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Freezing in Forest Soil As Influenced by Soil Properties, Litter, and Snow

by
David B. Thorud and David A. Anderson[1]

Water Resources Research Center
University Of Minnesota
Room 107, Hubbard Building
2675 University Avenue
St Paul, Minnesota 55114

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[1] Associate Professor, Department of Watershed Management, University of Arizona, Tucson, and Hydrologist, U.S. Forest Service, Tempe, Arizona, respectively (both formerly with the University of Minnesota School of Forestry).

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This Bulletin is published in furtherance of the purposes of the Water Resources Research Act of 1964. The purpose of the Act is to stimulate, sponsor, provide for, and supplement present programs for the conduct of research, investigations, experiments, and the training of scientists in the field of water and resources which affect water. The Act is promoting a more adequate national program of water resources research by furnishing financial assistance to non-federal research.

The Act provides for establishment of Water Resources Research Institutes or Centers at Universities throughout the Nation. On September 1, 1964, a Water Resources Research Center was established in the Graduate School as an interdisciplinary component of the University of Minnesota. The Center has the responsibility for unifying and stimulating University water resources research through the administration of funds covered in the Act and made available by other sources; coordinating University research with water resources programs of local, State and Federal agencies and private organizations throughout the State; and assisting in training additional scientists for work in the field of water resources through research.

This report is the tenth in a series of publications designed to present information bearing on water resources research in Minnesota and the results of some of the research sponsored by the Center. In the present investigation, laboratory experiments were conducted to obtain knowledge concerning the forest-associated variables that control soil freezing. The results of the research potentially have practical management implications with regard to the effect soil freezing under various forest conditons has on surface water runoff in Minnesota.

Freezing in Forest Soil as Influenced by Soil Properties, Litter, and Snow

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INTRODUCTION

Frozen soil is frequently assumed to promote surface runoff and possibly flooding during spring snowmelt and rainfall events in the north central and northeastern United States (Storey, 1955; Haines, 1965; U.S. Department of the Interior, 1953). Perhaps this assumption has not been adequately documented, but a considerable amount of circumstantial and some direct evidence is rather convincing. Even on the east slope of the Sierra Nevada Mountains, Haupt (1967) found that frozen soil could increase surface runoff on plots. Rantz and Harris (1963) suggested that California and Nevada floods of 1963 may have been partly a result of frozen soil.

Many studies under field conditions have demonstrated that frozen soil varies considerably in depth, persistence, spatial and temporal frequency, and probable permeability (Lull and Pierce, 1959; Pierce, Lull and Storey, 1958; Sartz, 1957; Weitzman and Bay, 1963; Haupt, 1967; Stoeckeler and Weitzman, 1960). A portion of the variation between localities can probably be attributed to differences in atmospheric conditions which determine the magnitude of the heat sink into which soil heat must flow to cause freezing. Thus frost depths of 30 to 50 inches might be found in Minnesota, while for comparable soil and snow conditions perhaps only 5 to 10 inches or less may be found in New England.

Other variables, however, that cause significant variations in soil freezing are organic accumulations on the soil surface, mineral soil conditions, and snow. The organic accumulations will hereafter be referred to generally as "litter" unless otherwise noted. The type and degree of forest cover significantly affects these variables and therefore the degree and type of soil freezing encountered (Pierce, Lull and Storey, 1958; Lull and Pierce, 1959; Weitzman and Bay, 1963; Bay, 1960; Bay, 1958). Deciduous and coniferous forest, young and old stands, varying densities, and many mixed conditions are found throughout the region of soil frost occurrence. Since these forests change naturally and are also changed by man, an understanding of the forest-associated variables that control soil freezing could potentially have practical management implications. Such knowledge could also improve our capability to predict hydrologic behavior for existing conditions without regard to management possibilities if frozen soil is important.

Useful information on freezing as influenced by litter, soil, and snow has been obtained from field studies. But it is usually difficult without special experimental arrangements to isolate the effect of specific environmental factors under field conditions (Striffler, 1959; Pierce, Lull and Storey, 1958; Kienholz, 1940; Potter, 1956; Colman, 1953). The integrated result of several variables which operated simultaneously during times of soil freezing is often measured. Therefore, it seemed expedient to study soil freezing in the laboratory where individual variables could be isolated, compared,and studied in combination.

An initial goal for our laboratory studies was an experimental evaluation of the relative importance of selected variables including soil type, soil density, litter, and snow. Specific evaluations included (1) loamy sand and silt loam soil types, (2) compacted and uncompacted loamy sand (for a study of soil density effects), (3) oak, red pine, and white pine litter in both air-dry and moist states, and (4) shallow snow layers accumulated naturally on both bare soil (loam) surfaces and on a red pine litter surface. These studies were largely a descriptive survey which we hope will identify problems for more theoretical development.

METHODS

Schmertmann (1958) described a laboratory method for freezing small, artificially prepared soil columns in a cold chamber. In our studies Schmertmann's technique was substantially modified in design, but the control principles were similar. We used large soil monoliths which were rectangular in initial studies and cylindrical in later experiments. The monoliths were frozen in 28-cubic-feet chest-type freezers (Figures 3, 6, and 7).

The monoliths with essentially undisturbed horizon sequences were taken intact from the field by excavating a large moat around a pedestal of soil which was then removed and fitted snugly into a styrofoam container. The rectangular monoliths were 10½ inches deep, 13 inches long, and 8½ inches wide (Figure 1). The weights ranged from 69 to 97 pounds, depending on soil type and state of compaction. The cylindrical monoliths were 9 inches in diameter, 8½ inches deep, and weighed between 28.8 and 32.1 pounds (Figure 4).

Control of boundary conditions was necessary in these experiments. The container enclosing the monolith had insufficient insulating capacity to prevent freezing from the sides and bottom. Additional insulating material and supplementary heat sources were placed around and under the monoliths to simulate freezing under natural circumstances. A double-layered styrofoam product was form-fitted to the rectangular monoliths (Figures 1, 2, and 3). In addition, 30-watt heat tapes imbedded in the insulation completely encircled the container at levels 2, 5, and 8 inches below the soil surface (Figure 2). Strips of aluminum foil were placed beneath each heat tape and extended between the two insulation sheets to broaden the heating zone. Slots were cut in the styrofoam at the corners to prevent concentrated heating due to the 90° bend in the tapes (Figure 2). These openings resulted in an outward heat loss from the tapes. The size of the slots was determined empirically by measuring soil temperature in the corner zone during freezing tests. Concentrated heating at corners was not a consideration for cylindrical monoliths and was one reason for their adoption in later studies.

For cylindrical monoliths, 3-foot, 30-watt heat tapes were wrapped around the outside of the styrofoam container at 2-, 5-, and 8-inch depths (Figure 5). Aluminum foil strips were placed between the tapes and the container. Then three sheets of polyurethane insulation were wrapped tightly around the container and taped (Figure 6).

The bottom insulation for cylindrical monoliths was also styrofoam material (Figure 4). In both monoliths a 3-foot heat tape was imbedded in the upper sheet. A metal plate was placed between heat tape and container (Figure 4) to facilitate uniform heating across the bottom. Uniform heating was confirmed by measurement for rectangular monoliths and was assumed for cylindrical monoliths.

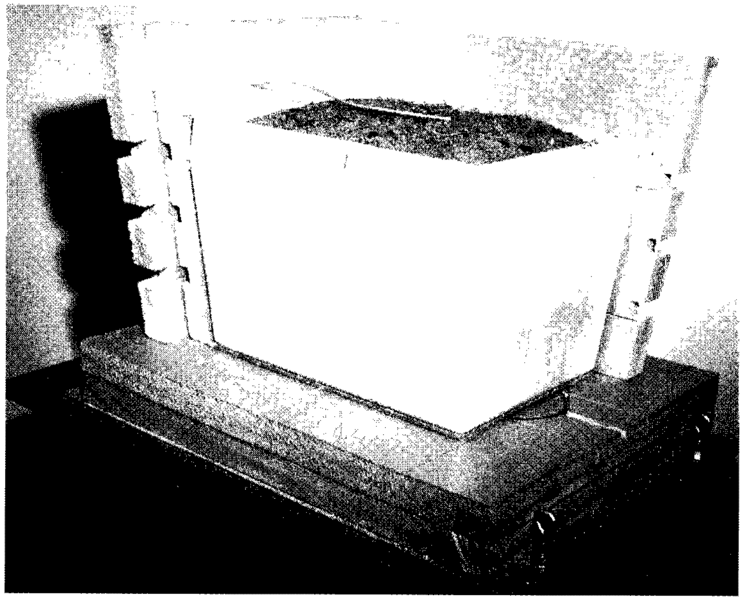


Figure 1. Rectangular monolith in container, surrounding insulation and thermistor of the type used in this study.

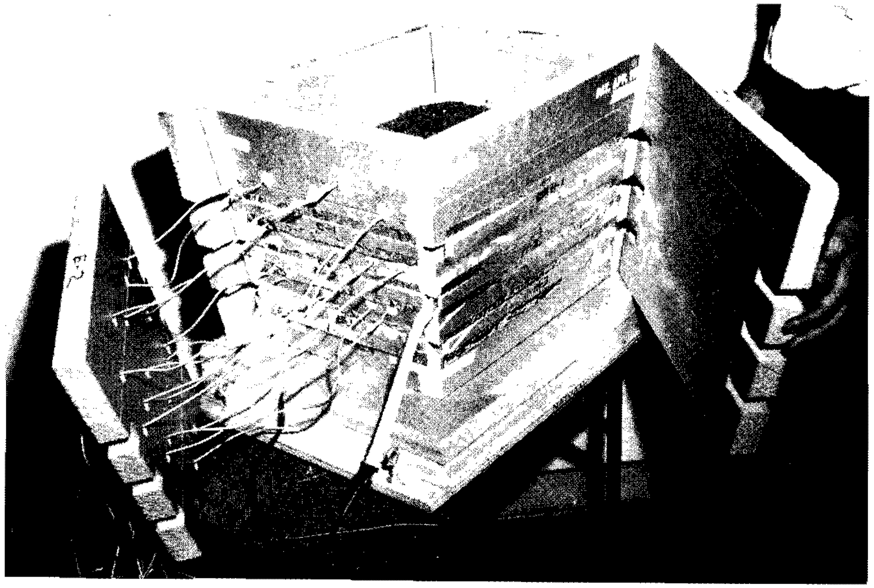


Figure 2. Nearly completed assembly. Styrofoam strips are in place over heat tapes except at exposed corners.

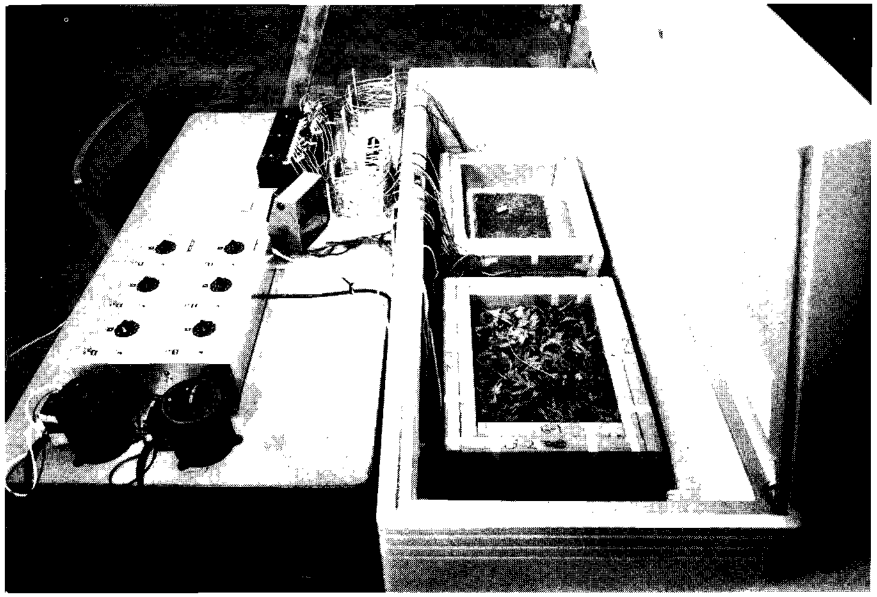


Figure 3. Monoliths in place and ready for a test. The thermistor thermometer and switch box are on the upper end of the table and a panel of transformers on the lower end.

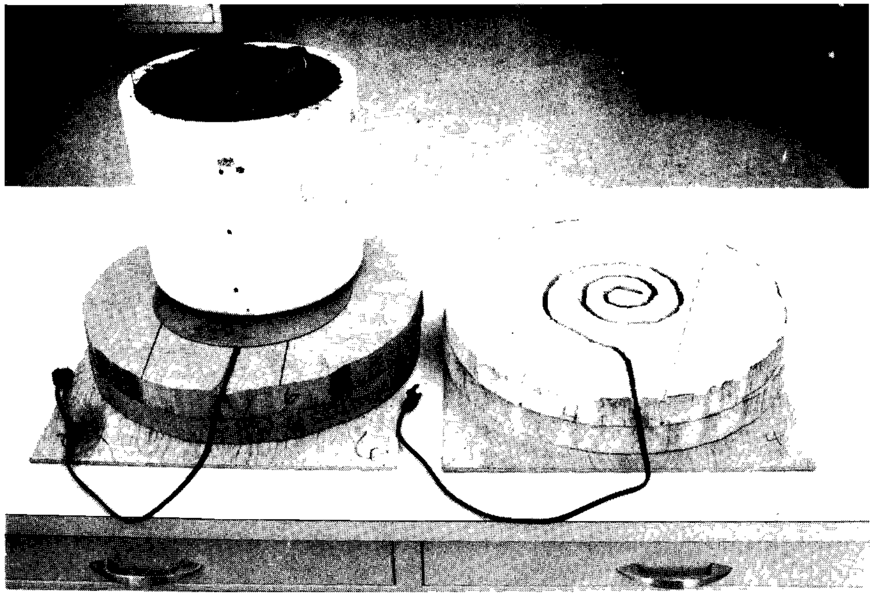


Figure 4. Cylindrical monolith on metal base plate, and bottom insulation which is shown at the right with an imbedded 3-foot heat tape.

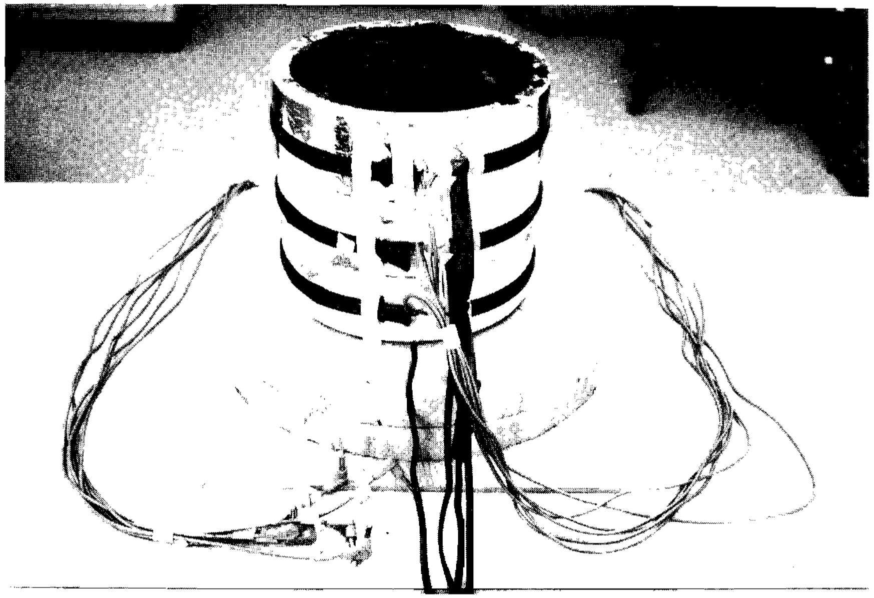


Figure 5. Cylindrical monolith with heat tapes, aluminum foil and thermistors in place.

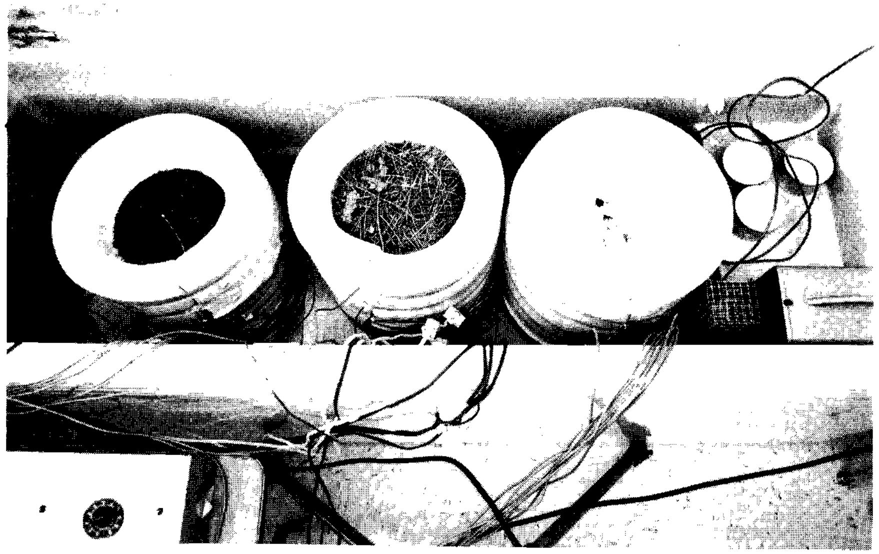


Figure 6. Cylindical monoliths with various surface conditions at the end of a freezing test.

Frost line progress and temperature changes were measured with Yellow Springs Instrument Company (YSI) thermistor probes and a YSI meter of ±1°F accuracy (Figures 3 and 7). The thermistors were inserted horizontally in hand-drilled holes on the long axis to minimize heat conduction effects along the leads (Figure 2). Thermistors were similarly inserted into the cylindrical monoliths with several inches of lead imbedded in insulation to avoid conduction effects. The thermistor beads were in the center of the monoliths at the heat tape levels of 2, 5, and 8 inches below the surface. An additional thermistor was placed at the 10½-inch depth in rectangular monoliths.

The heat tape output required to maintain a zero horizontal temperature gradient was determined with additional thermistors placed in or adjacent to the container wall at 2-, 5-, and 8-inch depths. If the container wall temperature deviated from the central soil temperature at the same depth, the heat output of the adjacent tape was increased or decreased with transformers until equality was achieved. A one or two percent change in line voltage would usually cause the proper temperature response of the container wall within a 2-hour period. The temperature of the soil between the wall and monolith center was usually within 1°F of and was often equal to the central soil temperature. Since horizontal gradients were largely avoided, we assumed that lateral heat flow was insignificant and that freezing occurred from the surface down. During freezing tests, tapes under the monoliths were set with transformers at a common voltage level to maintain a relatively constant heat output that would permit comparison of soil temperature patterns between monoliths.

For rectangular monoliths the ambient temperature in the freezer was set at +5°F (about -15°C) except for one test in which it was set at -13°F (-25°C). According to thermograph records the ambient temperature was largely within one or two degrees of these values during tests. The ambient temperature was maintained at -13°F for cylindrical monoliths except for some special snow studies described below. The freezers accommodated either two rectangular or three cylindrical monoliths (Figures 3 and 6).

We attempted to maintain a consistent soil water level in the monoliths since the effect of this variable on freezing processes was not to be evaluated. For this reason, prior to excavation the monoliths were thoroughly wetted and allowed to drain, thus creating a soil water condition approximating field capacity. Field capacity was selected because this moisture level is probably easier to achieve uniformly within and between monoliths than other moisture levels at less than saturation, and because moisture lost to the atmosphere during freezing as a result of large vapor pressure gradients away from the soil surface must be replaced. Since each monolith was to be frozen several times the water lost during freezing was necessarily returned before subsequent tests. It was assumed that drainage adjustments would re-establish the pre-test moisture distribution if the monoliths were started at or near field capacity. The water loss was determined by weighing the monolith before and after the test. A quantity of water equal to the loss was then sprinkled on the soil surface after the block had thawed and was allowed to drain prior to a subsequent test.

This technique for freezing soil is a closed system in which a large supply of free water is not available for moisture migration processes, although some internal migration most certainly occurs.

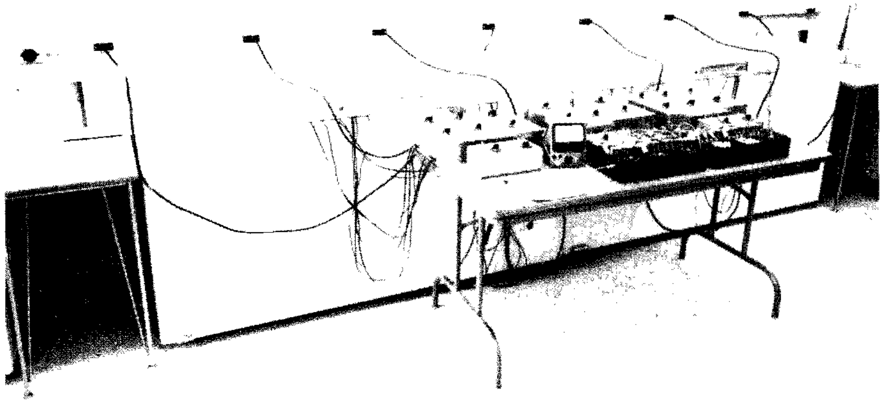


Figure 7. Freezing test in progress with cylindrical monoliths.

EVALUATION OF LABORATORY TECHNIQUE

Several tests to determine if the soil was freezing properly from the surface down were performed, in which the frost line location was first predicted with the thermistors and then checked by dissecting the partially frozen monolith. The actual frost line was consistently located at the predicted level in both rectangular and cylindrical monoliths (these moist soils froze at or close to 32°F), and the lower surface of frozen soil was at a uniform depth below the upper surface. The variation in frozen zone thickness was usually less than ½ inch.

During the freezing experiments with both monoliths, a constant climate and upward heat flux were necessary to permit comparisons between variables such as snow and litter without confounding. When levels of ambient temperature and basal heat tape output were initially decided upon, an effort was made to choose conditions that would create realistic temperature gradients. This goal was achieved, for the most part, although a few test gradients may have been somewhat large. The temperature differential between the 2- and 8-inch depths ranged from 2° to 4°F and 1½° to 2°F for the rectangular and cylindrical monoliths, respectively. These gradients were quite similar to ½° to 3°F gradients measured during the winter of 1966 in the oak stand where the loamy sand monoliths were obtained.

In order to make comparisons between treatments, it was important that freezing and temperature patterns for a given monolith remain consistent when the block was repeatedly frozen and thawed while in the same condition. The compacted (C-1) and uncompacted (UC-1) rectangular monoliths were frozen twice without a litter cover, to demonstrate the reproducibility of the technique (Figure 8). The time that was required for each depth to reach 39°F and 31°F after a reference temperature of 68°F had been attained indicated good reproducibility.

The variation between monoliths was also found to be minimal. It is doubtful that two monoliths of the same texture class and horizon sequence would exhibit exactly the same temperature patterns, because soils are anisotropic. We found, however, that if monoliths were carefully located and removed, similar temperature patterns between monoliths were obtained (Figure 9). The treatments indicated in Figure 9 were applied randomly, and no monolith received the same treatment twice. Curves for the bare treatment indicate the smallest variation between monoliths. The variability was greater for snow and litter treatments, possibly because these overlying insulating layers had more heterogeneous thermal characteristics than did the soil.

The rate of freezing in monoliths could be easily controlled by manipulating the ambient temperature and the basal heat tape output. A discussion of this capability and its application is presented in the Appendix.

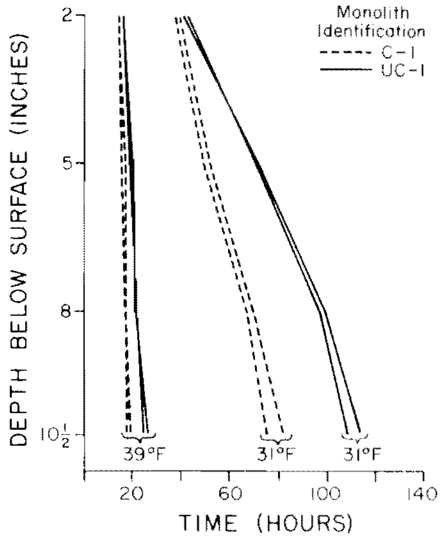


Figure 8. The 39° and 31°F isotherms for duplicated freezing tests of compacted (C-1) and uncompacted (UC-1) rectangular monoliths with bare mineral soil surfaces.

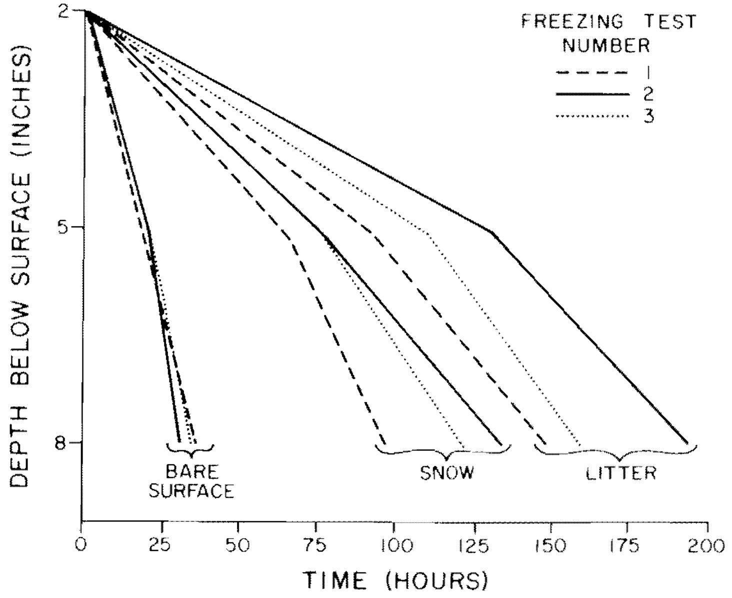


Figure 9. Time required for the 5- and 8-inch depths to reach 32°F after the 2-inch depth attained 32°F for bare, snow-covered, and litter-covered cylindrical monoliths. Three freezing tests were performed at an ambient temperature of -13°F (based on six monoliths).

RESULTS AND DISCUSSION

Rectangular Monoliths

Treatment effects for the rectangular monoliths were evaluated primarily with time-temperature curves for the 5-inch depth (Figures 16 through 20). Curves for the 5-inch depth essentially paralleled those for the other depths (for example, see Appendix Figure A-1). In plotting these data, time zero was started when the 5-inch depth reached a temperature of +71°F. This reference temperature was selected because all monoliths did not have the same initial temperature, due to variation in storage room conditions. The curves presented in this paper for rectangular and cylindrical monoliths were drawn through plotted points which had essentially no scatter. Only a few minor anomalies were observed in the cooling trends. Both types of monoliths appeared to have hard, impermeable frozen soil which would be classified as the "concrete" type. We are certain, on the basis of specific study and general observations, that little liquid water would infiltrate into or percolate through this frozen soil.

Effects of Soil Type

The freezing pattern and temperature response of a loamy sand and a silt loam soil were compared and evaluated by freezing each with a bare soil surface. Four uncompacted (UC) loamy sand monoliths were obtained in an old, relatively undistrubed oak stand near St. Paul, Minnesota. The textural composition for the UC-3 and UC-4 monoliths was uniform (Appendix Table A-1). Textural data for monoliths UC-1 and UC-2 were not obtained. Water contents were determined gravimetrically at the end of the last freezing test in four depth zones following rewetting to field capacity (Table 1). The water contents were at or somewhat above the .1 bar tension estimate of field capacity for the UC-1 monolith as determined on pressure plate apparatus (Table 1).

Monolith Identification	Depth Below Surface (inches) 0-2	2-4	4-6 (% water)	6-8	8-10	Total Weight (pounds)
UC-1	25.6	18.5	15.4	13.0	12.7	72.4
UC-2	20.2	15.7	13.8	12.9	11.4	70.2
UC-3	19.1	16.7	13.9	12.5	12.2	73.4
UC-4	19.3	14.9	12.5	11.9	11.6	70.4
Average	21.0	16.4	13.9	12.6	12.0	71.6
.1 bar water content (UC-1)	19.7	15.8	14.0	12.4	11.4	

Table 1. The percent water by oven-dry weight, the total weight for monoliths UC-1 through UC-4, and field capacity estimates (.1 bar) for monolith UC-1.

Two uncompacted silt-loam monoliths (G) were obtained under oak cover in the driftless area of southeastern Minnesota about 20 miles from Winona, Minnesota. The texture and water content data for these monoliths are uniform (Tables A-2 and 2). Moisture release data were not obtained.

Monolith Identification	Depth Below Surface (inches) 0-2	2-4	4-6 (% water)	6-8	8-10	Total Weight (pounds)
G-1	50.4	28.0	25.0	23.4	21.8	73.0
G-2	49.5	28.3	24.4	24.0	22.3	73.2
Average	50.0	28.2	24.7	23.7	22.0	73.1

Table 2. The percent water by oven-dry weight and total weight for monoliths G-1 and G-2.

Time-temperature curves for the two soil types (dashed lines and solid lines) at the 5-inch depth are presented for the +5°F ambient temperature in Figure 10 and for the -13°F setting in Figure 11. The temperature decline was similar in all uncompacted loamy sand monoliths (solid lines), even though three different freezers were used and the UC-3 and UC-4 monoliths were stored for a year longer than the UC-1 and UC-2 blocks before being frozen (Figure 10). Curves for the two silt loam monoliths (dashed lines) were also similar. These results support previous discussion concerning the small variation noted between bare cylindrical monoliths (Figure 9).

The time of freezing and temperature decline for the silt loam soil lagged behind that measured for the loamy sand at both ambient temperatures. At the +5°F setting, the loamy sand required about 28 percent less time to freeze (32 hours less) at the 5-inch depth than the silt loam. This value was 27 percent (16 hours less) for the -13°F ambient temperature. The 5-inch depth reached a temperature of +24°F 81 hours sooner in the loamy sand monolith at the +5°F setting. For the -13°F ambient temperature this difference between soil types was 36 hours. There was no distinguishable temperature difference between the silt loam and loamy sand when steady state conditions were obtained (Figure 11). If freezing tests were conducted for a sufficient period, steady state conditions were obtained for both rectangular and cylindrical monoliths (Figures 10, 11, 15, and 16).

Most of the differences in freezing time between the two soil types may have been due to water content variations (Tables 1 and 2). The silt loam soil as expected had a much higher water content than the loamy sand. This also indicates that much more "latent heat" liberated during freezing (80 calories per gram of water) must be disposed of from the silt loam monoliths before soil temperatures can drop significantly below freezing. Essentially all water in both soil types was frozen, and latent heat was no longer liberated at any depth by the time steady state conditions were obtained. At this point the soils behaved similarly even though the loamy sand must have had a lower ice content. The steady state temperature five inches below the surface was 22°F higher than the ambient temperature of -13°F (Figure 11).

The different pattern between the two soil types cannot be directly attributed to soil particle size differences. The water content of the silt loam monoliths was higher, and other variables such as soil structure may produce such results. These data, however, give a qualitative measure of the effect of soil type on freezing for comparison with the effects of different litter types. This information could also be useful in field studies of soil freezing phenomena where soil type, litter, and snow conditions vary.

Effects of Soil Density

The effects of increased soil density were evaluated by comparing uncompacted (UC) monoliths with compacted loamy sand monoliths (C-1 and C-2) that were removed from 17 by 22-foot plots in 1963. These plots were artificially compacted in the oak stand from which uncompacted monoliths were obtained. The mean increase in bulk density for the 0 to 3-inch zone was about 18 percent (Table 3). Deeper zones were compacted to a lesser degree.

Observation Number	Bulk Density (gm/cc) Compacted C-1	C-2	Uncompacted near C-1	near C-2
1	1.49	1.53	1.07	1.27
2	1.59	1.37	1.24	1.25
3	1.25	1.34	1.26	1.23
4	1.39	1.44	1.14	1.17
Average	1.43	1.42	1.18	1.23

Table 3. Oven-dry bulk density (gm/cc) for compacted and uncompacted soil in the 0 to 3-inch zone.

Bulk density was not sampled directly in the monoliths, but samples from both compacted and uncompacted plots throughout the experimental area indicated a fair degree of uniformity. The water content, total weight, and field capacity data for the compacted monoliths are presented in Table 4. The water content appeared to be less than the estimated field capacity below the 0 to 2-inch zone. The textural characteristics of these monoliths would be similar to those determined for uncompacted sandy loam monoliths (Table A-1).

Time-temperature curves for the 5-inch depth are presented in Figure 10 for the C-1 and C-2 monoliths (dotted curves). These curves indicate that an increase in soil density caused a measurable increase in the rate of freezing. At the 5-inch depth the compacted monoliths attained temperatures of +32°F and +24°F about 10 and 30 hours, respectively, before the uncompacted monoliths, when the ambient temperature was +5°F. The more dense soil was frozen at the 5-inch depth in about 17 percent less time than the uncompacted monoliths. Although the compacted monoliths froze and cooled more quickly there was little difference in the final steady state temperatures. This result was similar to that derived from the comparison between the silt loam and loamy sand monoliths at an ambient temperature of -13°F (Figure 11).

Monolith Identification	Depth Below Surface (inches) 0-2	2-4	4-6 (% water)	6-8	8-10½	Total Weight (pounds)
C-1	16.8	12.1	10.3	9.4	8.9	86.4
C-2	18.4	14.4	11.6	9.9	9.2	85.7
Average	17.6	13.2	11.0	9.6	9.0	86.0
.1 bar water content (C-1)	18.3	15.2	13.6	12.6	11.2	

Table 4. The percent water by oven-dry weight, total weight for compacted monoliths C-1 and C-2, and field capacity estimates (.1 bar) for monolith C-1.

Increased soil density caused more rapid freezing, but the effect appeared to be of a lesser magnitude than that observed between loamy sand and silt loam soil in an uncompacted state. The compaction effect was also of much less significance than the effect of litter variations which are discussed below. During the winters of 1962-63, 1964-65, and 1965-66 frost depths were periodically measured with Veihmeyer tubes in compacted and uncompacted plots in the oak stand. In 1963, about 300 measurements were made in both compacted and uncompacted plots. In 1965 and 1966, about 30 were taken in each plot type each year. The results of those measurements substantiate a tentative conclusion that increased soil density does not greatly increase the depth of frost penetration (Table 5). These data, however, are not directly comparable to the laboratory results because litter, snow, and climatic factors were different in the field. Furthermore, the average density of the compacted field plots in the 0 to 3-inch zone decreased from about 1.45 gm/cc in 1963 (standard deviation, .12 gm/cc) to about 1.35 gm/cc and 1.26 gm/cc by 1965 and 1966, respectively, thus reducing the expected effect of increased soil density. The bulk density of uncompacted plots during this time remained constant at about 1.15 gm/cc (standard deviation .12 gm/cc).

The reasons for somewhat more rapid freezing in compacted monoliths are not easily isolated. The definite increase in mineral soil density would tend to increase the thermal conductivity and thus heat loss, but compaction also affects soil water phenomena, causing a possible increase or decrease in the rate of freezing.

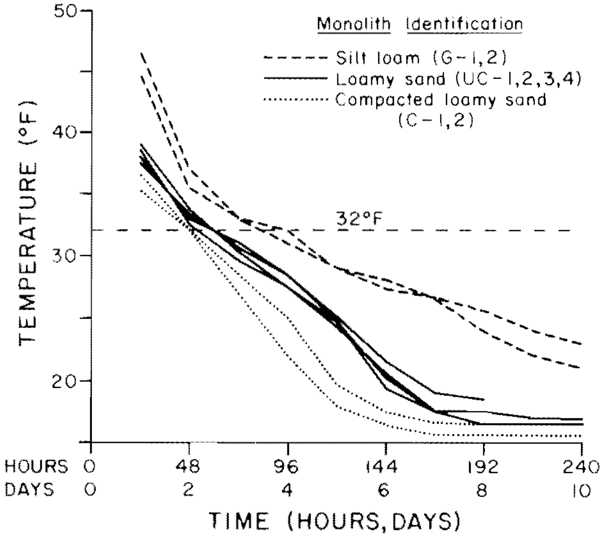


Figure 10. Soil temperature at the 5-inch depth with a bare surface for uncompacted loamy sand (UC) and silt loam (G) soil types, and for compacted loamy sand (C). The ambient temperature was +5°F.

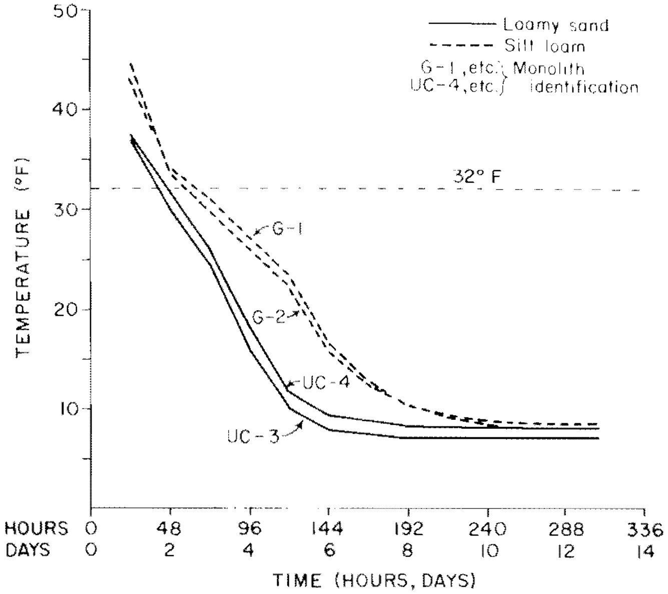


Figure 11. Soil temperature at the 5-inch depth with a bare surface for uncompacted loamy sand and silt loam soil types. The ambient temperature was -13°F.

Depth of Frozen Zone

Date	Compacted	Uncompacted	Snow Depth**
	(inches)		(inches)
Dec. 20, 1962*	11.6	7.5	0
Jan. 10, 1963*	12.8	9.6	2
Jan. 30, 1963	27.9	24.6	5
Feb. 27, 1963	36.0	33.8	5
April 2, 1965	8.4	8.1	20
April 15, 1965	6.4	6.0	11
April 1, 1966	8.6	7.9	0
April 6, 1966	8.1	7.6	0

* Significantly different at the 5% level of probability, but in 1962 and 1963 the litter on compacted plots was severely disturbed compared to uncompacted plots. Statistical tests were not performed for 1965 and 1966.

** At time of sampling.

Table 5. Depth of frozen soil in compacted and uncompacted plots on the indicated dates from 1962 through 1966.

Effects of Litter

The effect of initially air-dried oak, red pine, and white pine litter layers on soil temperature decline and rate of freezing was evaluated for both soil types. The oak litter was obtained in the oak stand from which the loamy sand monoliths were excavated. From 70 to 73 grams of oak leaves and small twigs were dropped on the monoliths, thus simulating natural leaf fall. The litter layer thickness of about 2 to 2½ inches approximated the natural depth. This method of application was acceptable, because there is little horizon development due to an annual turnover of the litter layer.

The red and white pine litter layers were cut out from the forest floor and retained intact because of their complex horizon development. The samples were obtained in pine plantations near the oak stand. These samples were also air-dried and laid intact on the monoliths. The depths of the red pine and white pine samples were fairly uniform at 2.3 and 3.3 inches. The air-dry total weights were 370 to 500 and 950 to 1100 grams, respectively.

The effects of litter on temperature decline and freezing for the loamy sand monoliths are presented in Figure 12 for the 5-inch depth. The white pine litter was obviously superior in terms of insulating effectiveness. At +5°F ambient temperature the 5-inch depth did not freeze. The temperature at this depth dropped sharply when the ambient temperature was lowered to -13°F at hour 322, but even then, freezing did not occur. The soil temperature was only +33°F and was changing slowly (approximate steady state condition) at 770 hours or 32 days. The 2-inch depth froze at about 600 hours. The depth and mass of the white pine litter considerably exceeded that for red pine and oak litter which probably explains the superior insulating qualities of this type.

The red pine litter was the next most effective insulation (Figure 12). Between 0 and 336 hours the temperature did not reach the freezing point, and only when the ambient temperature was lowered to -13°F for the UC-3 block did freezing occur at the 5-inch depth. This depth had reached a steady state temperature of about +17°F at about hour 770, 16°F lower than that for the white pine. The freezer in which the UC-4 block was placed was maintained at +5°F, and the 5-inch depth reached a steady state temperature of +35°F at about hour 264 (11 days). The temperature was still +34°F at hour 552.

Oak litter was the least effective insulator and the least compact, but even two inches of oak litter prolonged the time required for freezing and reduced the rate of temperature decline (Figure 12). Bare soil froze in only about 45 percent of the time required to freeze oak litter-covered monoliths at the 5-inch depth (58 hours versus 130 hours). Blocks UC-3 and UC-4 had distinctly slower rates of cooling than had the UC-1 and UC-2 monoliths. No certain explanation is offered for this difference. About four percent more litter was placed on the UC-3 and UC-4 units, and they were frozen in the 1965 series rather than in the 1964 tests with the UC-1 and UC-2 monoliths. It is difficult to understand why such a small increase in litter amount would cause this difference. And as pointed out previously, the 1964 and 1965 tests produced very similar results for bare soil conditions (Figure 10). Furthermore, based on thermograph records, the freezers performed properly at the appropriate ambient temperatures both years.

The effects of litter on the temperature decline and freezing for the silt loam monoliths at the 5-inch depth are presented in Figure 13. The ranking of litter types in terms of insulating effect is the same as that for the loamy sand monoliths, with the white pine type again proving the most effective by far. With a surface bare of litter, the silt loam soil froze in about 45 percent of the time required to freeze the oak litter-covered monolith at the 5-inch depth (90 versus 198 hours). This result was similar to that observed for loamy sand.

The 5-inch depth curves for each litter type are plotted for both soil types in Figure 14. Replicated tests within litter types and soil types were averaged, and only one average curve was plotted for each condition. After hour 322 the curves for red pine litter are not averages and represent just the -13°F ambient temperature. One conclusion drawn from this comparison is that as the effectiveness of overlying insulating layers increases, the relative effects of mineral soil differences diminish. More replication and study would be necessary to substantiate this conclusion, but it is notable that the two curves are practically equivalent for white pine. The white pine samples for both soil types were quite similar in total weight and depth.

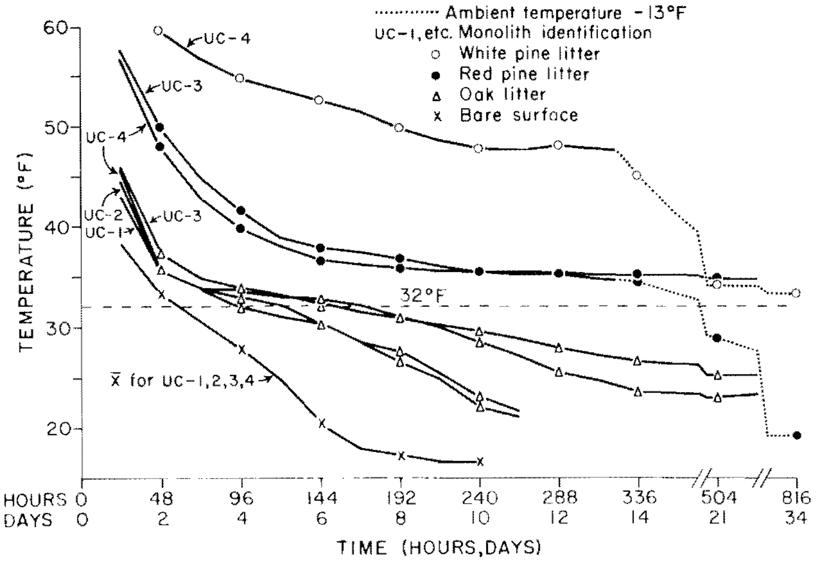


Figure 12. Soil temperature at the 5-inch depth for loamy sand with white pine, red pine, and oak litter cover and with a bare surface. The ambient temperature was +5°F except as noted.

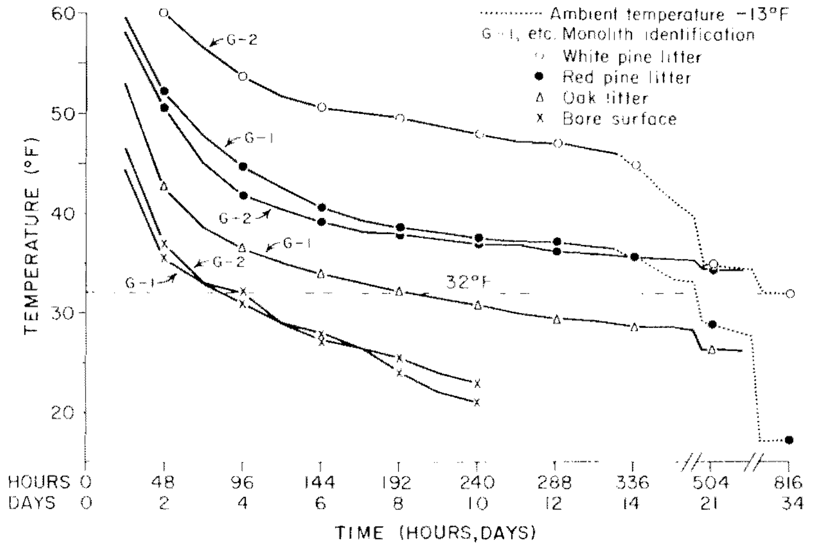


Figure 13. Soil temperature at the 5-inch depth for silt loam with white pine, red pine, and oak litter cover and with a bare surface. The ambient temperature was +5°F except as noted.

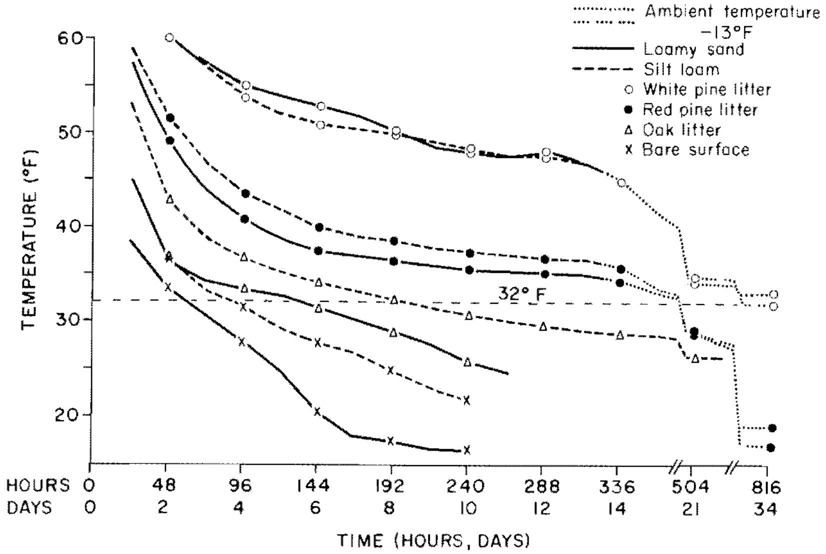


Figure 14. Soil temperature at the 5-inch depth for loamy sand and silt loam with white pine, red pine, and oak litter cover and a bare surface. The ambient temperature was +5°F except as noted.

When red pine litter was tested, the temperature decline of the silt loam soil lagged slightly behind that for the loamy sand. But after hour 336 the curves are practically equivalent for the -13°F ambient temperature which was imposed at hour 322. If the red pine curves for the +5°F setting after hour 322 were plotted in Figure 14, a similar equivalency would be noted between the two soil types. The red pine samples for the G-1, G-2 (silt loam) and UC-3 (loamy sand) monoliths were essentially equal in terms of depth and weight. Thus it seems that initially air-dry red and white pine litter masked differences in rates of soil freezing and temperature decline noted between the silt loam and loamy sand soil types when frozen without litter.

The temperature decline of the silt loam consistently lagged behind that for the loamy sand at the 5-inch depth with oak litter in place. This result may reflect a soil type difference that was not eliminated by the relatively low insulating capacity of the oak litter.

Cylindrical Monoliths

The cylindrical monoliths were used to compare the effects of snow, red pine litter, combined snow and red pine litter, and litter moisture content on soil freezing and temperature decline. A low ambient temperature (-13°F) was used to reduce the time required for a test and to assure freezing in the presence of effective insulators. Two series of tests involving a total of 12 different monoliths were performed. The first series compared the effects of snow, red pine litter, and a combination of snow and red pine litter. Monoliths 1 through 6 were utilized in these studies, and four freezing tests (F-1 through F-4) were performed. The effect of litter moisture was evaluated in a second series of four freezing tests involving monoliths 7 through 12. These freezing tests were also designated F-1 through F-4. Thus a total of eight freezing tests were performed with 12 cylindrical monoliths.

The cylindrical monoliths were obtained in the oak stand from which the rectangular, loamy sand blocks came. Soil in the cylindrical monoliths was classified as a loam (Table A-4). The water contents for monoliths 1 through 12 are presented in Tables 6 and 11. These water contents approximated field capacity estimates for monoliths 7 through 12 except for the 6- to 8½-inch depth which was somewhat dry (Table 11). Field capacity estimates were not determined for monoliths 1 through 6, but the data in Table 11 are probably applicable to these blocks.

Monolith No.	Depth Below Surface (inches) 0-2	2-4	4-6	6-8½	Total Weight (pounds)
		(% Water)			
1	32.4	22.2	19.4	17.9	31.9
2	39.1	32.3	23.4	19.2	31.6
3	38.6	26.8	25.5	19.3	30.9
4	42.5	29.3	21.2	19.3	30.9
5	33.9	25.9	20.8	18.5	31.3
6	39.1	23.1	17.3	17.1	31.7
Average	37.6	26.6	21.3	18.6	31.4

Table 6. The percent water by oven-dry weight and total weight for monoliths 1 through 6.

Effects of Air-dry Litter and Snow

The red pine samples were collected in the same stand as those used on rectangular monoliths. This litter was classified as a mor humus and was about two inches in depth. The humus (H) and fermentation (F) layers combined were generally 1 to 1½ inches thick, while the litter layer (L), using the more specific definition of "litter" as just undecomposed material, usually did not exceed one inch in depth. Essentially all unincorporated humus was collected because of a sharp demarcation between mineral soil and the overlying organic matter. The needle mat was very cohesive, which permitted minimum disturbance of the horizon sequence. The intact samples were returned to the laboratory and were air-dried. Litter weight, depth and density are presented in Table A-3.

Prior to a snowstorm all the monoliths were placed in the freezer and only the surface one inch was frozen by controlling the ambient temperature and basal heat tape output (see Appendix for specifics). During the storm, monoliths designated for snow were placed outside, and red pine litter was placed on the appropriate monoliths inside. Snow density was determined on the ground adjacent to the apparatus. Snow on the monolith was assumed to have an equivalent initial density. Two inches, which would be comparable to litter depths, were allowed to accumulate on the center of the monolith. Additional accumulations along the margin caused by eddying were gently removed with a spatula to maintain a uniform depth.

Snow collection and litter placement were generally completed within two hours. All monoliths were then placed in the freezers, and the ambient temperature was lowered to -13°F. Temperature changes in the monoliths were recorded until steady state conditions were obtained. Three freezing tests were conducted in which a bare, a litter-covered, and a snow-covered (without litter) monolith were placed together in one freezer. In a fourth test one litter-covered, one snow-covered (without litter), and a combined litter and snow-covered monolith were frozen. These treatments were applied randomly to the monoliths.

Since the soil surface of all monoliths was frozen prior to imposing treatment effects, the method of analysis could not be based on a reference temperature of +71°F as it was previously. These results were therefore analyzed with two index characteristics: (1) the time required for the 8-inch depth to attain +32°F after the 2-inch depth attained +32°F, and (2) the time-temperature curves for the 5-inch depth starting with +32°F as time zero.

The 2-inch snow layer was a less effective insulator than was air-dried red pine litter of the same depth (Figure 15 and Table 7). This difference was statistically significant at the five percent level of probability. About 1.5, 4.5, 6.5, and 10 days were required for the 8-inch depth to freeze after the 2-inch depth was frozen for the bare, snow-covered, litter-covered, and combined litter and snow-covered monoliths, respectively. The major effect that overlying insulating layers have on soil freezing phenomena is indicated by these data.

		Treatment		
Freezing Test No.	Bare	Snow (2 in.)	Red Pine Litter (2 in.)	Combined Red Pine Litter and Snow (2 in. total)
		(hours)		
1	37	96	146	***
2	32	130	192	***
3	35	121	157	***
4	**	94	140	245
Average	35	110	159	245

Table 7. Time required for the 8-inch depth to attain +32°F after the 2-inch depth attained +32°F.

A 2-inch total depth combination of litter and snow was the best insulator. Probably about 1¼ inches of snow were present on this monolith, of which an estimated ¼ inch was mixed in with the litter layer. Although this combination was not adequately replicated, the results indicate a possible interaction effect between snow and litter. Air voids that penetrate deep into the litter are typical for pine litter. These continuous voids possibly offer a pathway for convective heat loss. Snow may increase the effectiveness of litter insulation by filling the voids and thereby creating additional isolated small air pockets.

Time-temperature curves for the 5-inch depth using +32°F as a reference starting point are presented in Figure 15 for the F-3 test, which was representative of the other tests. This figure indicates the relative effectiveness of insulating layers in terms of rate of temperature decline and steady state temperature.

The rate of temperature decrease for the snow-covered monolith was quite different from the other two treatments and was more variable. Also, while the steady state temperature under snow was lower than under litter, the time required to attain this level was several days longer. This may be a result of changes in snowpack conditions during the test. Snow, unlike the litter in this short period, is a dynamic material. The density increased during the tests, and the depth and water content decreased; 50 to 75 percent of the snow was vaporized (Table 8). The relative humidity in the freezers was between 70 and

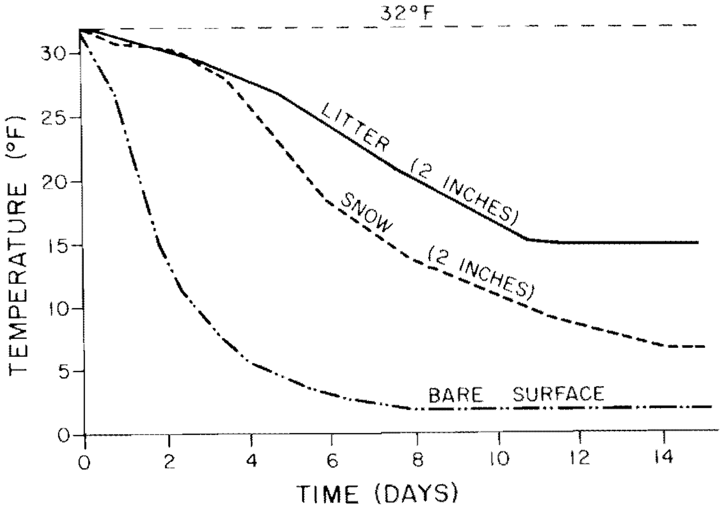


Figure 15. Soil temperature at the 5-inch depth for bare, litter-covered, and snow-covered cylindrical monoliths. This was test F-3 conducted at an ambient temperature of -13°F.

80 percent, and there was an upward heat flux through the snowpack. Evidently a sustained vapor pressure gradient away from the snowpack was large enough to permit considerable vaporization. Figure 6 shows bare spots that characteristically developed on snow-covered monoliths by the end of a test.

Crawford (1952) reported thermal conductivities for snow of .00029 and .00033 cal/cm^2 sec °C at densities of .14 and .18 gm/cc, respectively. Such small conductivity variations in this snow density range indicate that the comparatively extended time to attain steady state conditions possibly resulted from a gradual loss of snow (Table 8) and not necessarily from an increase in density.

	Before			After		
Freezing Test No.	Depth (inches)	Density (gm/cc)	Water Content (inches)	Depth (inches)	Density (gm/cc)	Water Content (inches)
1	2.1	.10	.21	.5	.16	.08
2	2.0	.08	.16	.4	.16	.06
3	2.0	.08	.16	.5	.17	.08
4a*	2.1	.11	.23	.4	.15	.06
b	1.0	.11	.11	—	—	—
Average (1-4a)	2.0	.09	.19	.4	.16	.07

*a: represents snow measurement on snow-covered monolith.

b: represents snow measurement for litter-snow combination; at the end of the test snow was mixed in with the litter and was unmeasured.

Table 8. Snow depth, density, and water content before and after freezing tests.

The 24-hour rate of temperature decrease for the first 72 hours after freezing is presented in Table 9 for three tests. The difference between litter and snow treatments was significant at the five percent level of probability. The rate of decline for bare soil was 5 to 12 times greater than that for snow and litter treatments.

	Treatment		
Freezing Test No.	Bare (°F)	Snow (°F)	Litter (°F)
1	7.3	.17	.06
2	7.3	.13	.06
3	7.8	.10	.10

Table 9. Temperature decrease per 24 hours at the 5-inch depth for the first 72 hours after freezing.

The steady state temperature was lowest for bare monoliths, and this condition was obtained two to three days sooner than in the litter-covered monoliths at the 5-inch depth. Steady state temperatures were not significantly different (five percent level) between the snow-covered and the bare monoliths (Table 10).

	Treatment			
Freezing Test No.	Bare (°F)	Snow (°F)	Litter (°F)	Combined Litter and Snow (°F)
1	.1	6.6	19.5	****
2	5.0	2.8	22.0	****
3	2.0	6.8	15.0	****
4	***	6.2	14.9	16.0
Average	2.4	5.6	17.8	16.0

Table 10. Steady state temperature at the 5-inch depth for bare, snow, litter, and combined litter and snow treatments.

The steady state temperature for the litter-snow combination was approximately equal to that for litter alone (Table 10). The litter in the litter-snow treatment was only about one inch in depth and had a lower density than the 2-inch litter samples (Table A-3). Although most of the snow vaporized, the amount remaining in combination with about one inch of litter was as effective an insulator as a 2-inch litter layer.

A tentative conclusion from this first series of tests is that air-dry red pine litter and snow of equivalent depth have somewhat similar insulating characteristics (Figure 15), although statistically significant differences were measured.

Effects of Litter Moisture

The effect of litter water content on soil freezing was evaluated for white pine, red pine, and oak litter with monoliths 7 through 12, for which soil texture and water data are presented in Tables A-4 and 11. New litter samples were obtained for these tests.

Attempts were made to keep all the litter samples approximately two inches in depth. The red pine samples were similar to those used in the first tests with cylindrical monoliths (Table A-3). Total depths ranged from 1.9 to 2.7 inches with air-dry densities of .10 to .15 gm/cc (Table 12). The white pine litter had more distinct humus (H) and fermentation (F) layers than did the red pine. The undecomposed white pine needle material (L layer) was generally ½ inch to ¾ inch thick. Greater humus accumulation in the white pine litter is reflected in slightly higher densities (Table 12). As discussed previously, the oak litter consisted essentially of relatively undecomposed organic materials. Oak leaves were applied to the monoliths by dropping them individually and gently pressing the developing litter layer occasionally by hand. Air-dry densities were .06 to .07 gm/cc (Table 12).

Monolith No.	Depth Below Surface (inches) 0-2	2-4	4-6	6-8½	Total Weight (pounds)
	(% Water)				
7	40.1	27.6	21.2	18.7	28.8
8	25.6	20.8	13.7	12.4	30.9
9	38.2	26.9	20.1	18.9	31.9
10	30.8	24.0	18.7	16.1	30.2
11	28.2	21.7	17.2	15.7	31.6
12	29.9	22.1	18.9	15.7	32.1
Average	32.1	23.8	18.3	16.2	30.9
.1 bar water content	30.5	24.7	20.9	20.6	

Table 11. The percent water by oven-dry weight, total weight of cylindrical monoliths 7 through 12, and field capacity estimates (.1 bar) for mixed samples from monoliths 9, 10, and 11.

Litter Type	Depth (inches)	Air-dry Density (gm/cc)	Water Content (cm)	Test Number
Oak	1.3	.07	.15	F-1
	1.6	.06	.16	F-1
	2.1	.06	.31	F-4
Red Pine	1.9	.14	.19	F-1
	2.7	.15	.33	F-1
	2.5	.10	.65	F-4
White Pine	2.5	.18	.76	F-1
	2.3	.15	.87	F-4
	2.2	.11	.68	F-4

Table 12. Litter depth, air-dry density, and total water content for oak, red pine, and white pine litter samples used on monoliths 7 through 12.*

***All F-1 samples were moistened in the field; all F-4 samples were moistened in the laboratory.**

Litter samples were applied to the monoliths in both an air-dry and moistened condition to determine the effects of moisture content on temperature decline and freezing patterns. The same sample was used for both conditions to minimize the effect of variation between samples. It was assumed that disturbances resulting from placement and removal of the sample for the two tests would not appreciably affect the insulating quality of the litter.

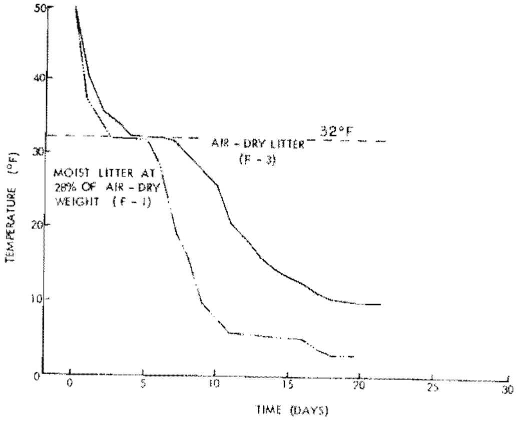
Two samples of each litter type were wetted in the field. A metal sleeve was placed on the litter surface, and about three inches of water were poured inside and allowed to drain for about ½ hour. Therefore, the recorded water contents (Table 12) are probably comparable to levels that can be encountered under natural conditions. The red pine was wetted to about 30 percent of the air-dry weight and the white pine and oak to about 65 percent. The total water content of the oak was .15 cm, the red pine .19 to .33 cm and the white pine .76 cm (Table 12). The samples were placed on monoliths in the moist condition for the first freezing test, then were air-dried and returned to the same monolith for the second test.

Two additional samples of each litter type were returned from the field to the laboratory and were air-dried. These samples were placed on monoliths in this condition for the first test, then moistened to about 100 percent of the air-dry weight and returned to the same monolith for the second test. Total water contents for these tests are presented in Table 12. The water content of all air-dry samples in these experiments was between five and seven percent of the oven-dry weight.

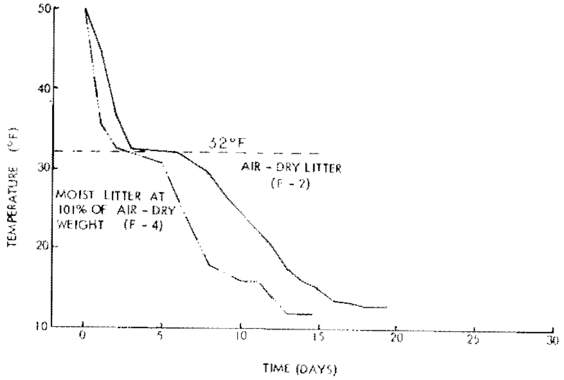
Two freezers were used in each of four freezing tests (F-1 through F-4). One monolith with red pine, one with white pine, and one with oak litter were placed in each freezer. The litter samples initially wetted in the field were used in the moist condition in test 1 (F-1) and in an air-dry condition in test 3 (F-3). In test 2 (F-2) the samples were air-dry, and in test 4 (F-4) the same samples were in a laboratory moistened condition. Ambient temperatures were maintained at -13°F. The litter moisture studies were evaluated primarily with time-temperature curves for the 5-inch depth (Figures 16, 17, and 18). One test with each litter type was discarded because of malfunctioning freezing apparatus.

In every case, moisture in the litter layer reduced the time required for freezing and increased the rate of temperature decline. A small amount of variability for the red pine litter is indicated in Figure 16. The maximum treatment effect occurred after the soil had frozen. This was also true for the white pine litter and to some extent for the oak type. The increasing spread between the dry litter and moist litter curves after freezing may be attributable to the four-fold increase in the thermal conductivity of water with a change in state from liquid to solid. The delay in temperature decline at about the freezing point of water is probably due to the latent heat of fusion which is liberated when water changes state from liquid to solid (Figures 16 and 17).

a. Monolith 8.



b. Monolith 10.



c. Monolith 10.

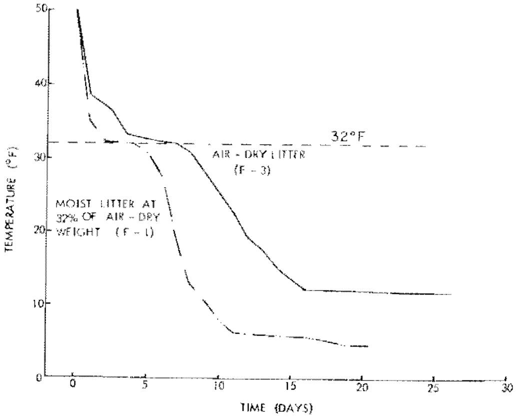
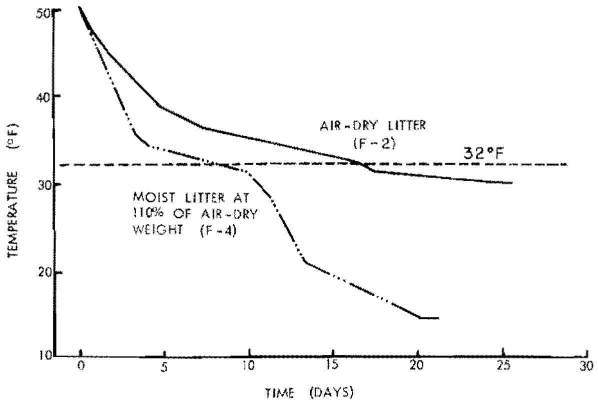
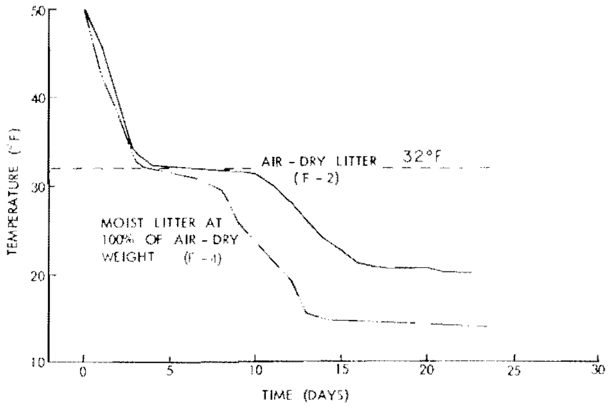


Figure 16. Soil temperature at the 5-inch depth for air-dry and moist red pine litter. The ambient temperature was -13° F.

a. Monolith 12.



b. Monolith 8.



c. Monolith 12.

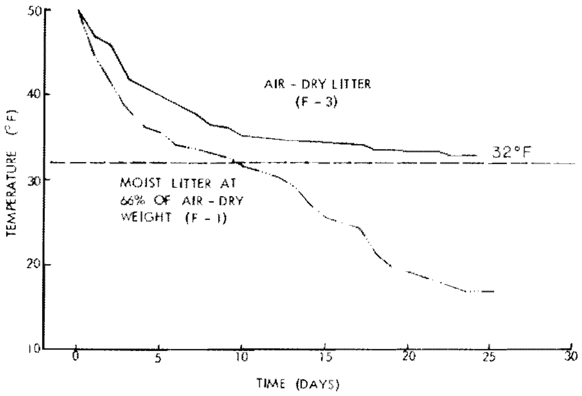
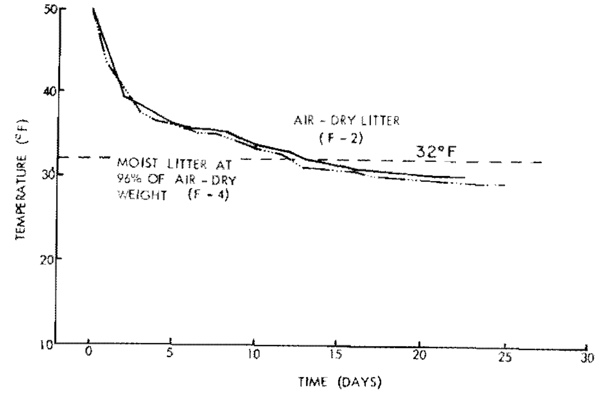
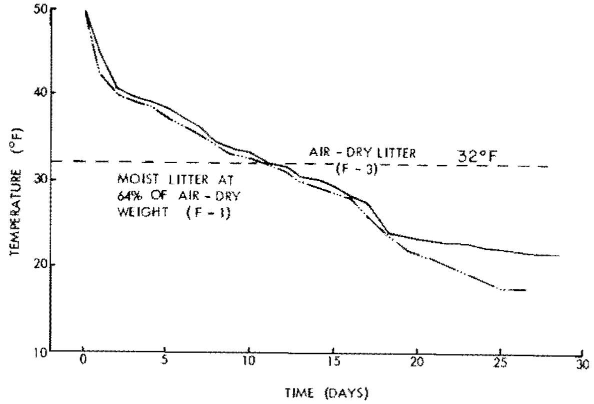


Figure 17. Soil temperature at the 5-inch depth for air-dry and moist white pine litter. The ambient temperature was -13° F.

a. Monolith 9.



b. Monolith 9.



c. Monolith 7.

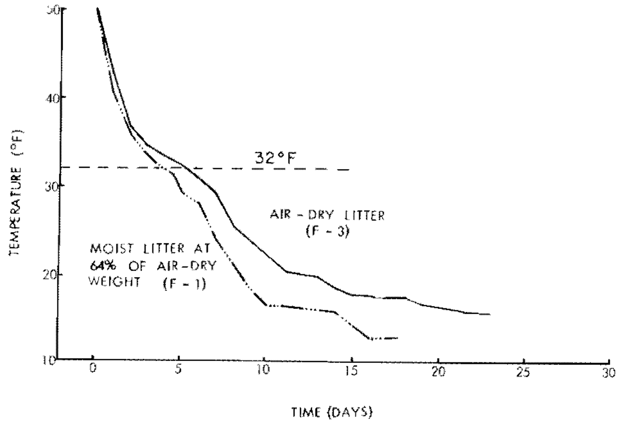


Figure 18. Soil temperature at the 5-inch depth for air-dry and moist oak litter. The ambient temperature was -13°F.

A considerable variability in temperature decline existed for monoliths covered with oak litter (Figure 18). Such variability was not expected on the basis of previous studies, nor was the high apparent insulating effectiveness which is particularly indicated in Figure 18-a. This apparent insulating effectiveness may have been due to "needle-ice" or "stalactite" type frost that developed between both moist and dry oak leaves and the soil surface. Stalactite frost has a lower density than solid ice and in effect may have provided additional insulation. The high soil water content of monoliths 7 and 9 (Table 11) could have facilitated needle ice development. The water content of these monoliths inadvertently was about 10 percent higher than the others. In some cases the vertical crystal growth was so great that the litter layer was lifted significantly, and bare soil was exposed. This may explain the low temperatures attained in monolith 7 for the F-1 and F-3 tests (Figure 18-c). About 30 percent of the soil surface was bare at the end of the F-1 test, due to lifting of the litter layer by needle ice. This frost type was not noted in the pine samples, but it would be more difficult to identify under a needle mat, and therefore some could have been present.

Litter moisture significantly affected the time required for freezing to occur at the 5-inch depth. The soil froze up to 3, 13, and 1 days sooner under moist red pine, white pine, and oak litter, respectively, than under the same litter samples in a dry state (Figure 19). The maximum reductions in time required for freezing were 43, 61, and 23 percent, respectively. Differences in fermentation and humus layer accumulations between species may account for this variability in reduced freezing time. For example, the oak litter samples were without humus while the white pine had about ¼ inch more than the red pine. Also the needle mat (L layer) was more closely woven in the white pine than in the red pine litter. Fermentation and humus materials in an air-dry state consist of many air-filled pores. Wetting may cause swelling which could reduce the size and number of these pores. Furthermore, some air in pores will be displaced by water which has a higher thermal conductivity than air. Therefore, the greater the proportion of these fine textured materials, the greater the expected reduction in insulating qualities upon wetting.

Differences in volumetric water retention between litter types in a moistened condition were observed. In terms of total water content, white pine was highest, red pine intermediate, and oak the lowest (Table 12). On a unit volume basis this ranking was the same with the water contents being .130, .063, and .047 gm/cc of litter, respectively.

The litter types were ranked in the same order in terms of reduced freezing time, with white pine showing the greatest reduction and oak the least. This suggests that litter types that can absorb and retain a relatively large amount of water per unit volume may have the greatest reduction in insulating effectiveness. However, for the range of conditions tested, excluding air-dry samples, no consistent relationship was found between the volumetric water content and rate of soil freezing within a litter type. The range of water contents within litter types may not have been great enough to cause measurable differences.

It should be noted that these litter moisture data represent conditions at the beginning of a test. Once the monoliths are placed in the freezer, changes in the water status of litter are not controlled or measured. Water is vaporized from the litter, and soil water probably moves into the litter layer in response to thermal gradients and those created by the freezing process itself.

Certainly much more effort is necessary to refine the relationship between litter water content and soil freezing. But these studies demonstrate the potential significance of this variable for forested conditions. Apparently the insulating effectiveness of litter is reduced with the addition of moisture. Also, the decrease in insulating effectiveness may be further decreased when litter water freezes. Since forest litter is usually moist and often frozen in addition to being compacted under a snow layer, studies which consider only air-dry litter are probably unrealistic. In this sense, our earlier experiments with air-dry litter may have somewhat diminished significance.

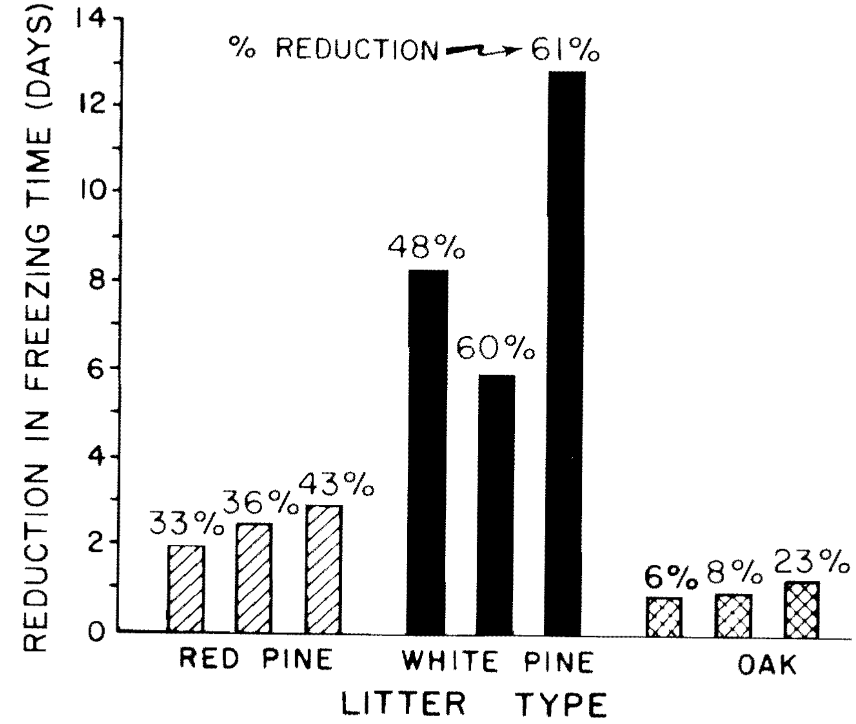


Figure 19. Reduction in freezing time at the 5-inch depth with the addition of moisture to red pine, white pine, and oak litter (reference for one white pine litter sample was 33°F). The ambient temperature was -13°F.

CONCLUSIONS AND SUMMARY

(1) The laboratory technique was functional. Boundary conditions were controlled, and when necessary a shallow frozen zone could be maintained by manipulating the basal heat tape voltage and ambient temperature.

(2) The effect of soil type differences was measurable but of less significance than the effect of variations in litter and snow insulating layers. A 28 percent reduction (about 32 hours) in the time required for the loamy sand to freeze compared to silt loam was noted at the 5-inch depth with an ambient temperature of +5°F. For the -13°F ambient temperature this value was about 27 percent. Both soil types had a high water content.

(3) About an 18 percent increase in the density of loamy sand also caused a measurable but comparatively small reduction in the time required for freezing. At the 5-inch depth the time reduction was about 10 hours or 17 percent with an ambient temperature of +5°F. These monoliths were also quite moist.

(4) Insulating oak, red pine, and white pine litter in an air-dry state greatly increased the time required for soil freezing and temperature decline. There was substantial difference in the insulating effectiveness of these litter types, with white pine the most effective and oak the least. At an ambient temperature of +5°F and with a bare soil surface, the 5-inch depth froze about 72 hours in advance of freezing when oak litter was present on loamy sand. This value was about 108 hours for silt loam. The reduction was about 55 percent for both soil types. At this depth and ambient temperature, freezing did not occur under white pine and red pine litter layers.

(5) Variations in litter layer characteristics may mask the effect of mineral soil differences on soil freezing when the litter is dry.

(6) A 2-inch layer of snow produced a measurable increase in freezing time that was somewhat less than that due to an equivalent depth of air-dry red pine litter when both conditions were compared to the freezing time for bare surface conditions. The ambient temperature was -13°F.

(7) There appeared to be an important additive insulating effect between snow and red pine litter when applied in combination. A 2-inch combined depth increased the time required for freezing a 6-inch depth of soil by about 54 percent when compared to the effects of a 2-inch red pine litter layer, and by 123 percent when compared to the effect of a snow layer that was two inches in depth initially.

(8) Litter water content significantly affected freezing rates. Compared to an air-dry state (five to seven percent moisture), litter with total water

contents ranging from .15 to .87 cm produced a substantial reduction in the time required for freezing. This reduction was as much as 61 percent (13 days) for white pine litter and as low as six percent (one day) for oak litter. The effect of moisture appeared to be most significant for dense, heavy litter.

(9) We suspect that soil freezing phenomena can perhaps be more accurately described and understood on the basis of associated snow, litter, and soil conditions than with gross forest cover type classifications.

(10) In the more speculative realm, it seems that the more soil freezing phenomena are controlled by mineral soil conditions, the fewer management implications and opportunities there are. If forest litter and snow are present, the importance of mineral soil conditions diminishes, and increasing emphasis should be placed on evaluating snow and litter cover. In the latter situation, management opportunities should be enhanced, because snow and litter can be changed to some extent by manipulations of forest type, structure, and density. However, snow is a dynamic and transient material and is therefore difficult to evaluate. Litter is less dynamic in itself but is quite variable in moisture content. Thus, even litter will not be easily evaluated if the moisture content fluctuates or changes state from liquid to solid.

SUGGESTED FURTHER WORK

(1) The effect of combined insulating layers (litter and snow) on soil freezing should be more fully evaluated with the litter in a field moist condition. These studies should include a range of litter and snow depths.

(2) The thermal properties (conductivity, diffusivity, etc.) of insulating layers in both a frozen and an unfrozen condition should be determined. For example, the thermal conductivity of complex insulating layers can possibly be measured *in situ* by incorporating some additional instrumentation into the laboratory freezing apparatus.

(3) This freezing technique could possibly be used to evaluate the formation and permeability of different types of frozen soil as influenced by soil moisture levels, texture, and other variables. Possibly an open system with a free water source could be incorporated in the apparatus.

(4) The technique may also be adaptable to studies of biological and other physical phenomena such as pesticide migration in soil that may be influenced by soil freezing (and thawing?).

(5) If the need is great enough, technological skills and knowledge are probably available to develop a general model that will predict soil freezing phenomena (rate of penetration, permeability, thawing). This model should involve a functional relationship between energy exchange at the substrate surface (snow, litter, or mineral soil) and the response of the entire substrate system to energy loss and gain. The development of such a model would probably require the combined skills of a micrometeorologist, soil physicist, heat transfer physicist, mathematician, and hydrologist. Initially the model might be quite refined and based on functional relationships between meteorological factors such as net radiation, sensible heat exchange, etc. and substrate variables such as thermal conductivity and diffusivity. Such a model could conceivably provide the basis for another less refined system that would predict on an extensive scale the development and decay of frozen soil and/or its permeability. This system could be practically oriented and could perhaps be operable with readily available index measurements of key variables such as air temperature or soil water content. The work of Scott (1964) is a step in this direction.

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APPENDIX

Effect of Variations in Ambient Temperature and Basal Heat Tape Output

The temperature response of soil in a cylindrical apparatus when both the basal heat tape output and the ambient temperature were changed is presented in Figure A-1. The temperature at all depths increased when the basal heat tape voltage was increased from 25 percent of full voltage to 35 percent about eight days after the test began. On day 11 the ambient temperature of the freezer was lowered from +14°F to -13°F, and as a result, soil temperatures at all levels sharply decreased. A homogeneous medium-textured sand mixture was in the styrofoam container for this test, but these results apply in principle to the experimental monoliths. Thus, by manipulating the basal heat tape output and ambient temperatures, the rate of frost penetration and temperature gradients within the monolith can be controlled, and natural temperature regimes can be simulated.

This capability was used for studies of snow insulating effects in which a shallow depth of frozen soil was maintained until a snow storm occurred. The snow would melt if the soil were at room temperature. About a 1-inch depth of frozen soil was maintained at the surface for 10 to 24 hours, and this time period could have been extended if necessary. The maximum temperature variation in several cylindrical loam monoliths was only about 1°F at all depths during this steady state period.

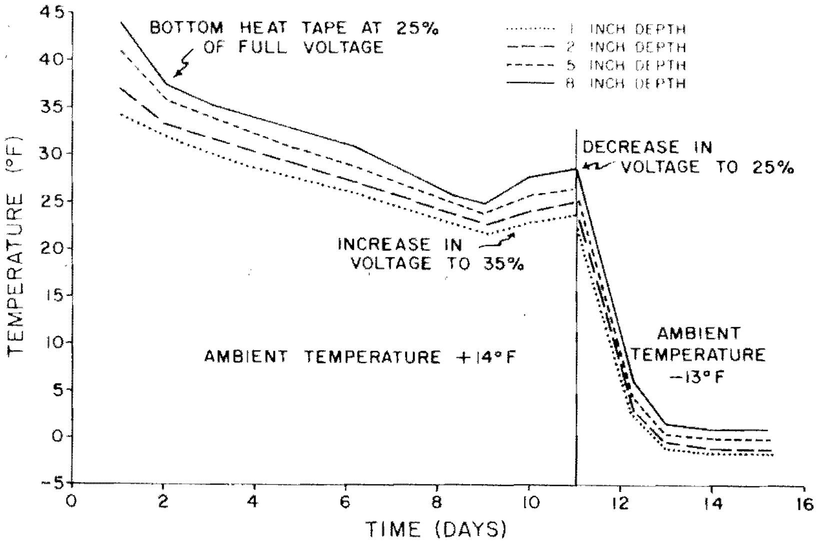

Figure A-1. Soil temperature in a cylindrical apparatus for various basal heat tape outputs and ambient temperatures.

Monolith Identification

Depth (inches)	UC-3			UC-4		
	% sand	% silt	% clay	% sand	% silt	% clay
0-2	70.4	24.5	5.1	76.7	18.4	4.9
2-4	71.4	23.8	4.8	78.0	18.3	3.7
4-6	72.3	23.6	4.1	79.1	17.3	3.6
6-8	73.4	23.0	3.6	79.6	16.8	3.6
8-10½	73.3	22.8	3.9	80.2	16.6	3.2
Average	72.2	23.5	4.3	78.7	17.5	3.8

Table A-1. The percent of sand, silt, and clay for monoliths UC-3 and UC-4 as determined by the pipette method.

Monolith Identification

Depth (inches)	G-1			G-2		
	% sand	% silt	% clay	% sand	% silt	% clay
0-2	36.5	46.9	16.6	35.1	48.5	16.4
2-4	41.1	43.5	15.4	38.2	46.2	15.6
4-6	39.2	44.8	16.0	40.0	44.8	15.2
6-8	41.6	42.8	15.6	39.4	44.6	16.0
8-10½	41.1	42.1	16.8	38.6	44.6	16.8
Average	39.9	44.0	16.1	38.3	45.7	16.0

Table A-2. The percent of sand, silt, and clay for monoliths G-1 and G-2 as determined by the pipette method.

Freezing Test No.	Depth (inches)	Weight (grams)	Air-dry Density (gm/cc)
1	2.1	281	.13
2	2.0	263	.13
3	2.0	259	.12
4a*	2.0	252	.12
b	1.2	113	.09
Average (1-4a)	2.0	264	.12

*a: litter measurements on litter-covered monolith
b: litter measurements on litter-snow combination

Table A-3. Depth, weight, and density of air-dry red pine litter samples used on cylindrical monoliths 1 through 6.

Depth (inches)	% Sand	% Silt	% Clay
0-2	59.1	34.9	6.0
2-4	60.6	28.9	10.5
4-6	62.2	33.1	4.7
6-8½	64.2	31.8	4.0
Average	61.5	32.2	6.3

Table A-4. The percent of sand, silt, and clay for mixed samples from cylindrical monoliths 9, 10, and 11 as determined by the pipette method.

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