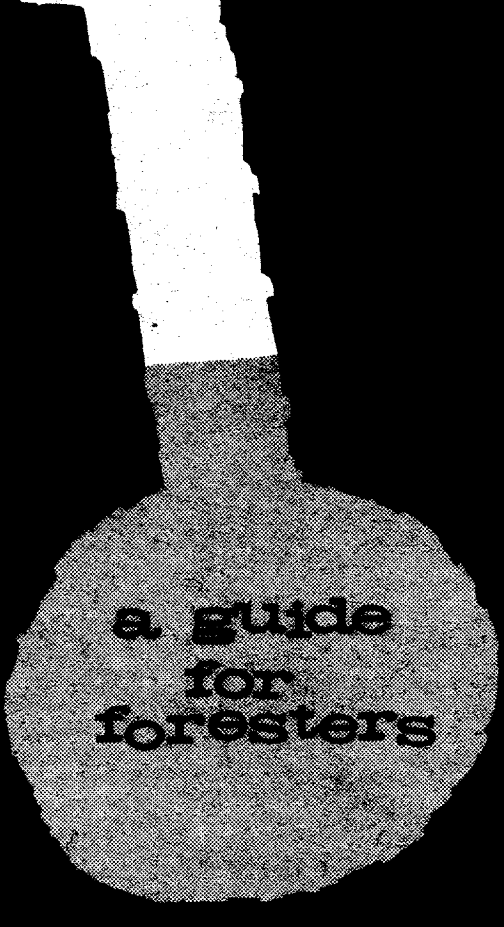
H. S. Larsen

thermal properties and surface temperatures of seedbeds

p.h.cochran



a guide for foresters

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
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INTRODUCTION

Regeneration of many logged-over areas may depend more upon thermal properties of the seedbed material than on any other factor. The probability and extent of seedling injury by heat or frost depend upon the temperature variations at the soil surface and in the air layer surrounding the seedlings. These temperature variations are markedly influenced by thermal properties of the seedbed material. This paper defines some important soil thermal properties, shows how they are influenced by soil water content, and relates these properties to temperature extremes at the soil-air interface.

THE DAILY SOIL TEMPERATURE CYCLE

As solar energy strikes the earth's surface, the energy is either reflected or absorbed. Part of the absorbed energy is used in evaporation and is returned to the atmosphere with water vapor. Some heat energy flows into the soil primarily by thermal conduction. Another portion of this absorbed energy is reradiated with the longer wavelengths characteristic of the earth's surface temperature. Further, some absorbed heat energy may be transported away from the soil surface by moving air currents of different temperatures. The amount of energy per unit time emitted, received, or transmitted across a unit area is called the energy flux density. The net amount of this energy flux density is called the net radiation flux (R_n). The components of the net radiation flux are illustrated in figures 1 and 2. These components can be given by the equation (Rose 1966),[1]

$$R_n = G + H + LE \text{ (cal. cm.}^{-2}\text{ sec.}^{-1}\text{)} \qquad (1)$$

where

G = heat flux density into the soil,
H = sensible (nonlatent) heat flux density into the atmosphere, including the amount of heat transported by air currents,
L = latent heat of vaporization (cal. g.$^{-1}$), and
E = evapotranspiration rate (g. cm.$^{-2}$ sec.$^{-1}$).

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[1] Names and dates in parentheses refer to Literature Cited, p. 19.

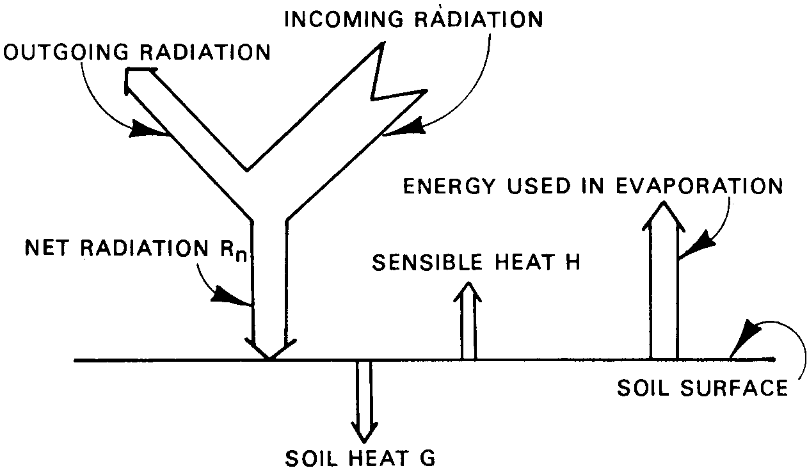

Figure 1.--*Daytime energy flux components at the soil surface (adapted from Rose, 1966).*

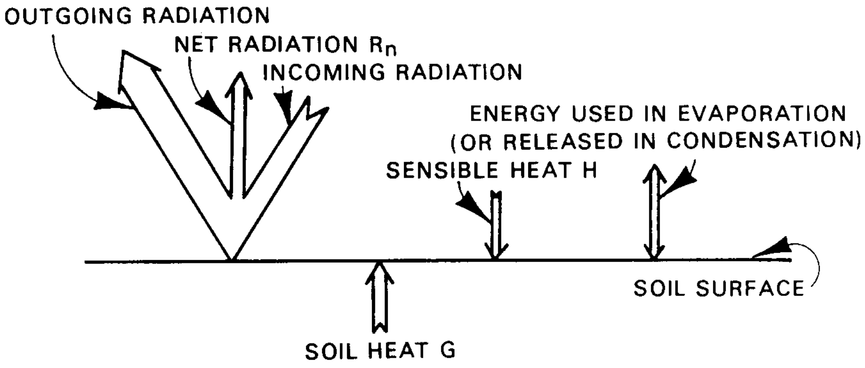

Figure 2.--*Nighttime energy flux components at the soil surface (adapted from Rose, 1966).*

The total net radiation flux and its components can be either positive or negative. Each component is highly variable within a given site, changing with time of day, season, weather, and other factors (Gates 1965). A complete discussion of all possible interrelationships between the various components is beyond the scope of this paper. The purpose here is to point out how the thermal properties of the soil and the heat flux density into the soil affect the variation in soil surface temperatures.

During a clear, calm day, the soil surface temperature is coldest at about sunrise. As the day progresses, the soil surface is warmed primarily by conversion of intercepted shortwave radiant energy to heat. During the morning, the surface temperature becomes higher than that immediately below the surface, creating a downward gradient. This downward gradient forces heat into the soil. The soil surface also continually emits longwave radiation at a rate proportional to its temperature. The soil surface temperature reaches a maximum between the hours of 1300 and 1400. Lowering of the sun's angle decreases the amount of radiant energy intercepted and converted to heat at the soil surface. The reduction in intercepted radiant energy and the continued emission of longwave radiation halts the increase in the surface soil temperature. After about 1800, the surface soil becomes cooler than the soil layer immediately below. The reversed temperature gradient now causes heat transfer upward to the surface. The loss of energy as outgoing longwave radiation results in continued cooling of the soil surface. This energy loss is only partially counterbalanced by the interception of radiation at the surface and by heat transfer upward from deeper soil depths. Thus, the surface temperature and the air layer immediately above it become progressively cooler through the remainder of the afternoon and night.

Daily temperature extremes at the soil surface vary greatly with different soils and soil water contents. These temperature variations are largely controlled by soil thermal properties.

SOIL THERMAL PROPERTIES

The thermal properties are defined by various combinations of thermal conductivity and volumetric heat capacity. Table 1 summarizes the following discussion of the thermal properties.

Table 1.--*A summary of five soil thermal properties*

Property	Formula or symbol	Measures	Consequences of--	
			Low value	High value
Thermal conductivity	K	Rate of heat transfer; quantity of heat flowing through 1-cm. cube in 1 sec. when one face of cube is 1° C. cooler than other.	Slow heat transfer with constant temperature gradient.	Rapid heat transfer with constant temperature gradient.
Volumetric heat capacity	C	Quantity of heat required to raise 1 cm.^{3} 1° C.	Large temperature response to given amount of added heat.	Small temperature response to given amount of added heat.
Thermal diffusivity	$a = K/C$	Index to rate of temperature change with time and depth.	Heat will not be transferred to as great a depth in a given time.	Heat will be transferred to a greater depth in a given time.
Thermal contact coefficient	$\sqrt{KC}$	Index to variation in surface temperature when heat is added or removed.	Greater variation in surface temperature.	Lesser variation in surface temperature.
Damping depth	$D = \sqrt{2a/\omega}$ [1/]	Penetration depth of temperature change in given time with given thermal diffusivity	Shallow penetration of significant temperature variations.	Deep penetration of significant temperature variations.

[1/] ω = radial frequency; $\omega = 2\pi/P$ where P = length of heating period. ω for 1 day = 7.27×10^{-5} sec.$^{-1}$.

Thermal conductivity.--The quantity of heat which would flow in 1 second through a 1-centimeter cube, where one face of the cube is 1° C. cooler than the face on the opposite side, is the thermal conductivity of the cube (K). It has the dimensions of calories per centimeter per second per degree Calcius. It is also called heat conductivity and coefficient of conductivity.

Volumetric heat capacity.--The quantity of heat which must be supplied to a 1-centimeter cube to raise its temperature 1° C. is the volumetric heat capacity of the cube (C). It has the dimensions of calories per cubic centimeter per degree Celsius. The temperature change (ΔT) when a given quantity of heat (Q) is supplied to a given volume (V) of material is given by the formula:

$$\text{Temperature change} = \frac{\text{heat quantity}}{\text{volume x volumetric heat capacity}}$$

or (2)

$$\Delta T = Q/VC.$$

This illustrates that the smaller the volumetric heat capacity, the greater the temperature change when a given amount of heat is added to or released from a given volume of material.

In the field, the amount of energy received by the soil surface changes during a day or a year. Part of the heat created by energy transformation is used to increase the temperature of the surface and part is transported away from the surface. As a result, the surface temperature gradient is continually changing. Because the soil heat flux density and the soil temperature gradient continually change with time, combinations involving both the thermal conductivity and the volumetric heat capacity must be used to explain soil temperature variations. Three of these combinations--thermal diffusivity, damping depth, and thermal contact coefficient--will now be discussed.

Thermal diffusivity.--Thermal diffusivity (a) is the ratio of thermal conductivity to volumetric heat capacity,

$$a = K/C. \tag{3}$$

At a given soil depth, thermal diffusivity relates the temperature change with time to rate of change of the temperature gradient at that depth. Thus, thermal or heat diffusivity is an index to the rate of temperature change with time and depth. Because of this relationship, the thermal diffusivity is called the temperature conductivity by some authors and may be confused with thermal conductivity by the casual reader.

Damping depth.--Two factors, thermal diffusivity and length of the heating or cooling period, determine the depth of penetration of a surface temperature change. For example, when heat is supplied to the soil surface, some heat is conducted downward and some remains near the surface causing a temperature increase. If the thermal diffusivity of the soil is low (low thermal conductivity in comparison with the heat capacity), heat will not be conducted to as great a depth as it would be if the thermal diffusivity were higher. The longer heat is supplied, the greater the depths to which temperature changes will penetrate. During the daily temperature cycle, the temperature fluctuates from the average up to a maximum, then down past the average to a minimum, and then back up to the average. This fluctuation can be approximated by a sin wave, and the temperature at the surface (T_s) can be described by

$$T_s = \bar{T} + \frac{\Delta T}{2} \sin(\omega t) \qquad (4)$$

where $\bar{T}$ is the average surface temperature and ΔT is the total variation in surface temperature. t is the elapsed time since the start of the cycle ($T_s = \bar{T}$) and $\omega = 2\pi/P$ where P is the length of the cycle. ω is called the radial frequency, and it is used to fit temperature data from cycles of different lengths or periods to a sin wave. A heating period of 1 day (86,400 seconds) has a radial frequency of $\omega = 2\pi/86{,}400$ sec. $= 7.27 \times 10^{-5}$sec.$^{-1}$.

Damping depth (D) takes into account both the heating period and thermal diffusivity,

$$D = \sqrt{\frac{2\ K}{C\omega}} = \sqrt{2a/\omega} \qquad (5)$$

Temperature variations are reduced to 4.7 percent of the surface temperature variations at a soil depth equal to $3D$. Thus, significant temperature variations are limited to a layer of approximately $3D$ (van Wijk 1965).

Equation 5 shows that temperature variations penetrate deeper in soils with high thermal diffusivities than in soils with low diffusivities.

Thermal contact coefficient.--The thermal contact coefficient equals $\sqrt{KC}$. This term indicates how much the surface temperature will vary when heat is supplied to or removed from the surface. The lower the contact coefficient, the greater the surface temperature variation. Stated another way, soils with low thermal conductivities and low volumetric heat capacities have high surface temperatures during the day and low surface temperatures during the night. Seedlings growing on such a soil are more subject to radiation frosts and to heat injury than seedlings growing on soils with higher thermal contact coefficients but otherwise in the same environment.

If the total variation in amount of heat passing into or out of a unit area of surface during a 24-hour period (the variation in heat flux density) is ΔG and the total surface temperature variation is ΔT, then

$$\Delta G = \Delta T \sqrt{KC\omega} \qquad (6)$$

The ratio of the daily temperature variation at the surface of two soils is approximated by (van Wijk 1965)

$$\frac{\Delta T'}{\Delta T} = \frac{\Delta G' \sqrt{KC}}{\Delta G \sqrt{K'C'}}, \qquad (7)$$

if identical surface covers, equal meteorological conditions, and equal evapotranspiration rates are assumed for the two soils. Also, equation 7 assumes that the heat flux density varies sinusoidally with time and that the time of maximum or minimum heat flux densities are identical for the two soils.

Equations 6 and 7 show that if the variation in heat flux densities for the two surfaces are equal ($\Delta G' = \Delta G$), the surface temperature will be inversely proportional to the contact coefficient (van Wijk 1965). In the field, soils with low thermal contact coefficients will usually have lower heat flux densities than soils with higher thermal contact coefficients; however, the thermal contact coefficient is extremely important in controlling the daily surface temperature variation.

The thermal contact coefficient is sometimes called the conductive capacity and written as $C\sqrt{a}$, but the two terms are the same since $\sqrt{KC} = C\sqrt{a}$.

VARIATION OF THERMAL PROPERTIES WITH SOIL WATER CONTENT

Water content has a pronounced effect on volumetric heat capacity, thermal conductivity, and therefore on other thermal properties. These, in turn, influence the severity of the seedlings' temperature environment. Volumetric heat capacity, thermal conductivity, thermal diffusivity, and thermal contact coefficient are shown as functions of the volumetric water content for the A1 horizon of the Lapine soil in figures 3 through 6.[2/]

There is a linear relationship between volumetric heat capacity and soil water content (fig. 3). Most dry soil materials have volumetric heat capacities of 0.16 to 0.26 cal./cm.^{3}-$^\circ$C.; water has a volumetric heat capacity of 1 cal./cm.^{3}-$^\circ$C. The greater the volumetric heat capacity, the lower the change in temperature with the application or removal of a given amount of heat. With this fact in mind, we can begin to appreciate the tremendous influence of soil water content on soil temperature. For example, if 1 calorie of heat is removed from or supplied to 1 cubic centimeter of A1 horizon material at a moisture content of 30 percent by volume ($C = 0.45$), the resulting temperature change according to equation 2 will be 2.2°C. However, if the soil is dry ($C = 0.15$), the temperature change will be 6.7°C.

Thermal conductivity increases rapidly with an initial increase in water content and then levels off somewhat (fig. 4). This pattern is generally true for soils, although thermal conductivity values for denser mineral soils are much larger.

Thermal diffusivity for the Lapine A1 horizon first decreases slightly and then increases with soil water content up to a soil water content of 20 percent by volume (fig. 5). The thermal diffusivity then continually decreases with increasing soil water content. The thermal diffusivity for most soil materials increases to a high and then decreases with increasing soil water content. The change in thermal diffusivity with water content for denser soil materials is usually greater and the diffusivity values are usually higher than those shown for the Lapine A1 horizon.

The thermal contact coefficient increases with increasing soil water content (fig. 6). Figure 6 shows the great influence of soil water content on surface temperature variation. For example, at a water content of 10 percent by

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[2/] The methods for obtaining these values are given by Cochran, Boersma, and Youngberg (1967). The Lapine soil is developed on Mazama pumice and has very low bulk densities and high porosities in comparison with other mineral soils.

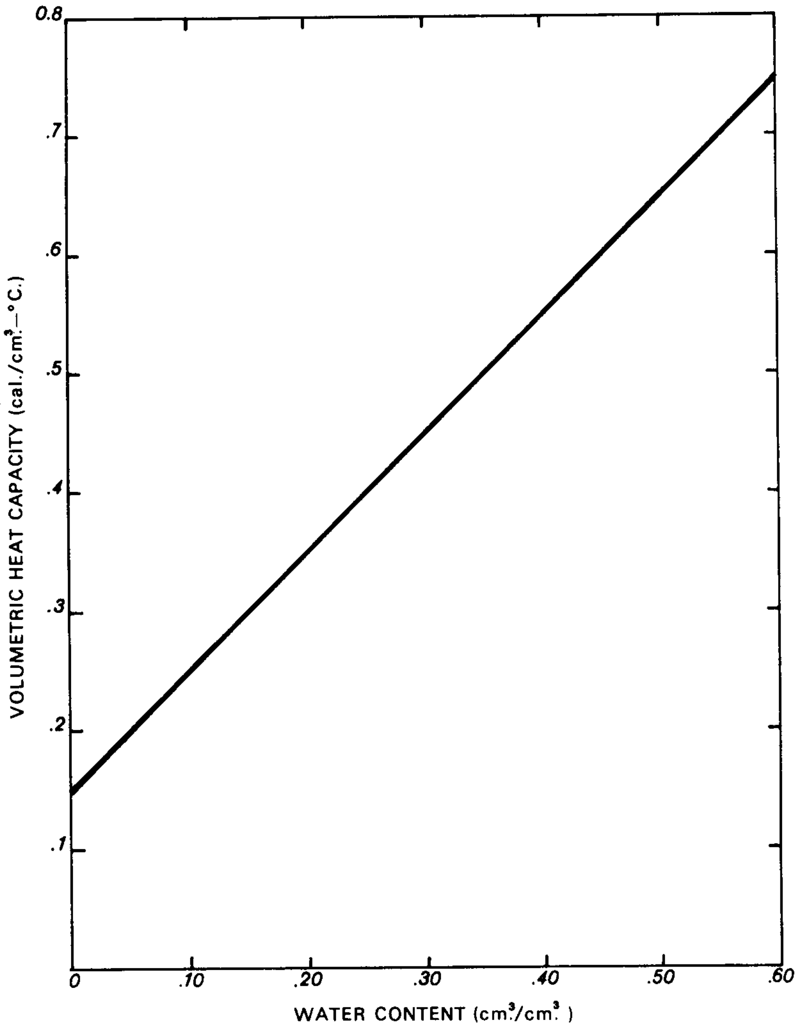

Figure 3.--*Volumetric heat capacity as a function of soil water content for the Lapine A1 horizon.*

volume, the thermal contact coefficient is about 0.012 cal./cm.^{2}-sec.$^{1/2}$-°C. At 35 percent water content, the thermal contact coefficient is twice as great--about 0.024 cal./cm.^{2}-sec.$^{1/2}$-°C. If the heat flux densities were equal for two soils having these thermal properties and if each soil was uniform in regard to the thermal contact coefficient with depth, the surface temperature variation for the driest soil would be twice as great as the surface temperature variation for the wetter soil.

Actually, the heat flux density would be somewhat less for the dryer soil if the soils were to be compared under equal meteorological conditions. If the surfaces of the two soils were fairly smooth and if the winds were light, the variation in the heat flux density for the driest soil could be about 25 percent

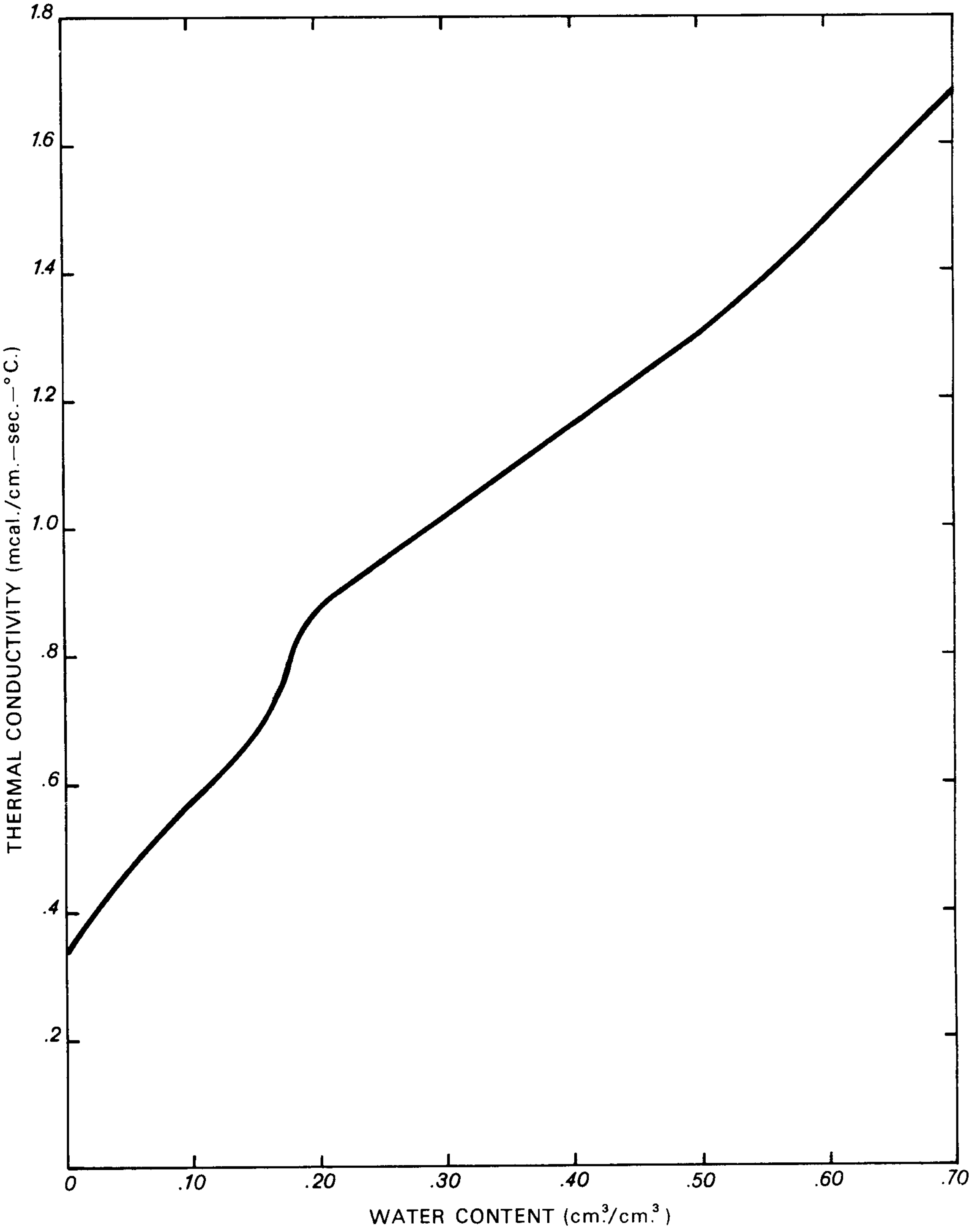

Figure 4.--*Thermal conductivity of the Lapine A1 horizon as a function of the soil water content.*

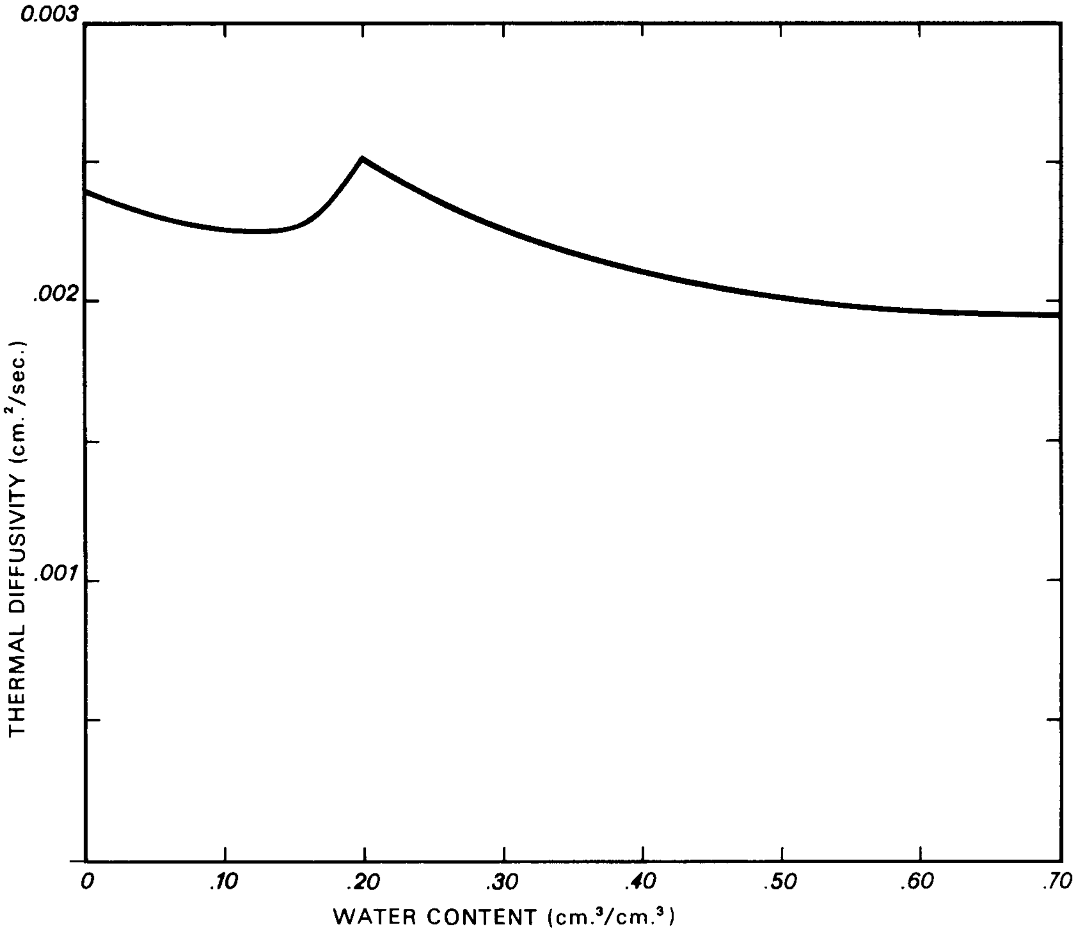

Figure 5.--*Thermal diffusivity of the Lapine A1 horizon as a function of the soil water content.*

less[3] than the heat flux density variation for the wetter soil. The surface temperature variation would still be much larger for the drier soil. If the temperature varied between 35° and 125° F. at the surface of the soil with 35 percent water content, the temperature variation could range between 13° and 148° F. for the soil surface at a water content of 10 percent. In the first case, frost or heat injury are not probable; in the latter, they are. Since the thermal diffusivities are roughly the same at these two moisture contents (fig. 5), the depth at which the daily variation is confined is the same. However, at high water contents the soil temperature change is smaller because the higher water content prohibits a large temperature increase with heat absorption.

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[3] This value was calculated as outlined by van Wijk and DeVries (1966) on pages 124 and 125.

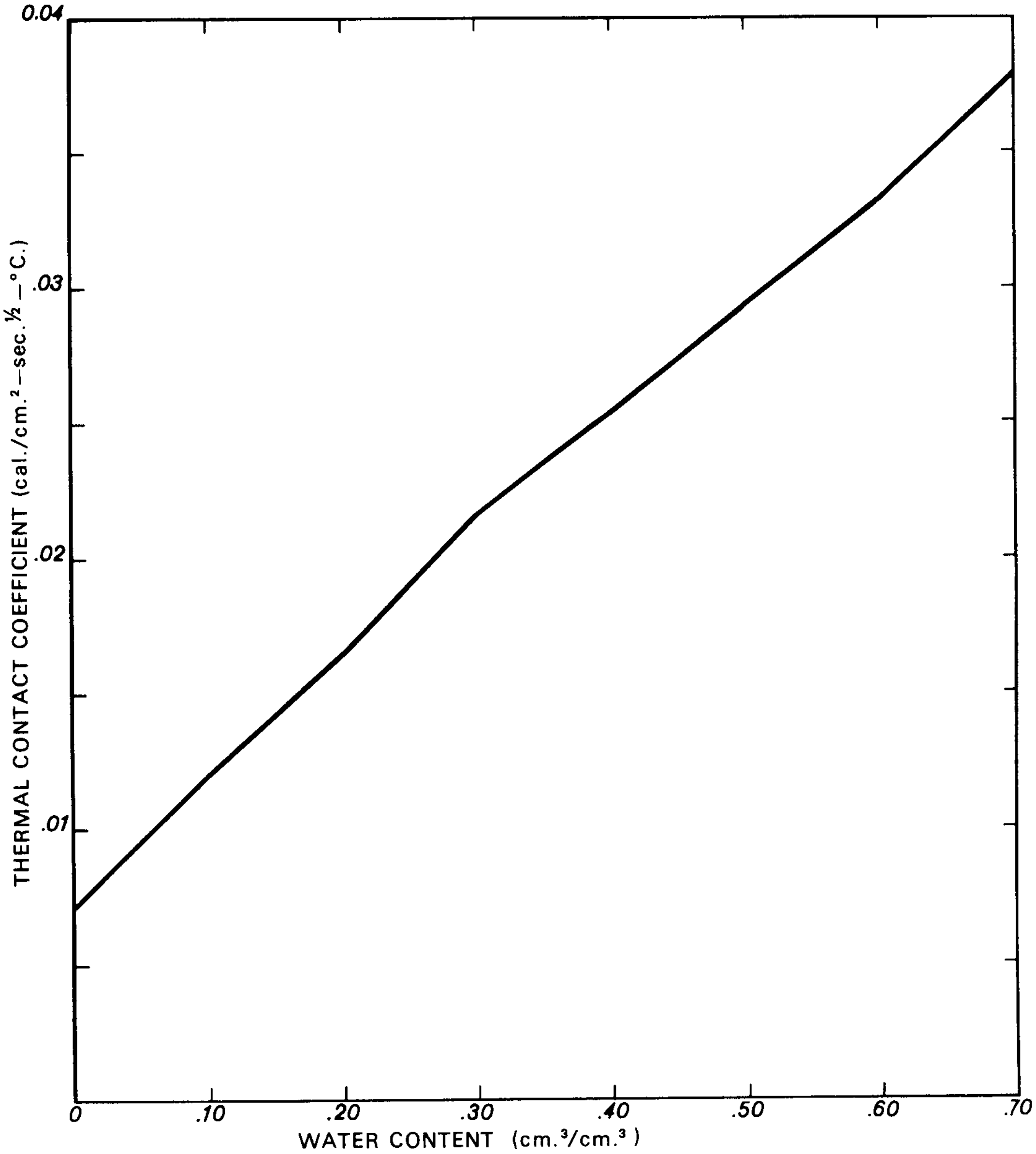

Figure 6.--*Thermal contact coefficient of the Lapine A1 horizon as a function of soil water content.*

THE EXTREME TEMPERATURE ENVIRONMENT IN THE PUMICE SOIL REGION

As pointed out by Cochran et al. (1967), pumice soils have lower thermal conductivities, lower volumetric heat capacities, lower diffusivities, and lower thermal contact coefficients at comparable water contents than other mineral soils of greater density. The thermal properties of pumice soils more closely resemble peats than mineral soils, and frost hazards to agricultural crops grown on peat soils have been recognized for many years (van Wijk 1965). Some thermal properties of the Lapine A1 and AC horizons are compared with those of a peat, a clay, and a sand soil in table 2.

Table 2.--*Thermal properties of sand, peat, clay soils, and the Lapine A1 and AC horizons for a moisture content of 40 percent by volume*

Material	Thermal conductivity, K cal./sec.-cm.-°C.	Heat capacity, C cal./cm.^{3}-°C.	Thermal diffusivity, a cm.^{2}/sec.	Thermal contact coefficient, $\sqrt{KC}$ cal./cm.^{2}-sec.$^{1/2}$-°C.
A1 horizon	0.00116	0.55	0.0021	0.0259
AC horizon	.00125	.55	.0023	.0262
Peat[1]	.00070	.52	.0014	.0191
Clay[1]	.0038	.70	.0054	.0515
Sand[1]	.0054	.70	.0077	.0615

[1] Values taken from van Wijk (1965).

Frosts commonly occur during the growing season in the pumice soil region of Oregon. For example, the likelihood of a freezing (0° C. or 32° F.) temperature is greater than 50 percent on any summer night near Chemult, Oregon (Eichhorn et al. 1961). Thermal properties of pumice soils result in large temperature gradients at the soil surface. Nightly, the surface and adjacent air layers become cold. This denser cold air moves downslope and accumulates on the "pumice flats," in depressional areas, and in stand openings. This advection of cold air results in even lower minimum temperatures, and heat transfer upward through the soil is insufficient to prevent frost. Certainly, the thermal properties of pumice soils aid in creation of more extreme temperature environment near the surface than would be found over clay or sand under the same conditions.

Berntsen[4] found that during the emergence period, lodgepole pine seedlings were more tolerant of 15° to 18° F. temperatures than were ponderosa pine

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[4] Berntsen, Carl Martin. Relative low temperature tolerance of lodgepole and ponderosa pine seedlings. 1967. (Unpublished Ph. D thesis on file at Oregon State Univ., Corvallis.)

seedlings. This differential tolerance to low temperatures, coupled with thermal properties of the pumice soils, must be an important factor in development of pure lodgepole pine stands and retardation of ponderosa pine establishment in "pumice flat" areas.

MODIFYING SURFACE TEMPERATURES

The land manager knowingly or unknowingly modifies the surface temperature through such practices as mulching, cultivation, soil compaction, irrigation, and shading or shielding seedlings. The temperature modification results from a change in the thermal properties of the surface and/or a change in the surface heat flux density.

The Effect of Mulches on Surface Temperatures

Many different kinds of natural mulches, such as plant litter and dry surface soils, and artificial mulches, such as paper, sand, and plastic, are encountered in forestry. The temperature at the surface[5] of a mulched seedbed is usually different than the temperature at the surface of an unmulched seedbed under the same meteorological conditions.

In general, the application of a mulch with a lower thermal conductivity, a lower volumetric heat capacity, and a lower thermal diffusivity than the underlying soil will cause an increase in surface temperature variation for two reasons:

1. Heat is not transferred to or from as great a depth for the mulched soil during a 24-hour period, and thus the temperature change is confined to a shallower depth.
2. The lower volumetric heat capacity of the mulch further accentuates the temperature change over that of the unmulched soil when heat is added or lost.

Figure 7 illustrates the modification of maximum and minimum surface temperatures by mulching with a material of lower thermal conductivity, volumetric heat capacity, and thermal diffusivity than the underlying soil.

If the thermal properties of the mulch and the soil are known, the influence of the mulch on the surface temperature variation (ΔT) can be approximated using the equation [6]

$$\frac{\Delta T_m}{\Delta T_s} = \frac{\Delta G_m}{\Delta G_s} \left[\frac{K_s C_s}{K_m C_m} \, \frac{\exp(4d/D_m) + 2r \left(\exp(2d/D_m)\right)\cos(2d/Dm) + r^2}{\exp(4d/D_m) - 2r \left(\exp(2d/D_m)\right)\cos(2d/D_m) + r^2}\right]^{\frac{1}{2}} \qquad (8)$$

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[5] Surface temperature is used in this text to designate the temperature at the mulch-air or soil-air interface and not the mulch-soil interface.

[6] Equation 8 is a rearrangement and modification of equation (6.28), page 177, of van Wijk and Derksen (1966). The amplitudes of van Wijk and Derksen have been changed to variations for this paper. Temperature variation is twice the temperature amplitude.

In this equation, the subscripts s and m refer to the soil and the mulch, respectively, and d is the depth of the mulch. Also,

$$r = \frac{\sqrt{K_m C_m} - \sqrt{K_s C_s}}{\sqrt{K_m C_m} + \sqrt{K_s C_s}}, \tag{9}$$

and the other variables are the same as previously defined (table 1 and equation 7). Equation 8 assumes that the evaporation rates from the two surfaces are the same and that the heat flux densities reach their maximums or minimums for both surfaces at the same time during a cycle described by a sin wave.

To grasp the effect of litter on surface temperature variation, suppose that a 10-centimeter layer of dry litter mulch having a thermal conductivity of 0.0006 cal./cm.-sec.-°C. and a volumetric heat capacity of 0.45 cal./cm.^{3}-°C.[7] is applied to a clay soil with a water content of 40 percent by volume having the thermal properties shown in table 2. If we assume that the heat flux densities for the mulched and unmulched surfaces are the same, we find by applying equation 8 that the litter increases the surface temperature variation over that of the unmulched surface by a factor of 3.1. Actually, the surface heat flux density would be reduced somewhat by the litter, but not nearly enough to prohibit a large increase in the surface temperature variation of the mulched surface. Even if the litter decreased the surface heat flux density by 30 percent, the surface temperature variation would still be 2.2 times the variation at the unmulched clay surface. In this example, a surface temperature variation of 50° F. for the clay surface would be increased to 110° F. at the surface of the litter (fig. 7). Thus, the increased mortality due to heat injury for seedlings emerging through litter layers and dry surface soils can be expected and is often observed. Also, the increased frequency of night frost on a cover of leaves is not surprising in view of the above calculation.

Mulches, when wet, can reduce surface temperature variation, even though their thermal conductivity and volumetric heat capacity are lower than the underlying soil. The evaporative heat flux density can be so great (the LE term in equation 1) that heat flux density into the surface (G) becomes extremely small. The surface temperature variation will remain small as long as the mulch is wet, but when it begins to dry, the surface temperature variation will start to drastically increase.

Mulching with materials having a higher thermal conductivity and volumetric heat capacity than the underlying soil can cause a decrease in surface temperature variation. For example, application of a 10-centimeter layer of sand to a clay, with both materials having thermal properties shown in table 2, will result in a 15-percent decrease in the daily surface-air interface temperature variation if the surface heat flux density is unchanged.

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[7] These thermal properties were estimated by the assumption that dry litter would have a somewhat lower thermal conductivity and heat capacity than the moist peat shown in table 2.

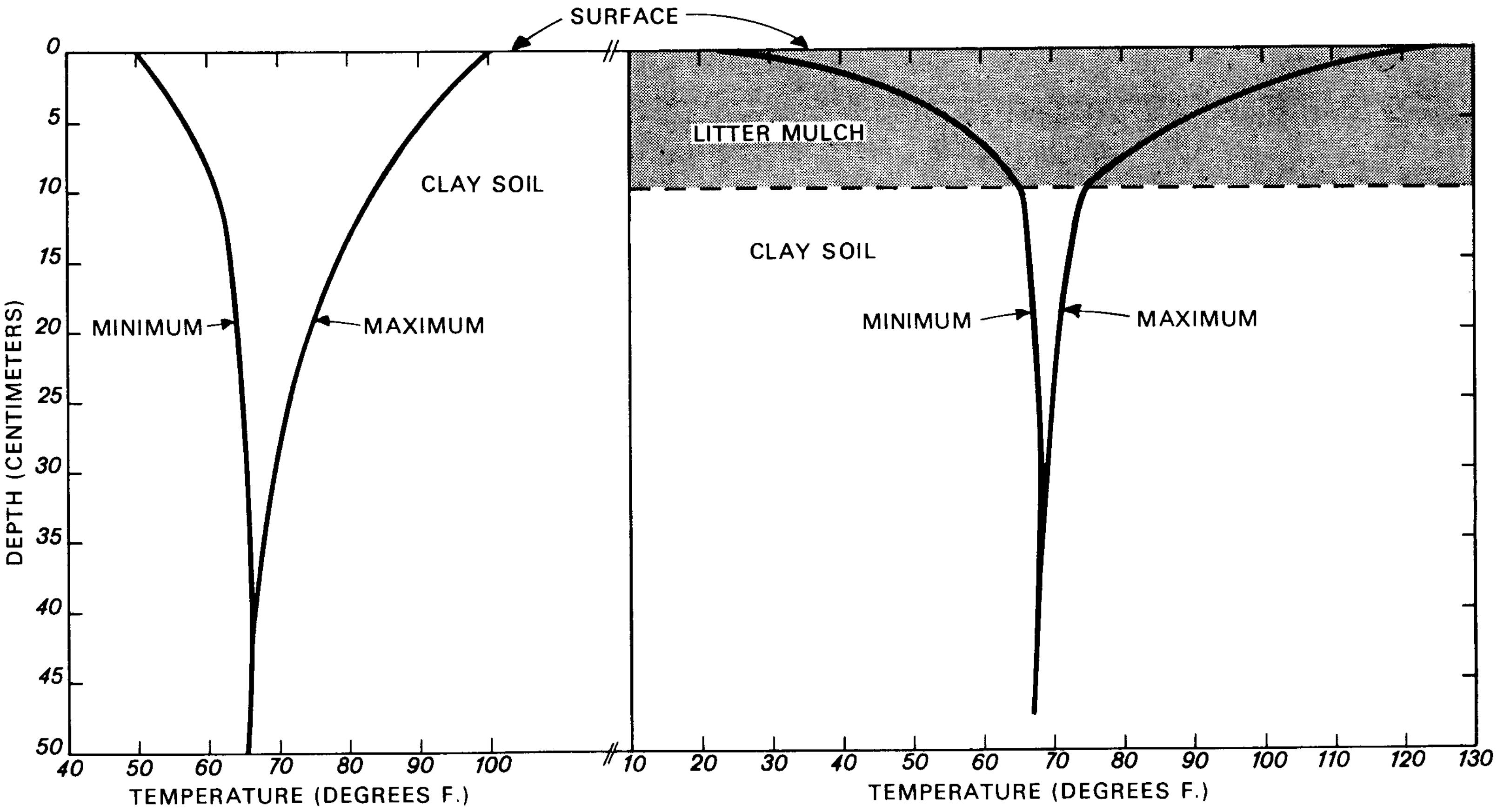

Figure 7.--*Daily temperature variation with depth for a mulched and unmulched clay soil where the litter mulch has a much lower thermal conductivity, volumetric heat capacity and thermal diffusivity than the soil.*

A thin layer of plastic can also affect the surface temperature by changing the surface thermal properties and heat flux density. Application of a sheet of plastic 0.1 centimeter thick, with a thermal conductivity of 0.0054 cal./cm.-sec.-°C. and a volumetric heat capacity of 0.41 cal./cm.^{3}-°C.,[8] to the peat soil in table 2 would increase the surface temperature variation by a factor of 1.2 if the surface heat flux density was unchanged.

Applications of mulches like plastic and paper can be expected to change the surface heat flux density. A greater temperature variation is expected at the surface of a black sheet of plastic mulch than at the surface of a white sheet because the black sheet will absorb more radiant energy, increasing the net radiation and the surface heat flux density. Some mulches used in agriculture greatly modify the heat flux density of the surface. Miller (1968) used greenhouse glass plates and water-filled clear polyethylene bags in separate trials for mulching sweet corn. The glass allowed shortwave radiation to pass into the soil but did not transmit the longwave radiation emitted by the soil. Also, evaporation was reduced under glass so more of the incoming radiation was used to warm the soil. The glass caused the soil to become warmer during the day and remain warmer at night. The layer of water absorbed shortwave radiation. Since water has a high heat capacity, it acted as a heat sink during the day, reducing the maximum soil temperature. At night, the water acted as a heat source, increasing the minimum soil temperature.

Mulches retard the evaporation of water; therefore, during the course of a growing season, the soil layer immediately beneath the plastic mulch will remain wetter than the unmulched surface. As a result of the differences in water content, the thermal contact coefficient of the exposed surface soil layer will become lower than the thermal contact coefficient of the plastic-covered soil. Unless the plastic greatly increases the surface heat flux density over that of the unmulched surface, the unmulched dry surface will have a higher surface temperature variation than the plastic covered wet soil because of its low thermal contact coefficient. A thin material such as plastic can also increase the surface-air interface temperature if it creates an air layer between the material and the soil. The thermal contact coefficient of even moist air is very low, and this insulating air layer so near to the surface will cause high temperatures during the day and low temperatures during the night.

The presence of moist soil just below a dry surface soil will prevent the surface temperature extremes that would occur if the entire profile was dry. To illustrate this, consider the ratio of the surface temperature variations of two pumice soils, one having a water content of 5 percent by volume in the A1 and AC horizons and the other having a water content of 5 percent in a surface layer 1.0 centimeter thick and then a water content of 30 percent by volume in the remainder of the A1 and AC horizons. The A1 and AC horizons have nearly identical thermal properties at equal volumetric water contents. One can deduce that the wet soil near the surface results in a 46-percent reduction in the surface temperature variation by applying equation 8 with the necessary information from figures 5 and 6, assuming equal heat flux densities. This aids in explaining

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[8] Thermal properties used here are those of plexiglass and are taken from Bulletin P. L. 229, Rohm and Haaf plexiglass design and fabrication data. Rohm and Haaf Co., 1949, pages 3 and 4.

the observations of Silen[9] who found that the presence of wet soil near the dry surface soil reduced the temperature-caused mortality of Douglas-fir seedlings.

Other Factors Influencing Surface Temperatures

In addition to the soil thermal properties, several other factors influence the surface temperature. The factors of slope, aspect, vegetative cover, and shading affect the net radiation flux density of the surface and hence the heat flux density of the soil surface.

The cooling effect of evaporation from the soil surface is an additional important factor which may be understood by consideration of equation 1. With a given net radiation flux density (R_n) an increase in evaporation causes an increase in the energy used in evaporation (LE) and a reduction in the soil and sensible heat flux densities (the G and H terms). The reduction in the soil heat flux density (G) would reduce surface temperature variation, as shown by equation 6.

Surface roughness and wind or air turbulence are also important factors which reduce temperature variation. With the possible exception of short, very calm periods at night, any air movement near the ground is characteristically turbulent. In turbulent flow, fluctuations in the path of air volumes are on a similar scale with the surface irregularities. These surface irregularities are large in comparison with the exceedingly small distances between air molecular collisions. As a consequence, the transfer of heat in air is not limited to molecular conduction, but is vastly increased by transfer of parcels of air away from the surface and their replacement by parcels of air of different temperature (Rose 1966). With increasing turbulence during the day, the sensible heat flux density and the evaporative heat flux density are increased; the soil heat flux density is reduced resulting in a decrease in the maximum surface soil temperature. At night, turbulence can raise the minimum soil temperature by causing a continuous, rapid exchange of cold parcels of air near the surface for warm air parcels above. The soil surface temperature gradient is reduced decreasing the heat flux out of the soil.

The influence of color on surface temperature has probably been overemphasized. A light-colored soil with the same thermal properties and surface characteristics as a dark-colored soil will have the lesser surface temperature variation because it will reflect more solar radiation and its soil heat flux density will be lower. However, in the field many dark surfaces such as charcoal layers and surface horizons with high organic matter contents have lower thermal contact coefficients than lighter colored exposed subsoils. In the later example, difference in thermal properties is more important in influencing surface temperature variation than is color. As an example, suppose that a deep, dark-colored, surface horizon has a thermal contact coefficient that is half as large as the thermal contact coefficient of a deep, light-colored soil. If the heat flux densities are the same, the surface temperature variation of the dark

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[9] Silen, Roy Ragnar. Lethal surface temperatures and their interpretation for Douglas-fir. 1960. (Unpublished Ph. D. thesis, on file at Oregon State Univ., Corvallis.)

soil will be twice the surface temperature variation of the lighter soil (equation 7). If the lighter soil had a heat flux density only 70 percent of that of the dark-colored soil but the thermal contact coefficients were equal, the dark-colored soil would have a temperature variation only 1.4 times as large as the light-colored soil. If the light-colored soil had a heat flux density only 70 percent of the heat flux density of a dark-colored soil and a thermal contact coefficient twice that of the dark soil, the dark soil would have a temperature variation equal to approximately 2.9 times that of the lighter colored soil.

Modifying Temperature Extremes in the Field

Any management practice which affects either the thermal properties of the seedbed or the heat flux density of the seedbed will modify the temperature environment of the seedlings. Examples of practices which would decrease the thermal contact coefficient of the surface and thus increase the surface temperature variation (unless the soil heat flux density is lowered significantly) are: (1) cultivation which increases the soil-air space and thereby reduces both the thermal conductivity and volumetric heat capacity; and (2) mulching with dry organic mulches or other materials which have lower thermal conductivities and volumetric heat capacities than the soil. Examples of practices which would increase the thermal contact coefficient of the surface and thereby decrease the surface temperature variation (unless the heat flux density was significantly increased) are: (1) compaction, which decreases the soil-air space and increases both the thermal conductivity and volumetric heat capacity; (2) mulching with materials which have a higher thermal contact coefficient and thermal diffusivity than the soil; (3) removal of litter and exposure of mineral soil; and (4) irrigating, which increases the moisture content of the soil and results in an increased thermal contact coefficient. Irrigation also results in an increase in the LE term of equation 1 and a reduction in the soil heat flux density, which also aids in the reduction of temperature extremes.

Irrigation by sprinkling (Geiger 1965) is also used for night frost protection in some nurseries. When water freezes, heat is given off (80 cal./g.), and this heat keeps the temperature of the plant tissue from falling below freezing. The sprinklers are turned on just before the air temperature drops below freezing. When the air temperature drops below freezing, the droplets of water on the seedlings begin to freeze. Some of the heat given off is absorbed by the plant tissue; and as long as the air temperature drop is not too severe, the plant tissue itself will not freeze, even though it is coated with ice. The sprinkling system employed allows unfrozen water droplets to continually hit each plant, keeping the ice coatings continually covered with liquid water so the tissue temperature will not drop below freezing. The sprinklers are left on until after sunrise when the air temperature rises above freezing and the ice covering the plants melts.

A modification of the soil heat flux density by partial shading obviously reduces the maximum daytime surface temperature. Shading can also raise minimum soil surface temperatures at night by reducing the net amount of outgoing longwave radiation.

Practicing foresters may have to irrigate, modify the soil surface, or shield seedlings to insure regeneration on some sites where severe surface temperatures occur. In addition, recognition of soil, topographic, and moisture conditions which increase the likelihood of frost damage or heat injury can be used to practical advantage. For example, creation of large openings within stands growing on flat or depressional areas in the pumice soil region of south-central Oregon will create an extreme frost hazard. Observations in this region indicate that planting ponderosa pine in such areas is often useless. Research is needed to determine the effect of width of strip cutting on variation in soil and air temperatures and survival and development of lodgepole and ponderosa pine seedlings. In other areas, planting or seedspotting next to stumps, logs, and rocks where the soil surface will be protected from direct solar radiation and where the seedlings can intercept some of the longwave radiation emitted at night will decrease the probability of heat injury and radiation frost damage. Removing the organic layer from around the base of planted seedlings or from the area of seedspotting will also reduce the probability of mortality, particularly from heat injury.

SUMMARY

Heat flux density and thermal properties of soil control surface temperature variation. Slope, aspect, shade, water content, evaporation rates, wind, surface roughness, and color all influence either the soil heat flux density, the thermal properties, or both. All other factors being equal, soils with lower thermal contact coefficients exhibit larger surface temperature variations.

Pumice soils have much lower thermal contact coefficients and thermal diffusivities than denser mineral soils. Large clearcut openings in flat or depressional areas in the pumice soil region accentuate the high probability of frost and often prohibit immediate establishment of ponderosa pine on these areas.

Modification of either the soil heat flux density or the soil thermal properties will change the environment of seedlings.

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