Roger D.; Babbitt, Ronald E. Overstory removal and residue treatments affect soil surface, air, and soil temperature: implications for seedling survival. Research Paper INT-377. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1987. 19 p.

Potentially lethal ground surface temperatures were measured at three locations in the Northern Rocky Mountains but occurred more frequently under treatments with greater overstory removal. Observed maximum and minimum temperatures of exposed surfaces are directly related to the thermal properties of the surface materials. Survival of planted seedlings was consistent with the pattern of potentially lethal temperatures. Care in manipulating overstory canopies and residues can enhance the potential for tree seedling survival.

KEYWORDS: temperature, seedling survival, timber harvesting, thermal properties

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