

Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile

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A direct comparison of temperatures and heat loads was made between simulated duff-covered (~2 cm) and uncovered mineral soil beneath a burning fuel pile. Temperatures were recorded in the duff, at the duff – mineral soil interface, and at 1-cm intervals downward to a depth of 4 cm. Covering reduced the peak temperatures about 200°C in dry mineral soil. Wet mineral soil covered with wet duff experienced a temperature reduction of over 500°C. Temperatures in wet mineral soil did not exceed 90°C and the heat load into the wet mineral soil was, on the average, 20% of the heat load into the dry mineral soil. Land managers wanting to minimize mortality of existing plants or loss of soil organics should strive to burn when mineral soils are approaching saturation near the surface.

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Les températures et les flux de chaleur reliés au brûlage d'un combustible ont été comparés entre un sol minéral découvert et recouvert d'une couche d'humus (~2 cm). Les températures ont été enregistrées dans l'humus à l'interface humus – sol minéral et à chaque centimètre de profondeur jusqu'à 4 cm. La couche d'humus a réduit par 200°C la température maximale atteinte dans le sol minéral sec. Le sol minéral humide recouvert d'une couche d'humus humide a subi une diminution de la température maximale de 500°C. Dans le sol minéral humide les températures n'ont pas dépassé 90°C et le flux de chaleur ne dépassait pas 20% de celui dans le sol minéral sec. Le gestionnaire qui veut minimiser la mortalité des plantes ou la perte du matériel organique doit faire l'impossible pour effectuer le brûlage contrôlé lorsque la surface du sol minéral est près de la saturation.

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Introduction

Throughout the forests of western North America, prescribed fire is widely used as a means of reducing unwanted fuels, preparing sites for seeding, and for managing vegetation. Forest managers want to accomplish these objectives while minimizing adverse impacts on the soil, such as excessive consumption of organic matter and soil sterilization.

Soil heating can alter the physical character of the soil, resulting in reduced infiltration (Austin and Baisinger 1955), reduced water absorption (Neal *et al.* 1965), and alteration of clay structure (Kohnke 1968). Some soil microorganisms may survive temperatures near 200°C (Dunn *et al.* 1979), but heating the soil to about 55°C induces tissue mortality in higher plants (Levitt 1980). Heating can also induce chemical changes that affect short- and long-term nutrient availability. Combustion of organic matter releases cations (Wells *et al.* 1979) that constitute important plant nutrients. Consumption of organic materials may have great, although delayed impact on the biological activity of the soil. Nitrifying bacteria and fungi in the soil require an organic substrate for growth. They consume organics and release nitrogen in a form that is readily available to plants. Combustion of organic matter in the soil may thus reduce the future supply of nitrogen. The impact on the site depends to a large measure on the amount of organic residue remaining after the fire (Harvey *et al.* 1979).

Common experience suggests that surface fires with abundant and persistent flames produce high temperatures in the mineral soil. A covering of moist duff is expected to suppress mineral soil temperatures initially, but surface burning is assumed to dry the duff, which then burns, often after the passage of the surface fire. The purpose of this study was to determine if thin duff

layers (~2 cm) suppress heat transfer into the mineral soil. The addition of moisture to either the duff or the mineral soil is expected to further affect heat transfer and will also be examined for its effect. The evaluation will be based on temperature profiles and heat loads in duff-covered mineral soil compared with bare mineral soil.

Background

The amount of duff (fermentation and humus horizons) consumed by a fire depends on a complex interaction of physical properties and the external heat supplied by a surface fire.²

Adding moisture to the duff and mineral soil causes three important changes in their character. It changes the heat capacity and thermal conductivity and it changes the character of heat transfer from simple conduction to mass transport once the water has changed phase to the vapor state (see Miller 1977). The flow of heat is further altered by the required absorption of the heat of vaporization to accomplish the change of phase. The heat capacity is increased in proportion to the volume fraction of the soil that is occupied by the water (DeVries 1963). Thermal conductivity also increases, but not in such a simple manner. For sand, the thermal conductivity can exhibit an apparent 10-fold increase by adding moisture (DeVries 1963).

The change in phase associated with the moisture in the mineral soil matrix depresses the temperatures at the soil interface, in comparison to dry mineral soils, by requiring the absorption of the heat of vaporization. Increased thermal conductivity because of moisture below the interface increases heat conduction away from the interface, further reducing the temperature gradient near the interface relative to the dry state.

²A fire propagating in duff is called a ground fire and, although it may be aided by a surface fire, is distinct from a surface fire (Brown and Davis 1973).

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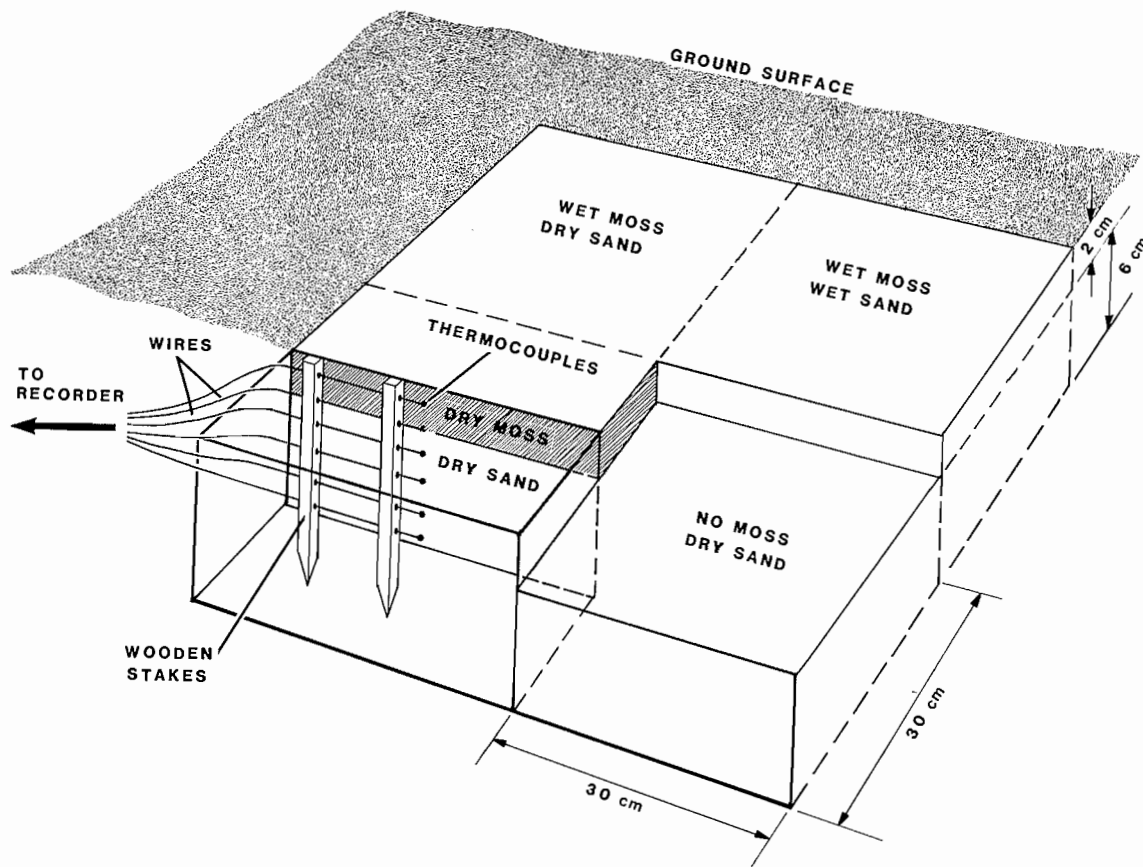


FIG. 1. A diagrammatic view of simulated soil profiles. Thermocouples are 30-gauge chromel–alumel wires. They are held in position by two wooden posts. The depth intervals are 1 cm. The top thermocouple is at the surface of the uncovered sand profile and 1 cm below the moss surface in the remaining moss–sand profiles.

Although moist duff conducts heat better than drier duff, wet duff limits heat transport into the mineral soil if it is not ignited. If the duff is sufficiently dry to be ignited, however, the combustion zone moves downward to the mineral soil interface. As a result, the mineral soil would experience a greater influx of heat under the dry duff conditions described above than it would if the duff layer were too wet to burn ($>30\%$ moisture) (Sandberg 1980; Brown *et al.* 1985), even though wet duff is a better conductor of heat.

Method

Four different duff mineral soil profiles were positioned under the same fuel pile measuring $2.5 \times 2.5 \times 0.75$ m deep. It was constructed of uniformly spaced dimensioned lumber, 4 by 9 cm in cross section. The fuel load was 560 t/ha and the moisture content was 11%. Mineral soil consisted of 8 cm of sand; 2 cm of peat moss represented the duff layer. The plot containing the four profiles was constructed within a square trench cut from the soil beneath the center of the fuel pile (Fig. 1).

Temperatures were recorded with 30-gauge chromel–alumel thermocouples in the duff, 1 cm above the duff–mineral soil interface, at the interface, and at 1-cm intervals downward to a depth of 4 cm. The thermocouple response time is of the order of 10 ms. Similar methods of measuring the temperature under fuel piles have been employed by others (e.g., Roberts 1965; Humphreys and Lambert 1965; Cromer and Vines 1966). However, these studies used existing soil rather than a simulated soil with known properties. They also did not vary the substrate.

One of the profiles in this study had no moss covering so that the sand (dry) could receive the full impact of the downward heat flux. It acted as

a standard to which the lower expected sand temperatures under the covered profiles could be compared. Two of the covered profiles were dry sand covered with dry moss and dry sand covered with wet moss to simulate conditions that would achieve moderate temperature reductions. The extreme conditions associated with the lowest expected mineral soil temperatures are simulated in the third covered profile with wet moss covering wet sand. All conditions simulate common soil moisture regimes in natural forest stands. Dry sand covered with dry moss simulates dry summer and early fall conditions when both duff and mineral soil are low in moisture. Dry sand covered with wet moss simulates the conditions when a light rain wets the duff, but does not recharge the mineral soil. Wet sand covered with wet moss simulates the spring when both duff and mineral soil are wet. Dry moss had 12% moisture content, wet moss had 117%, and wet sand was near saturation at 25% moisture content. The dry bulk density of the moss was 0.09 g/cm^3 , well within the range of duff observations we have made in the field ($0.05\text{--}0.20 \text{ g/cm}^3$).

The heat flux, I , through the sand surface was estimated from the temperature difference, ΔT , measured vertically through the top centimetre of sand. It is the product of the temperature difference and the thermal conductivity, k , of the sand layer.

$$[1] \quad I = k(\Delta T)$$

Approximate values for the thermal conductivity are $0.25 \text{ W m}^{-1} \text{ K}^{-1}$ for dry sand and $2.5 \text{ W m}^{-1} \text{ K}^{-1}$ for wet sand near saturation (DeVries 1963). Dry sand was assumed for all cases except for wet sand covered with wet moss and the initial response of dry sand covered with wet moss up to 90°C . Above 90°C , water is assumed to have evaporated from the soil matrix.

The cumulative heat load, H , passing through the top centimetre of sand, can be estimated by integrating the heat flux over time, t .

$$[2] \quad H = \int_0^t I dt$$

These two variables, H and I , allow comparisons to be made to evaluate the thin duff layer as a possible barrier to heat transfer into the mineral soil.

Results

The maximum flame height was 6 m. Flaming lasted for about 0.75 h; glowing, for another 2–3 h.

Figures 2 and 3 illustrate the effect of a duff cover. Covering the sand with 2 cm of dry moss lowered the peak temperatures from 680 to 360°C (Fig. 2). Adding water to the moss resulted in a similar reduction from 680 to 430°C (Fig. 3). The most striking change occurred when moisture was added to both the sand and the moss. Peak mineral soil temperatures were reduced from 680°C in the standard to about 80°C (Fig. 3).

A comparison of dry sand covered by wet moss and dry sand covered by dry moss suggests that dry moss tended to reduce the peak temperature, but extend the duration of heating (Fig. 2). This was not observed on the other profiles. Wet sand covered with wet moss experienced a reduction in both the temperature and the duration of heating (Fig. 3). Examination of the moss residue over dry sand showed complete charring in both cases, with some white ash found on the surface of the dry moss residue. Spikes in the temperature history 4 h after ignition (Fig. 2) suggest that moss continued to burn after the pile stopped flaming. However, the long delay leads us to view the temperatures beyond 4 h with skepticism.

Charring was incomplete in the wet sand covered by wet moss. The upper 1 cm was charred, but the lower 1 cm remained unburned. This is consistent with the observed temperatures. Temperatures in the moss 1 cm above the sand interface were near 300°C for about 1.5 h during the flaming period and early glowing of the burning pile, while 1 cm below at the moss–sand interface, the temperature did not exceed 90°C.

Paired temperatures profiles in the uncovered dry sand showed no significant differences. The heat flux rose initially above 10 kW/m² within the first 8 min after ignition and then dropped to between a range of 1.5–3.0 kW/m² for about 1 h. The heat flux into the sand ceased 2 h after ignition when the top thermocouple recorded a lower temperature than the lower thermocouple. The average of the total cumulative heat load passing through the top 1 cm of uncovered sand measured by the two arrays was 20 MJ/m² (Fig. 4), with a range from 19 to 21 MJ/m².

The heat flux through the top 1 cm of dry sand covered with dry moss rose to above 3.3 kW/m² in the first 20 min after ignition, well below the peak seen by uncovered sand. It then held at about 2.5 kW/m² until 1 h after ignition, when it began a steady decline to 0.17 kW/m² 4 h after ignition. At this time, the cumulative heat load had reached 18 MJ/m² (Fig. 4). There was an additional heat load received after 4 h associated with the temperature spikes shown in Fig. 2. However, it was not included in the heat load calculations because we were uncertain of its significance. It occurs well beyond the cessation of active burning and the onset of glowing 45 min after ignition.

Figure 3 shows the presence of moisture below 90°C in dry sand covered with wet moss as evidenced by the discontinuity at 90°C. This suggests that moisture has migrated from the wet moss into the sand as observed by Uggle (1974). The thermal conductivity in this region lies between dry and wet sand. The heat-transfer process is complicated by the transport of heat through the mass movement of moisture. Conceptually, the

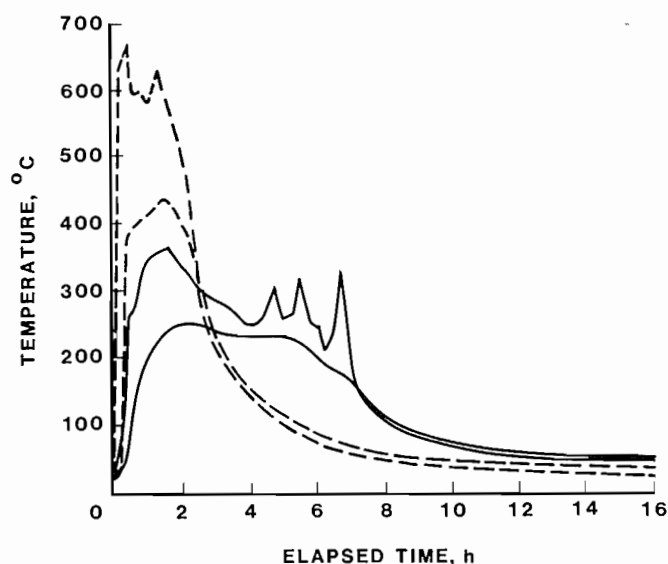


FIG. 2. Temperature histories in uncovered dry sand (---) and dry sands covered with dry moss (—). Two curves are shown for each profile. The upper curve is the temperature at the sand surface; the lower, 2 cm below the surface.

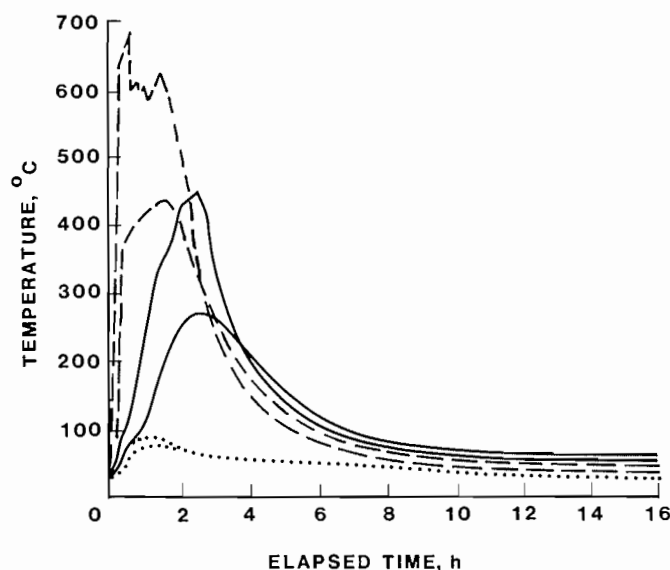


FIG. 3. Temperature histories in uncovered dry sand (---), dry sand covered with wet moss (—), and wet sand covered by wet moss (····). Two curves are shown for each profile. The upper curve is the temperature at the sand surface; the lower, 2 cm below the surface.

thermal conductivity in the simplified expression for heat transfer (Eq. 1) should be an effective value that accounts for the mass transfer of heat by moisture movement. However, for this analysis, below 90°C we used the thermal conductivity for wet sand near saturation. Above 90°C (35 min after ignition) there is no moisture in the top 1 cm of the sand, allowing us to use the thermal conductivity for dry sand. The heat flux was about 2.1 kW/m² after the moisture had left and held at that level until it started to decline 2 h after ignition. The heat flux ceased 3 h after ignition, 1 h longer than in uncovered sand. The total cumulative heat load through the top 1 cm of sand lies between 17 and 26 MJ/m² (Fig. 4), assuming that the sand within the first half hour after ignition is either dry or wet, the larger value being associated with wet sand.

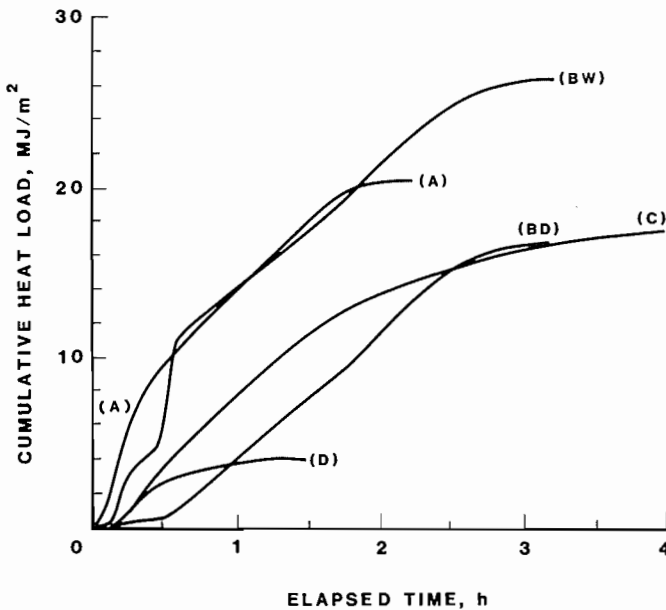


FIG. 4. Cumulative heat load passing through the top centimeter of sand versus time for (A) uncovered dry sand (hand-drawn average of paired observations), (BW and BD) dry sand covered with wet moss (BW, top 1 cm of sand assumed saturated; BD, top 1 cm of sand assumed dry), (C) dry sand covered with dry moss, and (D) wet sand covered with wet moss.

The heat flux in wet sand covered with wet moss rose to about 2.5 kW/m^2 15 min after ignition and remained at that level for about 5 min. It then dropped exponentially. There was no measurable heat flux 1.5 h after ignition. The total cumulative heat load through the top 1 cm of sand was only about 4.2 MJ/m^2 (Fig. 4), even though the thermal conductivity used was for that of wet sand near saturation, a value 10 times higher than dry sand.

Discussion

The direct comparison of the mineral soil temperatures in the soil profiles exposed to the same uniformly burning fuel pile illustrates the influence of soil moisture on mineral soil temperatures.

These data support the recommendations of Aufderheide and Morris (1949) to burn after rain has dampened both the duff and the soil if you wish to reduce the impact of heat on the mineral soil. Uggla (1974) confirms the advantages of burning when the soil is wet. He, too, observed a steep gradient at the duff interface and low temperatures in wet soil beneath slash fires.

It is important to note that although temperatures in the mineral soil were reduced by the presence of a wet duff layer, the moisture content of the mineral soil was a greater importance. This is supported by the observation of 1 cm of residual uncharred moss when the sand was wet as opposed to complete charring of the moss when the sand was dry. Mineral soil moisture is not considered by Van Wagner (1972), Shearer (1975), Norum (1977), Sandberg (1980), or Brown *et al.* (1985) when describing the dependence of duff consumption on duff moisture content. Differing amounts of soil moisture may explain some of the variation they observed, particularly at the higher duff moisture contents.

When sand and moss were both wet, the temperature in the sand did not exceed 90°C (Fig. 3). When burning over moist duff and soil, we have consistently found a levelling off of

temperature rise in the 77 to 84°C range. This appears to be due to the evaporation of moisture from the mineral soil matrix. Soil moisture provides a significant barrier to elevating temperatures above that range.

Lethal temperatures in excess of 55°C for higher plants (Levitt 1980) occurred in each of the "duff-soil" profiles. Lethal temperatures for microorganisms were greatly exceeded in all but the wet moss over wet sand profile. Microorganisms can, however, quickly reinvade the site if there is a suitable organic substrate (Wright and Bollen 1961; Dunn *et al.* 1979). If temperatures exceed 240°C , organic material is pyrolyzed (S.A. Susott, personal communication) and the source of food for mineralizing microorganisms is lost, thus the source of nitrogen for future revegetation is substantially reduced. These data suggest that wet mineral soil prevents soil temperatures from reaching the level of organic pyrolysis, while dry mineral soils may result in pyrolysis of organics and loss of nitrification. It is suggested that exceeding the temperature of pyrolysis, 240°C , has more serious implications than exceeding the lethal temperature of plants, 55°C .

From the heat transfer point of view, the top 1 cm of all sand profiles sustained heat fluxes within the range 1.7 to 2.9 kW/m^2 for periods of 5 min to 2 h. Both covered and uncovered dry sand profiles experienced heat loads at the sand surface within the range 17 to 26 MJ/m^2 (Fig. 4). However, wet sand covered with wet moss experienced only 4.2 MJ/m^2 , approximately 20% of the dry sand heat load. The addition of moisture to the mineral soil below wet duff significantly reduced the heat load and the duration of heating. Peak temperatures were reduced by more than 500°C compared with uncovered dry sand.

Aside from the reduction in the dynamic heating process as a result of moisture, these results imply that fire removes organic material from the soil, the amount depending on the moisture content of the mineral soil and the duff. Dry mineral soil covered with dry duff may lead to complete removal of the duff layer and some of the organics in the upper portion of the mineral soil. This achieves the often prescribed exposure of mineral soil and may lead to rapid establishment and growth of seedlings because of reduced competition and the release of nutrients. This may be followed by a decline in the growth rate owing to a reduced release of nutrients because of a lack of organic material. On the other hand, wet mineral soil covered with wet duff, the other extreme, may diminish the impact of the fire to such an extent that mineral soil is not exposed. A prescribed fire in broadcast or hand-piled slash may be desirable to remove portions of the duff, but it should not destroy the organics incorporated in the mineral soil (Day and Duffy 1963).

AUFDERHEIDE, R., and W. G. MORRIS. 1949. Broadcast slash burning after a rain. *Fire Control Notes*, 10(4): 1-6.

AUSTIN, R. C., and D. H. BAISINGER. 1955. Some effects of burning on forest soils of western Oregon and Washington. *J. For.* 53: 275-280.

BROWN, A. A., and K. P. DAVIS. 1973. *Forest fire: control and use*. 2nd ed. McGraw-Hill, Inc., New York.

BROWN, J. K., M. A. MARSDEN, K. C. RYAN, and E. D. REINHARDT. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. U.S. Dep. Agric. For. Serv. Res. Pap. INT-337.

CROMER, R. N., and R. G. VINES. 1966. Soil temperatures under a burning windrow. *Aust. For. Res.* 2(2): 29-34.

DAY, R. J., and P. J. B. DUFFY. 1963. Regeneration after logging in the Crowsnest Forest. *Publ. Can. For. Serv.* No. 1007.

DEVRIES, D. A. 1963. Thermal properties of soils. *In* *Physics of plant*

- environment. *Edited by* R. VanWijk. North-Holland Publishing Co., Amsterdam. pp. 210–235.
- DUNN, P. H., L. F. DEBANO, and G. E. EBERLEIN. 1979. Effects of burning on chaparral soils. II. Soil microbes and nitrogen mineralization. *Soil Sci. Soc. Am. J.* **43**: 509–514.
- HARVEY, A. E., M. J. LARSEN, and M. F. JURGENSEN. 1979. Fire-decay: interactive roles regulating wood accumulation and soil development in the northern Rocky Mountains. USDA For. Serv. Res. Note INT-263.
- HUMPHREYS, F. R., and M. J. LAMBERT. 1965. Soil temperature profiles under slash and log fires of various intensities. *Aust. For. Res.* **1**(4): 23–29.
- KOHNKE, H. 1968. *Soil physics*. McGraw-Hill, Inc., New York.
- LEVITT, J. 1980. Responses of plants to environmental stresses. Vol. 1. Chilling, freezing, and high temperature stresses. Academic Press, New York.
- MILLER, M. 1977. Response of blue huckleberry to prescribed fires in a western Montana larch-fir forest. U.S. Dep. Agric. For. Serv. Res. Pap. INT-188.
- NEAL, J. L., E. WRIGHT, and W. B. BOLLEN. 1965. Burning Douglas-fir slash: physical, chemical, and microbial effects in the soil. Res. Pap., Oreg. State Univ., For. Res. Lab., No. 1.
- NORUM, R. A. 1977. Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA For. Serv. Res. Note INT-229.
- ROBERTS, W. B. 1965. Soil temperatures under a pile of burning logs. *Aust. For. Res.* **1**: 21–25.
- SANDBERG, D. V. 1980. Duff reduction by prescribed underburning in Douglas-fir. U.S. For. Serv. Res. Pap. PNW-272.
- SHEARER, R. C. 1975. Seedbed characteristics in western larch forests after prescribing burning. U.S. Dep. Agric. For. Serv. Res. Pap. INT-167.
- UGGLA, E. 1974. Fire ecology in Swedish forests. *Proc. Tall Timbers Fire Ecol. Conf.* **13**: 171–190.
- VAN WAGNER, C. E. 1972. Duff consumption by fire in eastern pine stands. *Can. J. For. Res.* **2**: 34–39.
- WELLS, C. G., R. E. CAMPBELL, L. F. DEBANO, C. E. LEWIS, R. L. FREDRIKSEN, E. C. FRANKLIN, R. C. FROELICH, and P. H. DUNN. 1979. Effects of fire on the soil: a state-of-the-knowledge review. Gen. Tech. Rep. WO-7 (U.S. For. Serv.).
- WRIGHT, E., and W. B. BOLLEN. 1961. Microflora of Douglas-fir forest soil. *Ecology*, **42**: 825–828.