THE EFFECT OF FREEZING AND THAWING ON SOIL MOISTURE, BULK DENSITY, AND SHEAR STRENGTH UNDER OPEN AND FOREST CONDITIONS

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This is to certify that the

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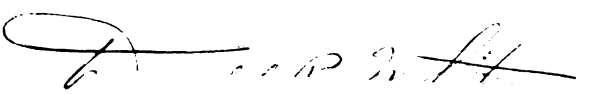

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ABSTRACT

THE EFFECT OF FREEZING AND THAWING ON SOIL MOISTURE, BULK DENSITY, AND SHEAR STRENGTH UNDER OPEN AND FOREST CONDITIONS

by Arthur William Krumbach, Jr.

Information is available on soil moisture contents and bulk density changes during freezing or thawing periods. However, information is needed on the soil moisture, bulk density, and shear strength regime during freezing and thawing periods, and their relation to soil, precipitation, and vegetative cover.

From November 1959 to May 1960 soil moisture, bulk density, and shear strength were studied in the upper 15 in. of two medium-textured soils in Kent and Clinton Counties, in the lower peninsula of Michigan. In each county three plots were established, one with hardwood cover, one with herbaceous cover, and one bare.

Texture, organic matter content, specific gravity, and Atterberg limits were determined for each soil. Depth, density, and water equivalent of snow and frost; frost type; soil moisture; bulk density; and shear strength were sampled periodically in 3-in. layers.

Daily air temperatures were similar in both counties but Kent County received more snow. During the period of continuous snow cover the Kent County Bare, Herbaceous, and Hardwood plots averaged 3.55, 1.21, and 1.23 in. more snow than the Clinton County plots. Prior to being covered with snow, bare plots in both counties contained more frost, and to a greater depth, then plots with vegetal cover. Amount and depth of frost were about equal in plots under similar cover.

Depth of freezing in Clinton County was correlated with air

temperature during the eight-day period before a sample date. Depth of frost on the hardwood plot was about 3.5 times less than the herbaceous plot, and frost in the herbaceous plot about 2.2 times less than in the bare plot.

In Kent County depth of freezing was consistently less in the hardwood-covered plot than the other two plots.

Bulk density of each 3-in. depth was inversely related to frost depth in the 15-in. soil layer and to moisture content in the same 3-in. depth. The relation exists because there is a repetitive process of moisture moving into areas, freezing, expanding, and causing more free pore space.

Moisture continued to move from the snowpack through this pore space--even though concrete frost was present throughout the study period.

That moisture was constantly moving through the frozen soil helps explain why moisture could not be statistically correlated with frost depth. Also, moisture may exist in frozen soil in the vapor as well as liquid phase, and may or may not be present in frozen soil.

Shear strengths were below the prefreeze level while the soils were thawing. However, after soils thawed and moisture contents had dropped below prefreeze level, shear strengths remained unusually low for a period of time. This is ascribed to the coating of soil aggregates with a thick moisture film early in the thaw period.

THE EFFECT OF FREEZING AND THAWING ON SOIL MOISTURE, BULK DENSITY, AND SHEAR STRENGTH UNDER OPEN AND FOREST CONDITIONS

By

Arthur William Krumbach, Jr.

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"Neither snow, nor rain, nor heat, nor gloom of night stays these couriers from the swift completion of their appointed rounds"

Inscribed over Central Post Office
New York City, New York

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The author is grateful to the Southern Forest Experiment Station and the Army Mobility Research Center for making this arrangement possible, and wishes to extend his thanks to P. A. Briglieb, Director, and R. S. Campbell, Chief, Range and Watershed Management Division of the Southern Forest Experiment Station, and to Mr. S. J. Knight, Chief, Army Mobility Research Center, and his staff for their advice and support.

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Identification of soils on the study plot by Mr. Edward Redmond and Prof. Schneider was a necessary step for which assistance the author is grateful.

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INTRODUCTION

Ground-water recharge during winter months, heaving of soil, and runoff from melting snow are of vital interest to man. In addition, during many a spring thaw, farmers and loggers suffer serious delay in their operations, whether it be land preparation, planting, or hauling logs.

These processes and delays are directly associated with the condition of the soil with respect to freezing or thawing and with concomitant climatic conditions. The amount and kind of precipitation that has fallen, the contribution of air temperature to rapid snowmelt, the soil conditions, including infiltration and storage capabilities of the soil, are all involved. Finally, interactions of climatic and soil variables are greatly influenced by the vegetation present.

Consideration of the status of the ground, whether frozen or thawed, has been limited primarily to descriptions of the occurrence, depth, and type of frost (e.g. Scholz, 1938, Pierce, Lull, and Storey, 1958). Much information has also been assembled on the effects of vegetation, snow, and climate on frost depth and occurrence (e.g. Pearson, 1920, Potter, 1956, Sartz, 1957).

The effects of excessive meltwaters flowing over frozen ground have been examined (Storey, 1955, Trimble, 1959, and others), and foresters in particular have noted the benefits of vegetative cover in reducing excessive runoff and erosion (e.g. Scholz, 1938, Kienholz, 1940, Hale, 1950).

Studies have been made on the physical phenomena associated with soil freezing (Post and Dreibelbis, 1941, and others); and, especially

from the engineering standpoint, on frost heaving in disturbed soils (e.g. Johnson, 1952). However, detailed experiences with soil moisture and soil physical properties, particularly knowledge of chronologic changes in these properties into, through, and beyond the winter seasons, are conspicuously lacking. Information is still needed concerning the behavior of soil moisture and physical properties during the winter freezing and thawing periods as related to ingress of water into the soil, runoff during thaw and water available to plants. Soil strength and compaction characteristics in the spring also need elucidation.

When more is known about dynamic processes which take place during soil freezing and thawing and about the actual effects of vegetation on these processes, a better understanding of the end effects, groundwater recharge, runoff, etc., will be possible, and the magnitude and duration of these effects may be predicted.

This study was designed primarily to provide information on the soil moisture, bulk density, and shear strength regimes under frozen and nonfrozen conditions. The relation of these regimes to weather, vegetation, and other soil characteristics was to be evaluated.

The investigation was conducted in southern Michigan on medium textured soils and included three cover conditions.

LITERATURE

Many investigators, including Beskow (1947), Siple (1952), Black, Croney, and Jacobs (1958), and Demby and Kohnke (1958), have reported that the soil moisture content of the upper layers of soil can increase well above normal moisture contents as a result of freezing and thawing action. Conversely, little information has been published concerning soil physical changes. Theoretical relationships have been worked out for the maximum amount of water a soil can hold, and for movement of water into frozen or freezing layers, but changes in soil pore space have rarely been measured.

While much information exists on construction of roads, runways, and other structures on disturbed soils, no studies were found which considered trafficability during thawing (or freezing), periods on natural soils.

Johnson (1952), summarized the state of knowledge of the soil during thaw as follows:

> "For some reason, the literature contains little information on the physical process of soil melting and the subsequent changes in moisture distribution which take place as the soil adjusts itself to an unfrozen environment,"

and Serova (1959), presumably speaking of Russian and European literature stated,

> "The object of most investigations has been an elucidation on the depth of a soil's freezing through (congelation) with respect to a region geographically, and to meteorological conditions (of that region)."

Specific references will be considered under the following headings:

1. Temperature Conditions Necessary for Soil Freezing.

2. Soil Moisture During Freezing Periods.
3. Influence of Precipitation and Vegetation on Soil Freezing and Thawing.
4. Influence of Soil Color, Evaporation, and Microrelief During Freezing and Thawing on Soil Moisture.

Temperature Conditions Required for Soil Freezing

Air Temperature

The magnitude and duration of air temperature below freezing is very important in influencing depth of freezing in the soil. Heat loss must be toward the air above the soil; thus, before soil freezing can begin, the air temperature must be below freezing.

Russell (1943), in reporting on the analysis of 10 million temperature readings between 1914 and 1931, concluded that an air temperature of 28 F is enough to cause soil surfaces to start freezing, while a rise to 32 F would start thawing.

Anderson (1947), working at North Fork, California, on gravelly sandy clay loam soils, found that a minimum air temperature of 31.1 F was necessary before soil freezing began on a bare plot, 29.0 F was required on a grass-covered plot, and 14.1 F on a brush-covered plot.

Franklin (1919) found that a temperature of -9.2 C at the soil surface would allow frost to penetrate 4 in. in 12 hr. At a surface temperature of -1.1 C, frost took four days to penetrate the same depth. This illustrates the importance of both magnitude and duration of temperature on frost formation.

Domby and Kohnke (1955) showed some effects of diurnal air temperature fluctuations on a Russell silt loam in Indiana. They found that

when temperatures dropped from above freezing during the day to a range of 20 to 25 F at night, soil would freeze to a depth of about 1 in. Hale (1950) found that 1 to 2 in. of frost could form under ponderosa pine stands with overnight freezing, but that it would disappear in the afternoon.

Schneider (1957) noted an important relationship between air temperature, freezing, and ground water. He found that water tables in Minnesota, which had dropped during freezing weather, rose after a few days of above 32 F temperature. The water table rise occurred too soon to be accounted for by snowmelt. He concluded,

> "When air temperature rises above 32°F, as it would in the spring, heat continues to move upward from the zone of saturation (below the frost); however, instead of moving through the frozen layer (as it would when air temperatures were below freezing) it starts thawing the bottom of the layer because an opposing thermal gradient (from the atmosphere) now causes heat to move downward from the atmosphere to the frozen soil."

Thus, water moved downward to the water table as a result of thawing of the frozen soil from below, and not from snowmelt.

Another important relationship between air temperature and frozen soil involves the availability of water to plants. Wilner (1955), in studying physiological winter drought in the Canadian prairies, found that for two years November to April air temperatures ranged from -2 to -33 F, and during this period no water was available for plant use in the upper 18 in. of soil, this depth being continually frozen.

Post and Dreibelbis (1942) studied freezing of silt loam soils under pasture, woodland, red clover, alfalfa, and winter wheat. They found that no freezing occurred 1 in. below the soil surface.

Air temperatures have been used to predict the depth of frost

penetration by Casagrande (1931), Shannon (1945), Anderson (1947), Wilkins and Dujay (1954), Crawford (1952), and Aldrich and Paynter (1953). Siple (1952) developed semiemperical systems for predicting maximum expected frost depth anywhere in the United States based on the number of hours of temperatures below 30 F during an average year.

In most cases, however, air temperature alone does not suffice for frost depth prediction. Soil thermal properties, snow cover, and vegetation each influence depth of freezing. For any one area the relationship may change from year to year and relations developed for one area may not be applicable elsewhere.

Soil Temperature

Post and Dreibelbis (1942) noted considerable variation in the soil temperature at which freezing would occur. For all plots, the temperature at which freezing took place was 18 to 26 F at 1/2 in. below the soil surface; 23 to 27 F at 3 in.; 22 to 25 F at 6 in.; and 22 to 26 F at 9 in. They state that, in general in the freezing layers, the deeper the freezing, the higher the temperatures in the frozen layer.

To extend the depth of freezing or to begin freezing, not only must soil temperatures be below 32 F but heat must be expended (Chang, 1957). Freezing of water requires the release of 79.63 g/cal per gram of ice.

Bouyoucos (1921) found that temperatures required to freeze soil water vary. Free water may freeze at -1.5 C (29.3 F), capillary water at -4 C (24.8 F), and hygroscopic water may not freeze until a temperature of -78 C (-108.4 F) is reached. These findings agree with those of Wintermeyer (1925).

Presumably the more free water in a soil, the faster the soil will

freeze at a given temperature. Belotelkin (1941) noted that the intensity and duration of temperatures required to induce soil freezing increased as the amount of capillary and hygroscopic water decreased.

Freezing should be more easily induced in coarse-grained soils than in fine-grained soils at moisture contents at or near saturation as there would be more free water in the coarse-grained soil. Beskow (1947) verified this; he found that lower temperatures were required to freeze fine-grained than coarse-grained soils.

As Crawford (1952) stated,

> "Moisture content is by far the most important intrinsic factor affecting soil temperatures, and any transfer of water in the soil will not only carry heat, but will alter thermal properties by its movement."

Thompson (1934) earlier clarified these relationships when he found heat conductivity of soil to be increased by addition of water producing better thermal attraction between soil grains. As the specific heat of the soil-water mass increases with increasing water content, more energy must be released to produce freezing.

Thus, more water may permit faster heat conduction, but at the same time, greater heat loss is necessary to induce freezing.

The effect of soil moisture on variation in soil temperatures necessary to induce freezing has been observed by many investigators, including Johnson (1952), Pearson (1920), and Atkinson and Bay (1940). Diurnal change (Demby and Kohnke, 1955) and soil color (Bouyoucos, 1916) also cause variation in temperature in respect to freezing.

A phenomenon observed by Potter (1956) deserves mention. Comparing spring and fall temperatures he found an overturn similar to the thermal overturn in bodies of water. He said,

> "In soil there is no actual mixing as in water, but there is similarity in having the lower levels warmer in the winter, a short period of rather uniform temperature throughout, and then warmer upper levels in the summer. On examination of the temperature curves for the five sites, and the two-year period, the writer was greatly surprised to find a distinct brief period in the spring and fall when the temperature lines converged, coincident with the reversal of the order of temperature gradient."

Potter observed this phenomenon in the 6-in. to 6-ft depth. He found for five sites the two-year average fall overturn date to be October 3, and the spring date to be May 5. Temperature range between all depths was 2.4 and 2.1 F for the two dates, respectively.

The relationship of soil density to soil temperature and frozen soil has been neglected. Crawford (1952) in his review noted that,

> "Practically all observers of soil temperature fail to record any effect of density."

Soil Moisture During Freezing Periods

Frost Types and Distribution

Post and Dreibelbis (1942) described three types of frost: (1) concrete--having very dense structure in which very thin ice lenses are formed, along with fine ice crystals; (2) honeycomb--which has a loose porous structure allowing free water vapor movement; (3) stalactite--which consists of small, vertical icicles that join heaved surface particles to the main body of soil below.

Hale (1950) recognized another frost type which he named "granular." Granular frost has scattered granules of ice binding the litter and F layers of humus.

That the physical structure of frost is important insofar as movement of water into and within the soil is concerned has been brought

out by Sartz (1958), Bay (1958), Trimble, Sartz, and Pierce (1958), and others. All agree that concrete frost is most important in that it may reduce infiltration to zero. Other types of frost, which are generally more porous, may allow water movement.

Trimble, Sartz, and Pierce (1958) observed that, in the northeastern United States, granular frost under hardwood and white pine stands may actually increase infiltration capacity over that of unfrozen soil.

Occurrence of frost types was discussed by Storey (1955).

> "Concrete frost has been observed most frequently in cultivated fields. Honeycomb and stalactite frost, which usually occur during shallow freezing, are found most frequently in meadows and pastures. In forested areas frost of the granular type is found oftenest. Honeycomb frost is found next in frequency."

He said further,

> "A concrete type of frost structure is formed practically in all soils which have been largely depleted of humus.
>
> "In the presence of humus, frost in the soil is usually of a porous structure.
>
> "A concrete type of frost structure is formed in heavily compacted soils, irrespective of the humus content.
>
> "A concrete type of frost structure frequently forms when frost penetrates below the humus layer. In lightly compacted pastures and meadows this occurs usually at depths below 3 or 4 inches."

Concerning concrete frost, Trimble, Sartz, and Pierce (1958) stated,

> "While remaining unchanged in appearance, at least to the naked eye, it gradually loses its hard rocklike consistency and may easily be broken by hand. In the case of pasture soils with a great number of grass roots, it becomes pliable and can be bent. Concrete frost eventually becomes quite pliable before it melts completely. At some point in this degenerative process, frozen ground becomes

> permeable to water. Of course, once it loses its concrete-like hardness, the definition, concrete frost is no longer applicable.
>
> "During times of thaw the melt pattern in some areas of concrete frost was very erratic, resulting in a close intermingling of frozen and unfrozen ground. This condition appeared to be associated with difference in micro-relief, which permitted certain micro-aspects and slopes to receive more solar radiation and thus to melt sooner."

Moisture Movement and Physical State

Bouyoucos (1921) was earlier quoted as finding that free, capillary, and hygroscopic water freeze at different degrees of temperature. Beskow (1947) found water in narrow pores to freeze below 0 C (32 F). Moreover, Anderson, Fletcher, and Edlefson (1942) found with below freezing temperatures that water farthest from the surface of the soil particles freezes first. This finding agrees with that of Grim (1952) who stated,

> "Directly adjacent to the adsorbing soil solidly adsorbed water is to be found, the center of a pore space is occupied by ordinary water, freezing at about 0°C, and between the ordinary water and the solidly adsorbed water there is a zone of liquid water possessing a melting point down to 22°C which serves as a passageway for the conduction of water to freezing centers."

Much frozen soil research has been concerned with whether or not massive (concrete) soil freezing has occurred, particularly in relation to frost heaving, Beskow (1947), Casagrande (1931), Taber (1932), Black, Croney, and Jacobs (1958).

Beskow (1947) reported that massive freezing always occurs when soil moisture content is below capillary saturation, in contrast, when moisture is greater than capillary saturation, quick freezing will yield massive ice, and slow freezing will develop stratified ice. Ice layers do not form when soil particle sizes are greater than 0.06-0.1 mm in

diameter; instead, homogeneous ice formation takes place.

In fine-grained soils Beskow (1947) noted that needlelike crystals were formed perpendicular to the surface (stalactite). If fine layers of silt or clay occur in a coarse soil, thick ice layers may form and frost heave take place, provided there is saturated soil below the frost layers. When soil is saturated below the frost layer, ice layers can form at discontinuities of soil texture, i.e. sand over silt, etc.

Beskow (1947) found increases in water up to 120% of original volume of the unfrozen soil under roads in Sweden. He also quotes Runeberg (1765) who found that so much moisture had moved into a clay layer during freezing that the ratio of water to soil by volume was 4 to 1.

Data of Post and Dreibelbis (1942) indicate that moisture content may increase from two to nine times that of the prefreezing content. Their data also revealed that moisture content in the frozen portion of the surface part of soil was generally a little over twice that of the nonfrozen part.

Many investigators have observed that moisture migrates to frozen layers. Anderson (1946) reported that moisture was drawn from 36 in. below the surface into the surface to 3-in. layer. He also noted that Lochhead (1924) found the moisture content of the 10-in. depth in a sandy soil dropped from 12.4 to 6.4% (by weight) as freezing progressed down to 8 in. Bouyoucos and McCool (1916) stated that water moves from wetter layers below up to the frost line. However, Domby and Kohnke (1955) found that soil just below a frozen layer became wetter when the frozen layer thawed.

Moisture movement to the frozen layer can occur by capillary and

by vapor movement, Bouyoucos (1915), Siple (1952), Beskow (1947), and Penner (1958).

Hadley and Eisenstadt (1953) reported on a laboratory study of vapor movement during freezing as follows:

> "A simulated soil made of glass beads 0.01 in. in diameter and a radioactive tracer technique were used to determine whether the moisture transfer was in liquid or vapor form. A critical moisture content of about 4% moisture by weight of the total dry weight separates liquid from vapor movement in the soil. The water moves from the hot to the cold point in the form of liquid water in wet soils. The increase in water content coincides closely with the ice point and no moisture movement is apparent when the temperature is kept above 32°F. The moisture moves in the form of vapor in soils containing less than 4% water and is not associated with freezing."

Explanation of capillary movement is summed up by Penner (1958) as follows:

> "Ice lensing occurs only in soils with small pores, so when water freezes it produces an effect similar to that of drying at that point. The liquid water moves from wetter to drier, i.e. frozen, areas. Freezing water releases heat which permits the soil to retain its temperature even though more heat is being lost. This permits lenses to grow until the water supply is exhausted, or rather until the force holding water to particle surfaces exceeds the forces involved in drying and formation of ice."

The process of increasing moisture-holding capacity was described in general terms by Siple (1952), as follows:

> "The freeze-thaw action of free water accumulated in soil has a 'jacking' or ratchet action which deforms the soil about it, and leaves voids during the thaw cycle which are replaced by free water."

He notes that water can move into the frozen layer by capillary action during freezing.

Studies have been conducted on the relation between soil freezing and aggregation. Jung (1942), in his experiments of induced freezing of soils with liquid air, found that the aggregating effect of frost

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decreases the faster a soil is frozen. With slow freezing, a few large crystals are formed resulting in large aggregates. A repetition of freezing causes a negligible decrease in the degree of dispersion, and the more free water in a soil the more ice crystals are formed. With slow freezing, Jung observed that soil particle dispersion decreased with increasing water content to full water content, then increased. Fast freezing caused dispersion to increase up to full water content, then to decrease.

Baver (1948) explains part of Jung's observations as follows: Slow cooling causes ice crystals to form in the tension-free pores. The crystals in turn draw water from surrounding particles (which would increase the size of the voids), resulting in dehydration of the particles. Dehydration in turn allows more intimate contact of the soil grains (aggregation). The large crystals melt, and form nuclei for more crystals. Quick freezing, on the other hand, causes many small crystals to form, resulting in breakup of the aggregates.

Decreases of up to 30% were observed in bulk density supporting the statement of Bouyoucos and McCool (1916) that freezing processes "...in a soil saturated with water account for not more than 5% bulk density changes." The Frost Effects Laboratory (1951) report stated,

> "If the total volume of unsaturated soil contained 1/3 water, freezing would yield expansion of only 3%. But, expansion of 60% has been observed."

Moisture must be moving into the frozen zone to account for large density decreases.

Domby and Kohnke (1955) reported changes in bulk density and moisture during freezing and thawing in the surface inch of a bare Russell silt loam. Night temperatures were 20 to 25 F, and day

temperatures above freezing. An inverse relationship between bulk density and moisture content was noted. For instance a 30% decrease in bulk density was accompanied by over 100% increase in soil moisture.

Domby and Kohnke noted that:

> "The most rapid decrease in water stability (of aggregates) occurred where soil was bare, but by the end of two winters most of the water-stable aggregates in the mulched soil also were broken down. Soil which was loose in the fall became compact during the winter, even where a surface mulch of two tons of straw per acre was present."

Slater and Hopp (1951) studied pore size and aggregation in silt loam soils planted to (1) year-round corn, (2) spring-manured corn, (3) corn-wheat-unmowed timothy-red clover, and (4) sod. Their results were similar to those of Domby and Kohnke (1955). They also reported that after 10 years under sod, structure and large pores remained unchanged. But, as to the cropland, they reported that those soils under continuous crop had greater aggregate stability and more large pore space than fields under continuous corn.

During thawing periods decreases in bulk density were observed in the upper 6 in. of soil, Krumbach[1/]. In the Lake States 50% decreases in density were found on well-drained, silt loam soils during thaw with associated moisture contents as high as 63% by weight. These occurred on well-drained soils. There were indications that similar although smaller changes also occurred in the 6- to 12-in. layer.

Post and Dreibelbis (1942) reported,

> "During the freezing process, the water holding forces

1/ Krumbach, A. W.
1959. Report on Freeze-Thaw Survey in the Lake States. (Unpublished data.)

> of the soil were overcome and ice became the soil carrier rather than the soil being the carrier of ice. The average volume weight of the frozen surface soil of Keene and Muskingum Silt Loams were found to be 0.63 and 0.93 respectively, while the volume of these same soils when nonfrozen were 1.27 and 1.36 respectively."

This is the equivalent of decreases in density of 50.4%, and 31.6% for the two soils.

Influence of Precipitation and Vegetation on Soil Freezing and Thawing

Snow

Snow can prevent frozen soil freezing layers from forming or can modify frost depth by insulating against freezing air temperatures. Likewise, snow may extend the duration of frost in the ground by insulating against warm air.

The influence of depth of snow on the amount of solar energy reaching the soil varies. Church (1941) stated,

> "The use of white and black bulb thermometers in snow indicates that radiation from the sun is effective on dark objects to a depth of 18 inches. Is this heat too slight to melt the ground until the snow cover has completely disappeared?"

Kuzmin (1957) found that a layer of dry snow 10 cm (4 in.) deep absorbs 65% of the solar radiation, and that wet snow of the same depth absorbs 97% of the solar radiation. He indicated that 8 in. (20 cm) of wet snow, or 16 to 20 in. (40 to 50 cm) of dry snow would effectively protect the soil against thawing from above. Mail (1936) found that 8 to 15 in. of snow maintained frost depth at 3 ft for 23 days when the average air temperature was 40 F.

Storey (1955) noted that:

> "A number of observations have shown that even though frost penetration has started before the first snow, when snow depths have reached 18 to 24 inches further frost penetration is stopped."

Eighteen inches of snow in northern Sweden and 8 to 12 in. in southern Sweden prevented soil freezing (Beskow, 1947).

Atkinson and Bay (1940) found, on wooded and bare sites in Wisconsin, that with 10 in. of snow, frost depth gradually decreased on 15 of 23 plots. In general, when snow was less than 10 in. deep, frost depth increased. In bare fields with 12 to 24 in. of snow, frost actually disappeared from the ground.

Potter (1956) studied frost depths in open corn land as opposed to a corn plot in the lee of a shelterbelt (in eastern North Dakota). In the winters of 1952-53 and 1953-54 the open plot had 4.5 and 9 in. of snow, respectively, and the sheltered plot, 36 and 120 in. The first winter Potter found that the limited snow cover on the open plot allowed frost to increase, from 12-in. thickness at the first snow, down to as deep as 3 ft. On the plot in the lee of the shelterbelt, the deep snow resulted in the frost line staying at about 1 ft, where it had been at the time of first snowfall.

With 10 ft of snow the second winter, frost disappeared from the ground on the plot in the lee of the shelterbelt, and temperatures at the 1-in. level rose to several degrees above freezing. The open field with a 9-in. snow cover again froze as deep as 3 ft.

Potter attributed the lack of increased frost penetration to the fact that resident heat from the ground can thaw the frost layer from below a heavy snow mantle. Other writers attribute the lack of frost penetration, or the actual melting of frost layers under heavy snow

cover to this same phenomenon; e.g. Belotelkin (1941), Holmes and Robertson (1960).

Snow on the ground prior to freezing may delay or prevent the formation of frost. Diebold (1938) working on predominantly sandy loam soils found that with air temperatures continually below freezing:

1. Freezing occurred only on an area bare of snow or vegetation (as compared to hardwood stands).
2. With 17 to 31 in. of snow, forest sites had no frozen ground.
3. Fifty-eight inches of snow prevented freezing on another area without vegetative cover.

On west slopes in the Cascade Mountains, Hale (1950) found that snow cover prevented freezing, while on east slopes with patchy snow cover freezing occurred (in Douglas fir and Lodgepole pine stands).

Tigerman and Rosa (1949) found in mountain soils of Utah that 18 in. of snow was sufficient to prevent soil freezing.

The effect of snow cover on temperature fluctuations is illustrated by the findings of Atkinson and Bay (1940).

> "Under 5 inches of snow cover there was less change in soil temperature at -20°F than there was under the 2-inch snow cover at -8°F, indicating the insulating effect of snow."

They also found under 6 in. of snow fluctuations amounting to 2 F at the soil surface, while under 12 to 24 in. of snow there were no fluctuations.

A snow mantle may either speed up the rate of soil thawing by the addition of meltwater to the frozen ground, or it may delay thawing by insulating the frozen ground from high air temperatures.

Belotelkin (1941), studying spruce flat, spruce swamp, fir flat, northern hardwoods, and open areas in New Hampshire, found thawing from

the soil surface did not begin until all snow had disappeared. However, thawing of frost occurred from below.

In Ponderosa pine plots, north slopes with snow tended to thaw three weeks later than south slopes with no snow, Hale (1950).

It is well known that snow meltwater contributes to the moisture content of the soil; however, its contribution can vary.

Diebold (1938) found the rate of disappearance of snow was equal in forest (chestnut-oak, aspen, beech-birch-maple) and open areas. Snow lasted longer in the forest since there was a greater depth at the start of the thaw.

Storey (1955) says that 1 in. of concrete frost may prevent snow meltwater from entering the ground, and Mosolov (1926) found that increases in soil moisture from snowmelt "...varied widely depending upon relief, depth of soil freezing and soils structure."

No quantitative information was found concerning the addition of meltwater to the soil.

Trimble (1959) states that snowpacks must reach a certain density before melt ("ripening") begins. In the eastern United States this density is near 30%, in the West it is 40 to 50%. He points out that these are averages, and snowpack density varies from top to bottom.

In summarizing Russian work Kuzmin says,

> "Fresh snow has the greatest water holding capacity; it can hold 55-35% of water of the total weight of wet snow at its initial density 0,13 - 0,21 (0.13 g/cc - 0.21 g/cc). Coarse-grained snow has the least water holding capacity; at its initial density 0,39 - 0,45 (0.39 g/cc - 0.45 g/cc) holds 25-15% of water."

Rain

Rain may hasten the thawing process. Atkinson and Bay (1940)

found this to be true in bare plots. In 1937 at the beginning of the thawing period there was 18 in. of frost in the ground, which required 27 days to thaw without rain. In 1938, with 1.8 in. of rain 34.5 in. of frost disappeared in 16 days. Though air temperatures during thaw had some influence, the effect of rain in removing frost from these bare plots was clearly evident.

Bay (1958) found that spring rains greatly hastened frost removal. Chang (1947) said,

> "Thawing is a rapid process in soils which permit the free passage of rain water. Partly because of the easy percolation of spring rain, and partly because of their low content of frozen water, the rate of thawing is greater in light than in heavy soils."

Goodell (1939) reported that rain may occasionally result in the formation of an ice coat on the soil surface and in the litter.

Bay, Wunneke, and Hays (1952) found that rain during thaw resulted in greater runoff and soil losses than did thawing alone.

Information on the amount of rain entering frozen soil is scanty; USDA workers report that, "...approximately 80% of an one-half inch rainfall was retained in a Pulaski County (Virginia) watershed...the ground was frozen to a depth of at least 0.25 of a foot before and during the storm."2/

Vegetation

Vegetation is important in part by its effect on snow cover and, thus, on freezing and thawing. Depth, duration, and type of frost are all affected.

MacKinney (1929) compared freezing on a plot with litter and

2/ Unpublished data, U. S. Department of Agriculture.

a plot from which litter was removed, both in a mixed red and white pine plantation in Connecticut. He found that litter retarded the first date of frost penetration by one month; once freezing began, there was no difference in freezing rates. Litter decreased frost penetration over 40%; the litter-covered plot showed 5 to 8 in. of frost as opposed to 8 in. in the bare plot. He stated:

> "The character of the frozen soil was influenced markedly by the litter. The soil on the bare plot froze solidly, and the air spaces were practically filled with ice. On the other hand, the frozen soil beneath the litter cover was porous and loose, at no time being frozen too hard to allow the insertion of a shovel. In the litter covered soil the ice formed around the soil particles leaving the spaces between the soil particles open."

Presumably MacKinney had observed concrete and honeycomb frost. He found also that rain could penetrate the frost under the litter, but not under the bare plot.

Studying differences between an ungraced woodlot and a close-cropped bluegrass pasture, Scholz (1938) reported that frost was deeper in the pasture throughout the freezing season; a maximum depth of 10 in. in the pasture, and 4 in. in the woodlot. Snow depths were the same over both plots at about 10 to 11 in. Scholz reported,

> "The manner in which the frost left the ground is also of interest. In the open pasture, the direct rays of the sun and above-freezing air temperatures progressively thawed out the soil, beginning at the surface, and working down into the subsoil until the frost had completely disappeared. In the woodlot, however, at those points where frost still occurred, thawing evidently took place from the bottom up, for in no case did the ice crystals disappear in the surface soil prior to the thawing of lower layers. Yet, all frost had disappeared in the woods two days before the pasture soil was completely thawed."

Similar observations were made by Krumbach[3/] in Wisconsin. Comparing a pasture, a woodlot, and a plowed field, it was found that the plowed area started thawing before the woodlot, but finished later. The woodlot thawed in patches. The pasture began and ended thawing after both the woodlot and plowed field.

Goodell (1939) studied sites with oak and oak-hickory on silt loam over clay soils, grassed areas on clay, and an open area on silt loam. He found that no soil freezing occurred in the woodlots; a maximum of 1.5 in. occurred under the pasture; while in contrast the open (corn) plot had maximum of 5.5 in. of freezing. There was essentially no snow cover.

In comparing corn stubble, wheat mulch, small grain stubble, and grass sod sites, Potter (1956) reported that the grass sod had higher minimum temperatures. Variation of soil temperature during the freezing season was less under grass than under the other types of cover.

Kienholz (1940) studied six forested areas, an open area, a light sod area, and a heavy sod area. He found that soil freezing in the forested areas did not begin until 15 to 35 days after the plowed area started to freeze. There were 125 days when frost occurred in the open plot compared to 94 days in white pine. The duration of freezing on the heavy sod site approximated that of the forest; frost duration in light sod was similar to the open site. Maximum frost depths in the winter of 1938-39 were 8.5 in. in the open compared to 2.9 in. under white pine. The average depth of freezing was also deeper in the open site.

3/ Krumbach, A. W.
1959. Report on Freeze-Thaw Survey in the Lake States. (Unpublished data.)

Pine and hemlock sites intercepted light snowfalls, had less drifting of snow, less surface crust formation, longer duration of snow on the ground, and less and lighter snow than the open or the sod areas. Thus snow disappeared from the pine and hemlock sites before it left the open sites.

Although snow depth varied little from site to site, differences in freezing did occur. White pine was more effective in lessening frost penetration than oak on a ridge site; the latter more effective than red maple, which, in turn, was more effective than mixed hardwood. Winding up the list in decreasing order of effectiveness of preventing frost penetration were the heavy sod, light sod, and bare cover types.

Kienholz (1940) found that leaves in depressions were very effective in reducing frost in the ground, and suggests perhaps organic matter thickness, not type, determines over-all effectiveness. The thicker the organic matter, the less frost in the ground.

When snow differences are considered, relationships are somewhat similar. Comparing northern hardwoods, chestnut oak, aspen, and bare sites, Diebold (1938) reported that the snow depth was equal in the forested areas, while bare areas on the flat had none. The northern hardwood plots had 11 in. of snow on March 18, 1936, while seven of eight open areas were bare.

Diebold noted that only bare plots showed runoff from a 7.9-in. rainfall, indicating that frost caused the bare plots to be impermeable, while the forest plots were able to absorb water.

Belotelkin (1941) in studying spruce, fir, northern hardwoods, and open areas, found that forest cover and its interrelationships with snow cover had a profound effect on time of soil freezing, and rapidity

of thawing. Penetration of frost was least in the hardwood stand, and greatest in the spruce swamp. Thawing began and finished earlier in the hardwood stand. He attributed this to the insulation provided by more snow and thicker litter in the hardwood stand. He found, also, that even though coniferous areas had frost in the ground later than hardwood areas, thawing patches in these plots before all freezing had gone soon permitted infiltration.

In a five-year study on a sandy clay loam near Northfork, California, Anderson (1946) found no freezing under brush sites, and less under grass than under bare areas. On the average, soil freezing occurred 17 days earlier and ceased 45 days later on bare than grass sites.

Sartz (1957) studied frost for two years in several timber types in southern Maine, northern New York, south central New York, northwestern Massachusetts, and northeastern Pennsylvania. He found that concrete frost began to form 3 to 47 days after the ground began to freeze in open land, and 26 to 48 days after freeze in hardwoods. Two-year averages for last frost ranged 0 to 26 days later in softwoods, and from 22 days earlier to 4 days later in hardwoods than in open land.

Pierce, Lull, and Storey (1958) noted that frost was found more frequently and to greater depth in open lands as opposed to hardwood or conifer. They found average frost depth in hardwood stands to be about one-half that in conifer stands. Open areas were found to have twice as much snow on the ground as forested areas; snow depth averaged about 2.7 in. more in hardwood than conifer stands; hardwood forests and reproduction areas averaged 1.75 times deeper snow than open areas; and

snow depths were 1.5 times greater in conifer forest than in hardwood.

The relationship between forest types and depth to permafrost (and soil moisture content) was noted in Alaska by Lutz and Caporaso (1958). They found that the minimum depth to permafrost under black spruce stands was 12 to 20 in.; under white spruce 24 to 26 in. (if frost is present); under paper birch 36 to 48 in.; under quaking aspen at least 48 in.; and under balsam poplar at least 6 ft (if permafrost was present at all). Thus in an area where conditions suitable for frost formation are present throughout the year, forest types could be used as indicators of depth to frost.

Influence of Soil Color, Evaporation, and Microrelief on Soil Moisture During Freezing and Thawing

Soil Color

Dark colored surfaces absorb more heat than light colored surfaces. Bouyoucos (1916, 1913) reported on studies of five sandy soils, and one peat soil. After four years of investigation, he stated,

> "This investigation goes to prove that soils with white colors and low moisture content, or with black color and high water content have lower average temperatures during the spring and summer than soils possessing these properties in medium proportion. In other words, the white color of a soil reflects so much of the sun's rays that it prevents the soil from attaining a high temperature, in spite of its low water content and small amount of evaporation, while the excess water of a black soil, such as peat, consumes so much of the heat in its evaporation process, that it keeps the temperature of the soil low in spite of its black color and hence its great heat absorbing power."

Everson and Weaver (1949) worked with carbon black in Merrimac fine sandy loam during the spring and summer of 1944 and 1945. Carbon black was mixed to a depth of 2 in. at the rate of 4,000 lb per acre.

They found that maximum temperatures at the surface and 2 in. below the surface averaged 2 and 3.4 F higher, respectively, than for untreated soils. Minimum daily temperatures were 0.8 and 0.5 F higher on the treated than untreated plots for the soil surface and 2-in. depth, respectively.

These authors continued studies into 1945 and 1946 on Agawan fine sandy loam soils. In 1945 carbon treated soil thawed two days earlier than untreated, in 1946 one week earlier; and it could be plowed two weeks before the untreated soil. On January 27, 1945, they found the carbon treated soil thawed to 2 in. under snow, while the untreated did not. In the winter of 1944 treated soil remained unfrozen until December 22, while the untreated soil froze December 3.

Darker soils may result in higher energy intake, with increased soil temperature, delay in soil freezing, and advancement of thawing.

Evaporation

No quantitative information was found on evaporation in relation to freezing and thawing. Bouyoucos (1916) inferred that evaporation may keep a soil cool.

Anderson (1946) worked out an equation for predicting evaporation when the soil was freezing. In reference to the upper 3 in. of soil he stated,

> "Freezing of a soil kept bare of vegetation greatly increased the evaporation loss from the soil. The evaporation during freezing periods was three times as great as during similar nonfreezing periods, nearly four times as great as combined transpiration-evaporation from brush-covered soil during same periods and about 12 times as great as evaporation from a free-water surface during the same periods."

Daily measurements were made, and no internal drainage was indicated. Freezing and thawing would bring water to the surface in

amounts greater than by movement during nonfrozen periods which would account for the greater differences than on a bare soil. The brush-covered soil had not frozen during these periods, and probably the free-water surface had frozen over the night, greatly reducing evaporation.

Microrelief

Trimble, Sartz, and Pierce (1950) reporting on a study in New Hampshire stated:

> "During times of thaw the melt pattern in some areas of concrete frost was very erratic, resulting in a close intermingling of frozen and unfrozen ground. This condition appeared to be associated with differences in micro-relief, which permitted certain micro-aspects and slopes to receive more solar radiation and thus to melt sooner."

This was the sole reference to microrelief. Perhaps mocrorelief effects may well be the explanation for spotty freezing or thawing patches observed in many investigations.

Conclusions from Literature

Temperature

Air temperatures must be below freezing to induce soil freezing; a temperature of 32 F is not low enough as sufficient heat loss does not take place. Overnight air temperatures in the temperature range of about 20 to 25 F will cause freezing in the upper 1 to 2 in. of soil.

Soil temperature must also be well below 32 F before the soil freezes. In one instance, a temperature of 18 F was recorded before the upper 1/2 in. of soil froze. Investigators agree that the lower the soil moisture content, for a given soil, the lower the soil temperatures necessary to induce freezing. Further, at or near saturation,

the finer the soil texture, the lower the soil temperature necessary for freezing.

The tension at which moisture is held in the soil is also related to its ease of freezing. The more tension on the water, the lower the temperatures necessary to freeze it.

Moisture Movement and Physical State

In general, slower freezing results in greater soil aggregation, and vice versa. Considering changes in soil volume on a strictly theoretical basis even a saturated soil should not increase more than 5% upon freezing. However, increases in volume up to 60% over the unfrozen state have been found. This indicates moisture movement into the frozen or freezing soil layer.

Soil Moisture During Freezing Periods

Studies of soil moisture under the frozen layer indicate that moisture may be drawn from as deep as 36 in. up into the frozen layer.

Water entering the frozen soil from above is affected by the frost type; concrete frost presumably prevents snow meltwater, or rain water from entering the soil. However, stalactite or honeycomb frost may increase the infiltration capacity above the level expected when the soil is not frozen.

Moisture contents in a frozen layer were reported to increase to as much as nine times the moisture content of the layer just before freezing.

Investigators have suggested that moisture may move into the frozen layer both through vapor and capillary action, and at least one found evaporation rates increased when the soil surface was freezing.

Precipitation

Eight to twenty inches of snow have been shown to effectively insulate the soil from the effect of air temperature change. The effectiveness of a given depth of snow increases with its wetness.

Snow in its insulating role, may result in a soil freezing later in winter than a soil without snow, or with a thinner snow mantle. In the spring the same relationship may exist with the time of thaw. Snow may also hasten soil thawing in the spring through the release of meltwater.

Spring rains generally hasten soil thawing.

Vegetation

Open areas freeze before forested areas. Conifer-covered soils freeze before hardwood soils. Grass-covered soils freeze before forested but after bare soils. Open soils generally thaw before conifer-covered soils, but after hardwood soils. Grass-covered soils thaw after bare soils. Snow accumulation is generally greater in hardwood than coniferous areas, and greater in open areas than coniferous areas.

Deficiencies in Knowledge

Information was minimal or lacking on the following points:

1. The moisture content of the soil during freezing and thawing periods. (Though some information was available on comparative moisture contents, there was no investigation found which followed the moisture regime in detail through continuous periods of freezing or thawing including comparative effects of soils and vegetation.)
2. The number, magnitude, and duration of soil thawing periods.

3. Changes in soil moisture-holding capacities during freezing and thawing periods. Information presented on soil pore space was not for sequential freezing or thawing periods and did not measure the type of pore volume (i.e. 60-cm tension levels, field capacity, total pore space, wilting point, or intermediate values).
4. Duration of soil moisture contents, or moisture-holding capacities after the final spring thaw.

LOCATION AND DESCRIPTION OF STUDY AREAS

General

Six plots were selected on medium-textured, level (less than 6% slope) soils. One set of three plots was established in a region of high snowfall, and one set in a lower snowfall area. One plot in each set was bare, one under herbaceous cover, and one in hardwood forest.

Location

One set of plots was located in Kent County, Michigan, a high snowbelt area, and one set in Clinton County (Figure 1). The plots were about 70 miles apart.

Kent County Plots

Kent County plots were located in Gratton Township (Figures 2 and 3). The hardwood plot was about 1/4 mile north of the herbaceous plot, and the bare plot about 2-1/2 miles northwest of the hardwood plot as indicated below:

Plot	Location
Bare	SW 1/4 of NW 1/4 Sec. 6, T8N, R9W
Herbaceous	SW 1/4 of NW 1/4 Sec. 17, T8N, R9W
Hardwood	SW 1/4 of SW 1/4 Sec. 17, T8N, R9W

Clinton County Plots

Plots in Clinton County were located in Dewitt Township (Figure 4). The bare plot was 40 ft north of the herbaceous, and the hardwood plot was about 1/8 mile southwest of the other two. Locations were:

Plot	Location
Bare and herbaceous	NE 1/4 of SW 1/4 Sec. 2, T5N, R9W
Hardwood	SW 1/4 of SW 1/4 Sec. 2, T5N, R9W

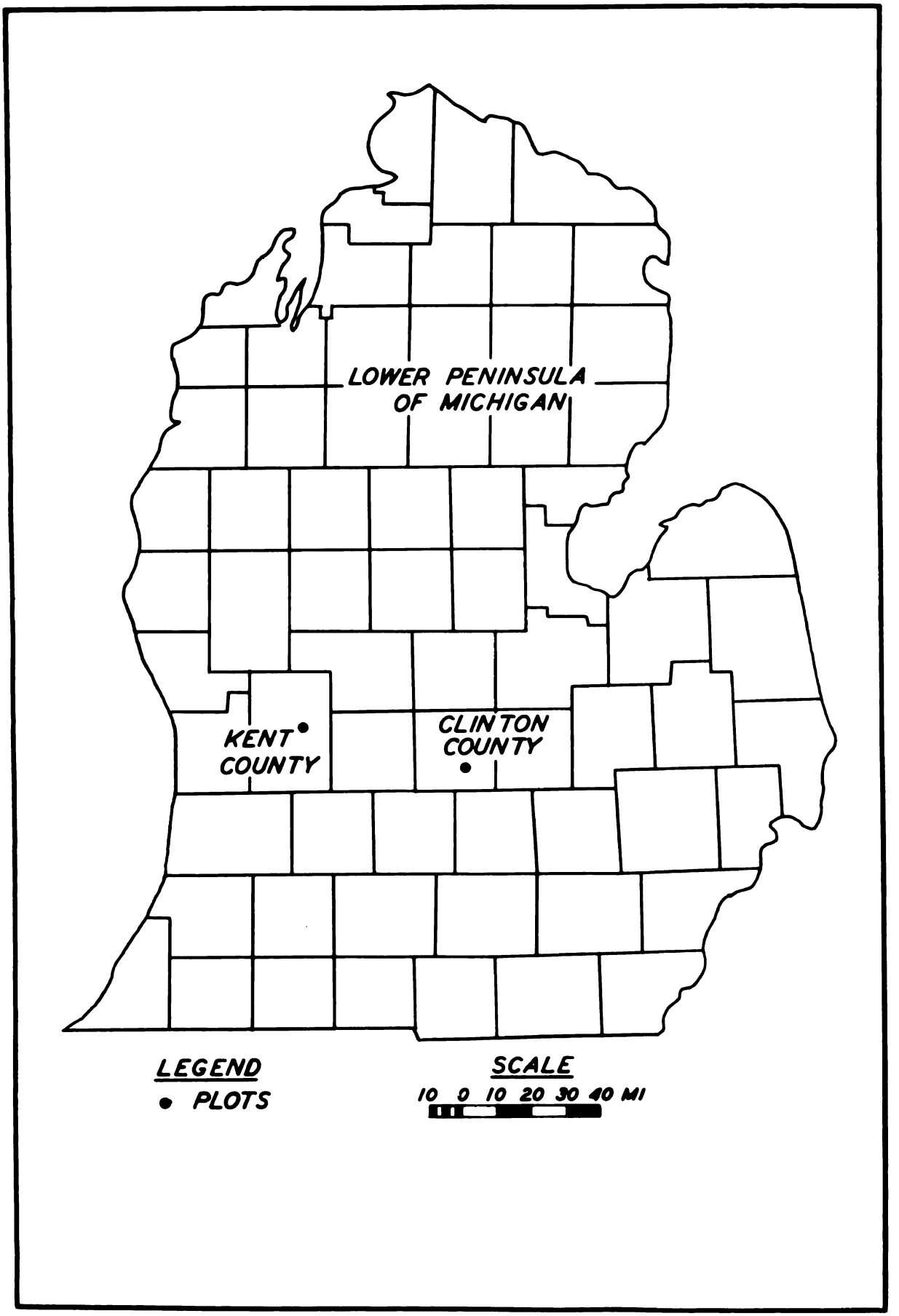

Figure 1. Relative location of study plots in Lower Michigan

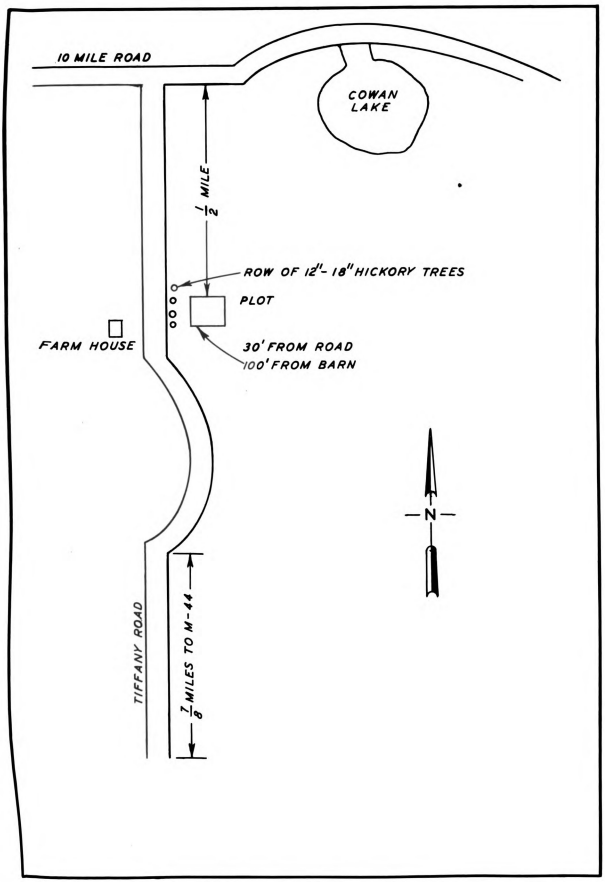

Figure 2. Location of bare plot in Kent County

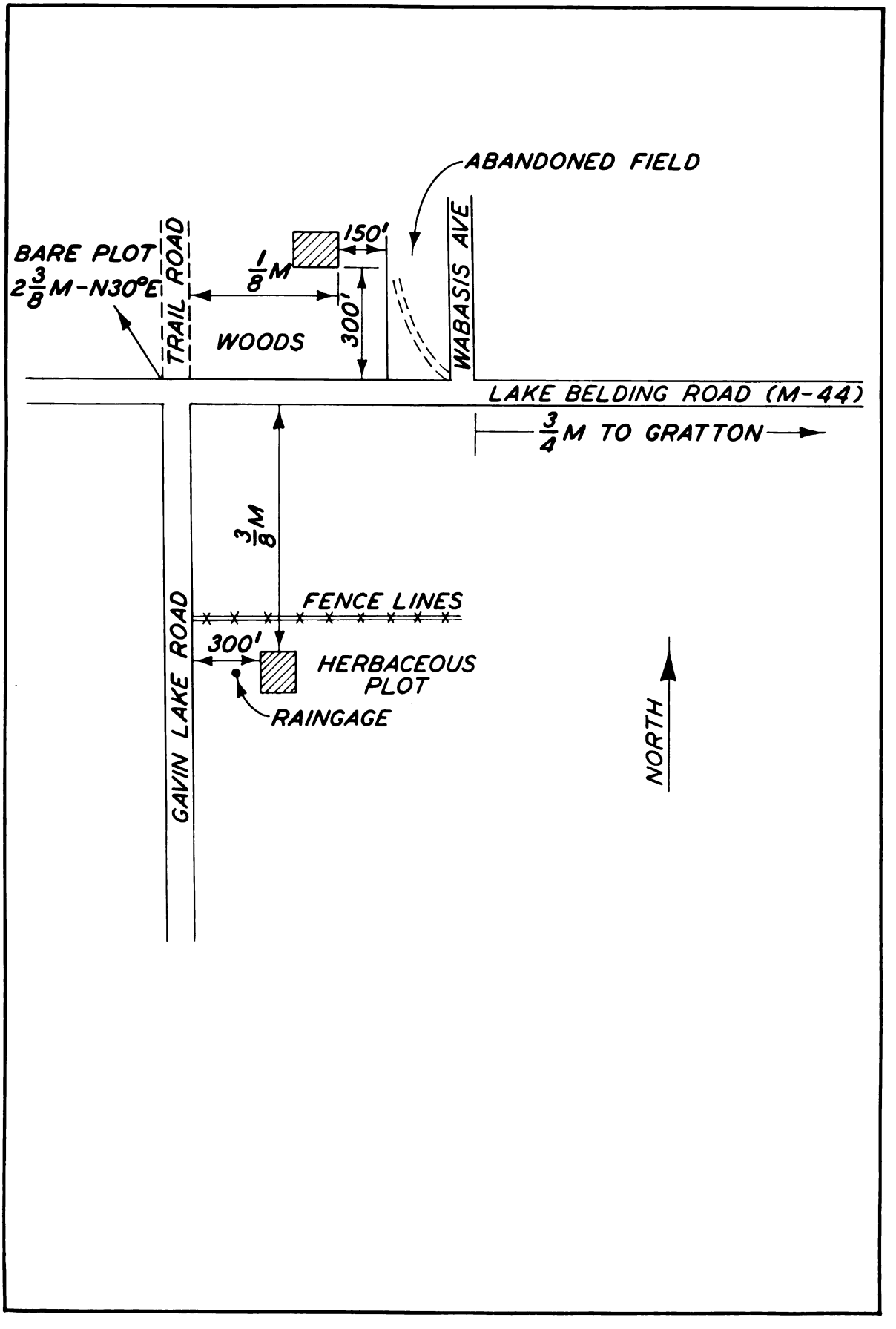

Figure 3. Location of herbaceous and hardwood plots in Kent County

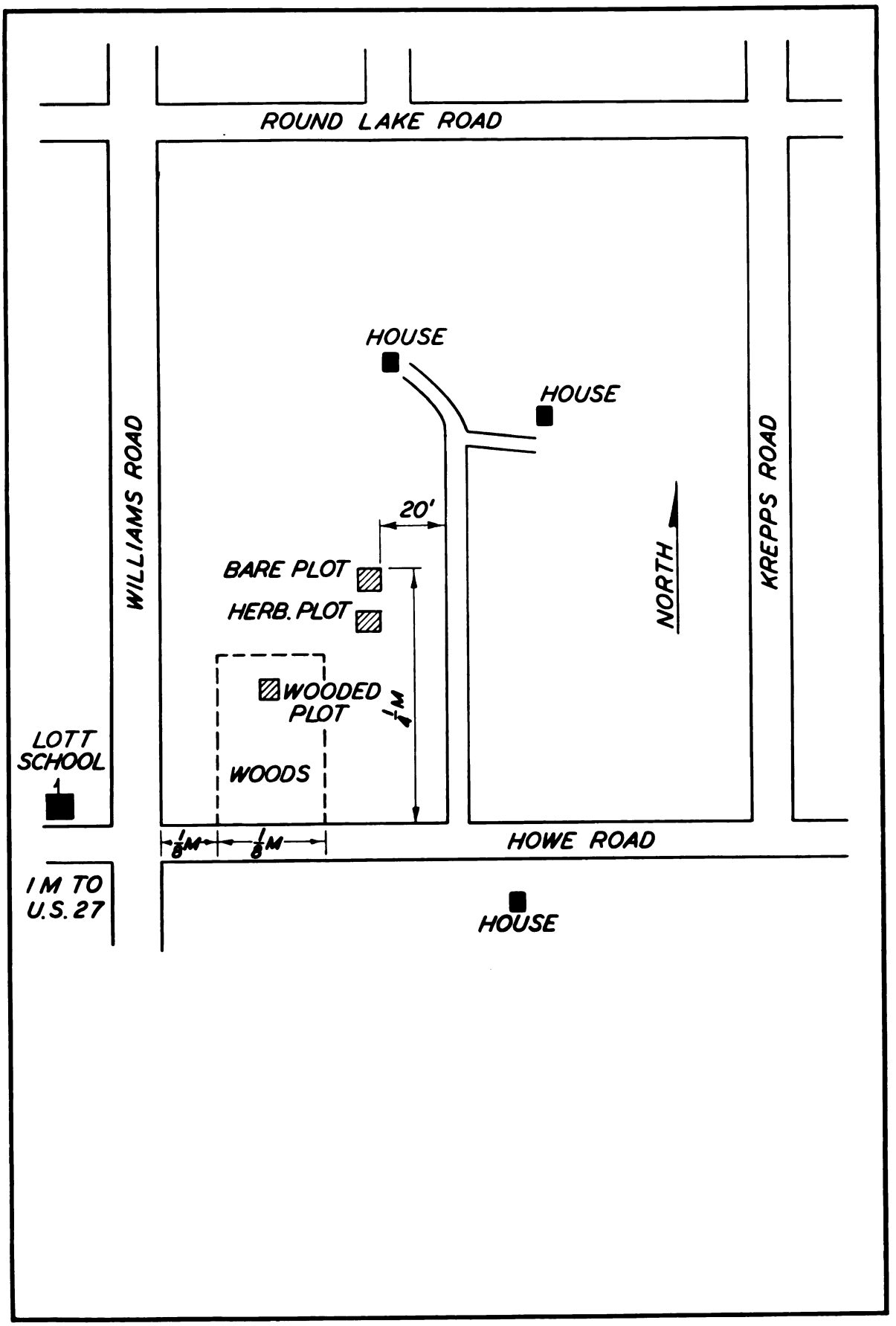

Figure 4. Location of plots in Clinton County

Land Use and Vegetation

Bare Plots (Figure 5)

Corn stubble was present on the Kent County plot throughout the study. The plot had been manured the preceding winter (1958-59), but no raw manure was observed.

The Clinton County Bare plot had been in the third year of an alfalfa-red clover-alfalfa rotation. Three weeks before the first sampling the plot had been plowed to 6 in. and packed.

Herbaceous Plots (Figure 6)

The Kent County plot was in the fourth winter since cultivation, and had not been grazed. Predominant cover, based on visual estimate, consisted of 30% Ladino clover, 30% quack grass, and 20% each alfalfa and wild mustard. Many other species were present (Table 1).

The Clinton County plot was in the third year of an alfalfa-red clover-alfalfa rotation, and had not been grazed. Alfalfa made up almost 100% of the cover but some red clover was present from the previous year. Other species were scattered in the plot (Table 1).

Hardwood Plots (Figure 7)

Neither hardwood plot had been grazed, nor was there evidence of recent cutting. The Kent County plot showed some evidence of fire with scars on the base of trees over 5 or 6 in. in diameter.

Herbaceous species were generally similar and well distributed in the two woods (Table 2). In the spring the Clinton County plot had a profuse cover of dogtooth violets not noted in Kent County.

There were noticeable differences in both the number and variety of tree species (Table 3). In Kent County the predominant overstory species were red oak, soft maple, and black cherry, with understory

Facing southeast from northwest corner of Kent County Bare plot.
(Thermocouple stack in center of photo)

Facing east across south half of Clinton County Bare plot

Figure 5. Surface conditions of bare plots

Facing southwest across Kent County Herbaceous plot. Thermocouple stack, left center; resistance stack in background of right elbow of man

Facing north on Clinton County Herbaceous plot. Hvorslev sampler shown with plunger extended

Figure 6. Surface conditions of herbaceous plots

Table 1. Vegetation of the herbaceous plots

Plant Name	
Common	Scientific
Kent County and Clinton County Plots	
Ladino clover	*Trifolium* sp. (commercial hybrid)
Red clover	*Trifolium pratense* L.
Alfalfa	*Medicago sativa* L.
Quack grass	*Agropyron repens* (L.) Beauv.
Dandelion	*Taraxacum* sp.
Mullein	*Verbascum thapsus* L.
Kent County Plot Only	
Wild mustard	*Brassica* sp.
Corn cockle	*Agrostemma Githago* L.
Curled dock	*Rumex crispus* L.
Goldenrod	*Solidago* sp.
Common plantain	*Plantago Major* L.
Wild carrot	*Daucus Carota* L.

Facing southwest across center of north edge of Kent County Hardwood plot

Facing south from center of Clinton County Hardwood plot. Note water in tree-throw depression to left front of man

Figure 7. Surface conditions of hardwood plots

Table 2. Herbaceous species of hardwood plots

Common Name	Scientific Name
Kent County and Clinton County Plots	
Poison ivy	*Rhus radicans* L.
Wild geranium	*Geranium maculatum* L.
May apple	*Podophyllum peltatum* L.
Violets	*Viola sp.*
Trillium	*Trillium grandiflorum* (Michx.) Salisb.
False Solomon's seal	*Smilacina racemosa* (L.) Desf.
Bracken fern	*Pteridium aquilinum* (L.) Kuhn.
Raspberry	*Rubus occidentalis* L.
Kent County Plot	
Honeysuckle	*Lonicera sp.*
Bellwort	*Uvularia sessilifolia* L.
Clinton County Plot	
Dogtooth violet	*Erythronium americanum* Ker.
Bittersweet	*Solanium dulcamara* L.
Strawberry	*Fragaria virginiana* Duchesne

Table 3. Tree species on hardwood plots

Common Name	Scientific Name
	Kent County and Clinton County Plots
Black cherry	Prunus serotina Ehrh.
Sugar maple	Acer saccharum Marsh.
Soft maple	Acer rubrum L.
White ash	Fraxinus americana L.
Red oak	Quercus rubra L.
White oak	Quercus alba L.
Sassafras	Sassafras albidium Nutt.
Chinquapin oak	Quercus prinoides Willd.
	Clinton County Plot
Swamp white oak	Quercus bicolor Willd.
Green ash	Fraxinus pennsylvanica var lanceolata (Borkh.) Sarg.
Shagbark hickory	Carya ovata (Mill.) K.
Pignut hickory	Carya glabra (Mill.)
Slippery elm	Ulmus rubra Muhl.
American elm	Ulmus americana L.
Large-toothed aspen	Populus grandidentata Michx.

and reproduction composed mainly of soft maple. The average d.b.h. was 8.3 in. and the basal area 102.1 sq ft per acre. (See Appendix Table A1.)

In Clinton County the average d.b.h. was 5.4 in. and the basal area 76.0 sq ft per acre. There were 479 stems (2 in. and above) per acre as compared to 281 on the Kent County plot. Red oak made up the majority of the overstory with scattered slippery elm, soft maple, and white ash.

Understory trees on the Clinton County plot included the species above plus shagbark hickory, basswood, green ash, swamp white oak, and pignut hickory.

The organic horizon on the Kent County plot varied from a thin duff mull to a coarse mull; the humus layer ranged in thickness from none to about 1/2 in. thick. A surface humus layer was never found in the Clinton County plot, hence the organic horizon was listed as a coarse mull.[4/]

Soil Descriptions

Unless otherwise noted the soils in each county were developed from glacial till. In the main, the land surface is gently rolling.[5/]

Kent County Bare Plot

This plot drains toward the low area of Twining Loam in its center. Tile has been laid through this low area and the spoil from the ditch

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4/ Based on the classification presented by Hoover and Lunt (1952).

5/ For detailed information on the physiography and geology of each county see Veatch (1953), Wildermuth and Kraft (1926), and Johnsgard, et al. (1942).

thrown up to the south, resulting in a spoil deposit in soil area C, Figure 8.

Twining fine sandy loam (soil area A, Figure 8). This imperfectly-drained soil developed from loamy parent material on ground moraine. It has a 1 to 2% slope with a southern aspect.

Horizon	Depth, in.	Description
A_p	0-8	Fine sandy loam; very dark grayish brown (10 YR 3/2, moist); weak, medium, subangular blocky structure; friable; abrupt smooth boundary.
A_{2g}	8-16	Loamy fine sand; brown (10 YR 5/3 moist), with few, medium, distinct, dark yellowish brown mottles (10 YR 4/4); weak, coarse, subangular blocky structure; very friable; clear, wavy boundary.
B_m	16-18	Sandy clay loam; brown (7.5 YR 4/2 moist), with many, fine, distinct dark yellowish brown (10 YR 4/4) mottles; moderate, medium, subangular blocky structure; very firm; fragipan.
B_{2g}	18-34	Clay loam; brown (7.5 YR 4/2 moist), with many fine, distinct, dark yellowish brown (10 YR 4/4) mottles; moderate, medium, subangular blocky structure; firm; clear, wavy boundary.
C	34-60+	Loam; 40% brown (7.5 YR 4/2 moist). 40% dark yellowish brown (10 YR 4/4), 20% gray; friable; slightly effervescent.

Twining loam, deeply leached (soil area B, Figure 8). This imperfectly drained soil is slightly eroded and has a 2%, south-facing slope. Ground water was 65 in. below the surface at the time of sampling.

Horizon	Depth, in.	Description
A_p	0-8	Loam; very dark brown (10 YR 2/2 moist); weak, medium, granular structure; friable; abrupt, smooth boundary.

(Continued)

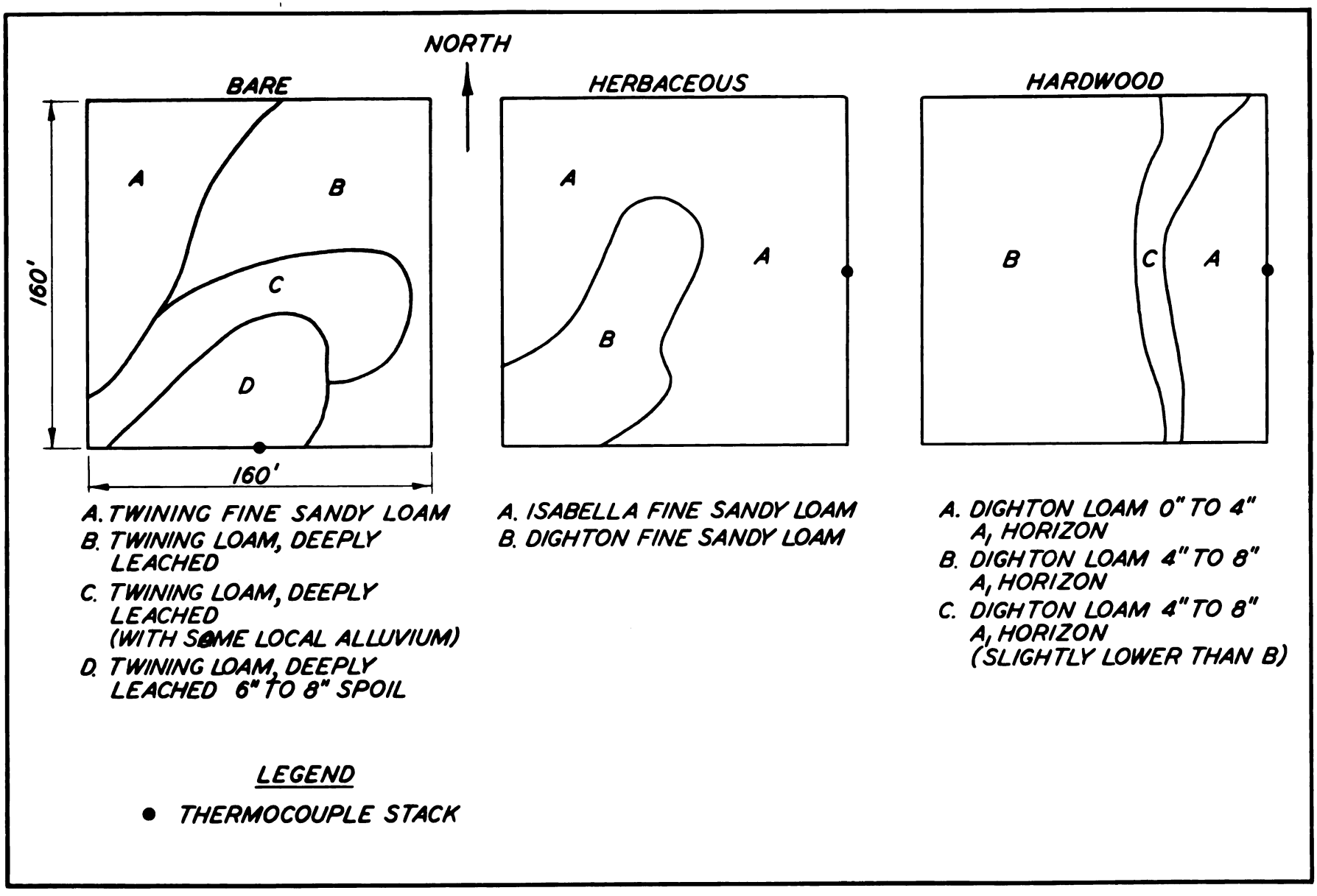

Figure 8. Detailed soil maps of Kent County plots

Horizon	Depth, in.	Description
A_2	8-18	Sandy loam; brown (10 YR 5/3 moist) with common, medium distinct, dark brown (10 YR 4/3 moist) mottles; weak, medium, subangular blocky structure; very friable; clear, wavy boundary.
B_{21}	18-40	Clay loam; brown (7.5 YR 5/4 moist, 10 YR 5/3 moist, 7.5 YR 5/2 moist); moderate, medium, subangular blocky structure; firm; gradual boundary.
B_{22}	40-60+	Sandy clay loam; brown (7.5 YR 5/4 moist, 10 YR 5/3 moist, 7.5 YR 5/2 moist); weak, medium, subangular blocky structure; friable.

Twining loam (soil area D, Figure 8). The till parent material shows indications of added local alluvium. This is the lowest area of the plot. The slope is less than 1%. No erosion was apparent. Drainage is imperfect.

Horizon	Depth, in.	Description
A_p	0-8	Loam; very dark brown (10 YR 3/1 moist); weak, coarse, subangular blocky structure over fine, moderate, crumb structure; friable; abrupt, smooth boundary.
A_2	8-11	Loam; dark gray (10 YR 4/1 moist); weak, medium, subangular blocky structure; friable; clear, wavy boundary.
B_{21g}	11-20	Sandy clay loam; extremely mottled, dark grayish brown (10 YR 4/2 moist), to gray brown (10 YR 5/2 moist), to strong brown (7.5 YR 5/6 moist); moderate, medium, subangular blocky structure; friable; gradual boundary.
B_{22g}	20-30	Clay loam; extremely mottled, dark grayish brown (10 YR 4/2 moist), to gray brown (10 YR 5/2 moist), to strong brown (7.5 YR 5/6 moist); weak, medium, subangular blocky structure; friable; clear, wavy boundary.

(Continued)

Horizon	Depth, in.	Description
C_{21}	30-40	Clay loam; strongly mottled, 40% gray (N 5/0 moist), 40% strong brown (7.5 YR 5/6 moist), 20% pinkish gray (7.5 YR 6/2 moist); fine, weak, subangular blocky structure; friable; calcareous; gradual boundary.
C_{22}	40-60+	Loam, friable, calcareous.

There is a distinct hardpan in the bottom of the A_2 horizon in area A and not in area B. Depth to lime is 30 to 40 in. in area A; greater than 5 ft in area B. There may be a relationship between the hardpan and the depth to lime. The hardpan is not readily visible, consistence being its most outstanding characteristic. It is very effective in causing a perched water table.

Deep plowing (probably to combat the hardpan) has destroyed all evidence of the podzol sequm.

Kent Herbaceous Plot

The soil is generally uniform and the entire plot is well drained. The plot has a west facing slope of 2%.

Isabella fine sandy loam (area A, Figure 8). The parent material is glacial till with some local alluvium. Erosion is slight. The soil is well drained with a deep water table.

Horizon	Depth, in.	Description
A_p	0-9	Fine sandy loam; dark brown (10 YR 3/3 moist); weak, coarse, subangular blocky structure; very friable; abrupt, smooth boundary.
B_{21}	9-14	Sandy clay loam; dark brown (7.5 YR 4/4 moist); weak, fine subangular blocky structure; friable; gradual boundary.
B_{22}	14-28	Sandy clay loam; dark brown (7.5 YR 4/4 moist); weak, medium, subangular blocky structure; friable; gradual boundary.

(Continued)

Horizon	Depth, in.	Description
B_3-C_1	28-34	Loam; dark yellowish brown (10 YR 4/4 moist); weak, fine, subangular blocky structure; friable; gradual boundary.
C	34-48	Sandy clay loam; dark brown (10 YR 4/3 moist); friable; gradual.
Dg	48-60+	Medium sand; yellowish brown (10 YR 5/4 moist), with common, medium to coarse distinct dark brown (7.5 YR 1/4 moist) mottles; loose.

Dighton fine sandy loam (soil area B, Figure 8). The parent material is local alluvium. Physiographically the area appears to be a minor drainageway in the tillplain. Slope is 1% with a southwest exposure. The soil is well drained with a deep water table.

Horizon	Depth, in.	Description
A_p	0-10	Fine sandy loam; very dark gray-brown (10 YR 3/2 moist); weak, medium, subangular blocky structure; very friable; abrupt, smooth boundary.
A_2	10-20	Fine sandy loam; dark brown (10 YR 4/3 moist); very weak to weak, fine, subangular blocky structure; very friable; clear, wavy boundary.
B_{2t}	20-32	Sandy clay loam; dark brown (7.5 YR 4/4 moist); weak, medium, subangular blocky structure; friable; clear, wavy boundary.
C_1	32-46	Loamy sand; dark brown (10 YR 4/3 moist); single grain structure; loose consistency; clear, wavy boundary; many rounded pebbles.
C_2	46-60	Sandy loam; dark yellowish brown (10 YR 4/4 moist); very friable.

Kent County Hardwood Plot

General. Soils here are classified as Dighton, rather than Isabella, because of the sand substratum at 3-1/2 to 4 ft. Soil area C (Figure 8) is slightly lower than the rest of the plot and has a thicker

A_1 horizon. Lime content is low throughout. The podzol A_2 horizon is discontinuous and poorly defined.

Kent County Hardwood Plot

Soils have substratum at 42 to 48 in. Soil area C (Figure 8) is slightly lower than the rest of the plot and has a thicker A_1 horizon. Lime content is low throughout. The podzol A_2 is discontinuous and poorly defined. Physiography is that of ground moraine.

Dighton loam (Figure 8). In this area slope is less than 2% and area is well drained with a deep water table.

Horizon	Depth, in.	Description
A_1	0-3	Loam; black (10 YR 2/1 moist); moderate, medium, granular structure; very friable; clear, wavy boundary.
A_2	3-4	Sandy loam; dark gray (10 YR 4/1 moist); weak, fine, granular structure; very friable; discontinuous boundary.
B_{21}	4-6	Loam; dark brown (10 YR 4/3 moist); weak, fine, granular structure; friable; clear, irregular boundary.
A_2	6-13	Loam; brown (10 YR 5/3 moist); weak, fine, subangular blocky structure; friable; clear, irregular boundary.
B_t	13-30	Sandy clay loam; dark brown (7.5 YR 4/4 moist); moderate, fine, subangular blocky structure; friable; clear, irregular boundary.
C	30-50	Loamy sand; dark brown (10 YR 4/3 moist); few bands sandy loam, dark brown (7.5 YR 4/4); very weak, medium, subangular blocky structure; very friable to loose; gradual boundary.
D	50-60+	Clean medium sand; pale brown (10 YR 6/3 moist), with few bands of loamy sand, dark brown (7.5 YR 4/4); single grain; loose.

Clinton County Bare
and Herbaceous Plots

General. Both plots are located on the top of a broad knoll. Parent material is a loam till.

Celina loam (area A, Figure 9). The slope is 1% and the general aspect is south, southeast on the herbaceous plot, and north, northwest on the bare plot. Erosion has been slight. The soil is moderately well drained with a deep water table.

Horizon	Depth, in.	Description
A_p	0-9	Loam; very dark gray brown (10 YR 3/2 moist); weak, fine, crumb structure; friable; abrupt, smooth boundary.
A_2	9-13	Loam; brown (10 YR 5/3 moist); weak, fine, platy structure; friable; clear, irregular boundary.
B_{21tg}	13-25	Clay loam; dark brown (10 YR 5/3 moist), with many coarse, faint brown (10 YR 5/3 moist) mottles; moderate, medium, subangular blocky structure; friable, slightly sticky and plastic; gradual boundary.
B22tg	25-33	Clay loam; dark brown (10 YR 5/3 moist), with common, coarse, distinct, dark brown (7.5 YR 4/4 moist) mottles; moderate, medium, subangular blocky structure; slightly plastic; clear, wavy boundary.
C_{1g}	33-44	Clay loam; dark brown (10 YR 4/3 moist), with common, medium to coarse, faint, dark, yellowish brown (10 YR 4/4 moist) mottles; weak, medium, platy structure; slightly sticky to plastic; slightly effervescent; gradual boundary.
C_{2g}	44-60+	Loam; brown (10 YR 5/3 moist), with many coarse, distinct, yellowish brown (10 YR 5/6 moist), and common, medium, distinct gray (10 YR 5/1 moist) mottles; friable; nonsticky to slightly plastic; strongly effervescent.

Conover loam (area C, Figure 9). Conover areas are minor drainageways in the plots, with slopes which are generally less

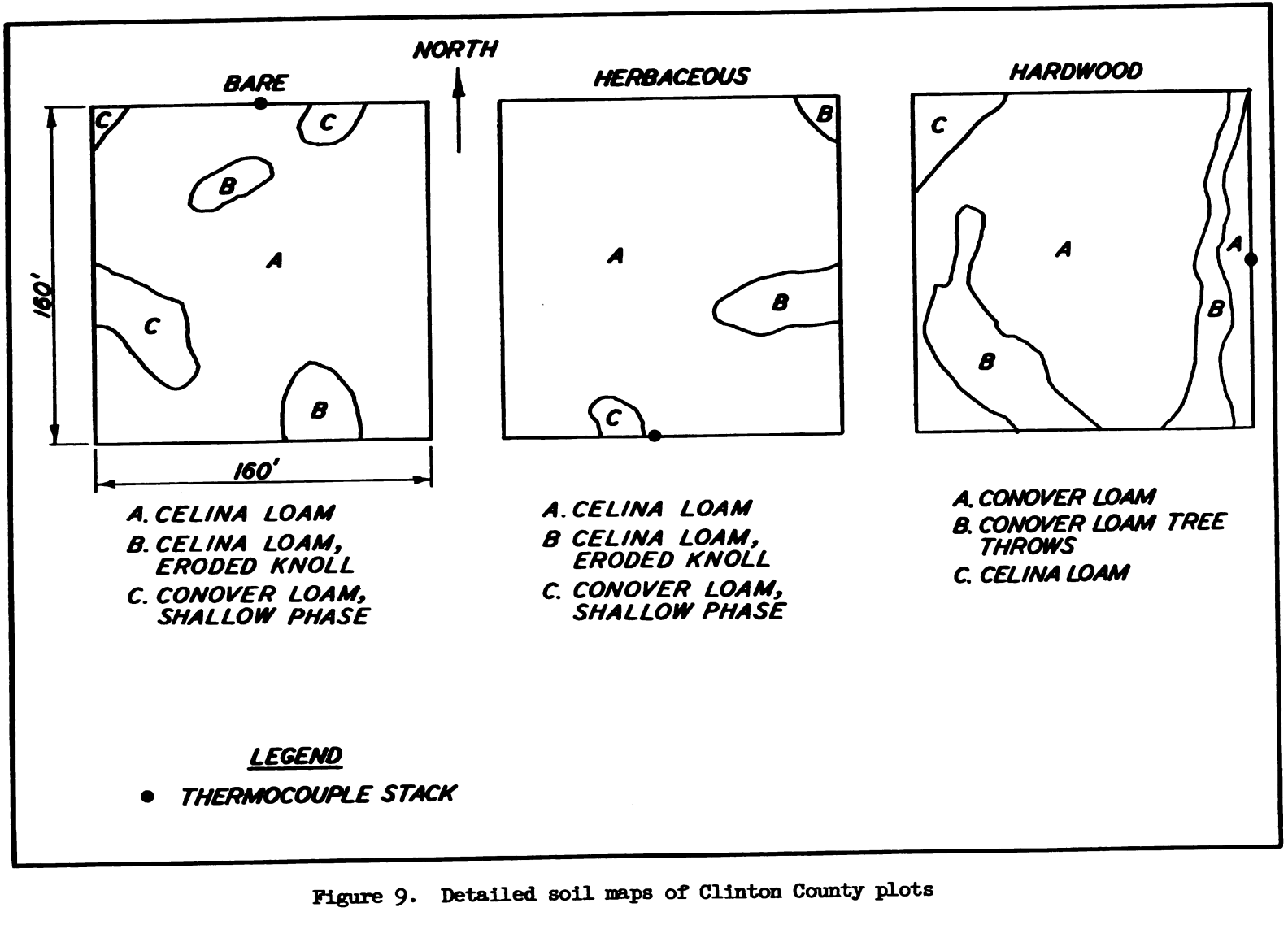

Figure 9. Detailed soil maps of Clinton County plots

than 1%. Internal drainage is moderate, and moderate erosion is present from water action. Mottling in soil is partially a result of a drainage deficiency.

Horizon	Depth, in.	Description
A_p	0-12	Loam; very dark brown (10 YR 3/2 moist); weak, fine, crumb structure; friable; abrupt, smooth boundary.
A_2	12-14	Loam; brown (10 YR 5/3 moist); weak, medium, subangular blocky structure; friable; discontinuous boundary.
B_{21g}	14-26	Clay loam; dark brown to brown (10 YR 4/3-5/3), with many, medium, distinct, dark yellowish brown (10 YR 4/4 moist) mottles, and common, coarse, prominent, strong brown (7.5 YR 4/6 moist) mottles; moderate, medium, subangular blocky structure; firm, sticky to slightly plastic; gradual boundary.
B_{22g}	26-36	Clay loam; brown to dark brown (10 YR 5/3-4/3 moist), with black manganese concretions; moderate, medium, subangular blocky structure; firm, sticky to slightly plastic; gradual boundary.
Cg	36+	Loam; brown (10 YR 5/3 moist), many, medium, distinct, dark yellowish brown (10 YR 4/4 moist) mottles, and common, fine, distinct light brownish gray (10 YR 6/2 moist) mottles; fine weak, platy structure; firm; slightly effervescent.

Considerable material has been removed from the smaller knolls (area B, Figure 9), and deposited in the lower areas (area C, Figure 9). In the shallower Celina areas, the plow layer extends into the upper B horizon; in the Conover areas, local deposition produces an A_1 horizon 10-14 in. thick. The majority of the area is well developed Celina soil. Mottles in the Celina B horizon indicate difference in material, not drainage restriction.

Clinton County Hardwood Plot

General. Most of the plot appears imperfectly drained. The best drained area is Celina loam (area C, Figure 9) in the northwest corner. The tree-throw depressions (area B, Figure 9) are low areas of imperfect drainage.

Conover loam. The slope is about 1% over the plot. This is a naturally imperfectly drained soil, and at the time the soil profile description was written water was 2 ft below the soil surface.

Horizon	Depth, in.	Description
A_1	0-6	Loam; very dark gray (10 YR 3/1 moist); strong, fine, crumb structure; slightly sticky to plastic; clear, wavy boundary.
A_2	6-10	Loam; dark grayish brown (2.5 YR 4/2 moist); weak, medium, subangular blocky structure; nonplastic to slightly plastic; clear, wavy boundary.
B_{1g}	10-14	Clay loam; gray brown (10 YR 4/2 moist) with many coarse, faint, dark brown (10 YR 4/3 moist) mottles, weak, medium, subangular blocky structure; sticky to plastic; clear boundary.
B_{21g}	14-24	Clay loam; dark grayish brown (2.5 YR 4/2 moist) with many, medium to coarse, distinct, dark, yellowish brown (10 YR 4/4 moist) mottles; moderate, medium, subangular blocky structure; sticky to plastic; clear boundary.
B_{22g}	21-32	Clay loam; gray brown (10 YR 5/2 moist) with many coarse, distinct, dark brown to strong brown (7.5 YR 4/4-5/6 moist) mottles; moderate, medium, subangular blocky structure; very firm hardpan at 24- to 26-in. depth, with rest of horizon sticky to plastic; clear boundary.
C_{1g}	32-40	Sandy clay loam; grayish brown to dark yellowish brown (10 YR 5/2-4/4 moist) to dark brown (7.5 YR 4/4 moist) mottled horizon; nonsticky to very slightly plastic; gradual boundary.

(Continued)

Horizon	Depth, in.	Description
C_{2g}	40-60+	Loam; dark yellowish brown (10 YR 4/4 moist), with common, coarse, prominent, light brownish gray (10 YR 6/2 moist) and many, coarse, distinct, strong brown (7.5 YR 5/6 moist) mottles; slightly sticky to plastic, slightly effervescent.

The majority of the area is Conover loam (soil area A, Figure 9). It is interesting to observe that more xeric species, such as shagbark hickory and white oak, occur in common with "wet site" species like American elm and ash.

Climate

The climate of Kent and Clinton Counties varies in a few respects (Table 4). Most important Kent County has a growing season averaging

Table 4. Summary of climatological data

	Kent County		Clinton County	
Plots				
Station of record	Greenville*		East Lansing**	
Distance and direction from plots	12.6 - ENE		7.5 - South	
Years of record	22		22	
Temperature factors		1959-60		1959-60
January mean temperature (°F)	22.2	25.7	25.5	26.0
June mean temperature (°F)	66.4		69.3	
Maximum temperature (°F)	104.0		99.0	
Minimum temperature (°F)	-25.0	-2.0	-9.0	-5.0
Last spring frost	26 May	28 Apr	16 May	8 May
First fall frost	27 Sept	28 Oct	16 Sept	16 Sept
Mean growing season (days)	148		157	
Precipitation factors				
Mean annual precipitation (inches)	30.5		29.9	
Mean snowfall (inches)	43.2		39.9	

* In Montcalm County, 11 miles east of the Kent County plots.
** Moved from Lansing (Capitol City Airport) June 1954, and back in May 1959. Airport is 5 miles southwest of the Clinton County plots.

9 days longer than in Clinton County, with attendant later last spring frost dates and earlier first fall frost dates. Further, the average snowfall is 3.3 in. more in the Kent County area.

In 1960 the mean January temperature was 25.6 and 26.0 F in Kent and Clinton Counties, 3.5 and 0.5 F higher than their respective averages.

An interesting feature was that the first and last frosts occurred almost a month earlier and a month later than normal in Kent County, while the last frost was the same date as the average in Clinton County, and the first frost 8 days earlier.

EXPERIMENTAL PROCEDURE

Design of Sampling Plots

An important consideration in designing plots was the need to avoid trampling the snow on areas prior to sampling. Various authors had warned that compaction of snow cover might affect depth of freezing of soil buried beneath it or near it. Plots 10 ft square were selected as large enough to provide space for maneuvering within the sample square, yet small enough to permit layout of many squares in a reasonably sized sample plot.

Each of the six sample plots was designed to contain 256 10- by 10-ft squares (arranged in a 160- by 160-ft plot), divided into 4 quadrants of 64 plots each. Figure 10 is a diagram of a sample plot.

Installation of Plots

One corner of the plot was established and boundaries were run in cardinal directions using a hand compass and tape. Stakes were placed 10 ft apart along opposite sides of the plots to guide sampling. One stack of thermocouple units and two stacks of plaster-of-Paris resistance blocks were placed at points on the plot boundary, Figure 10.

Resistance blocks were installed in a 1-ft-diameter hole about 18 in. deep. At the designated depths a jackknife was used to cut a rectangular hole just large enough to insert the resistance block with some pressure. Extra space around the block was packed with soil from the same depth.

The resistance blocks were offset 90 degrees from one block to the

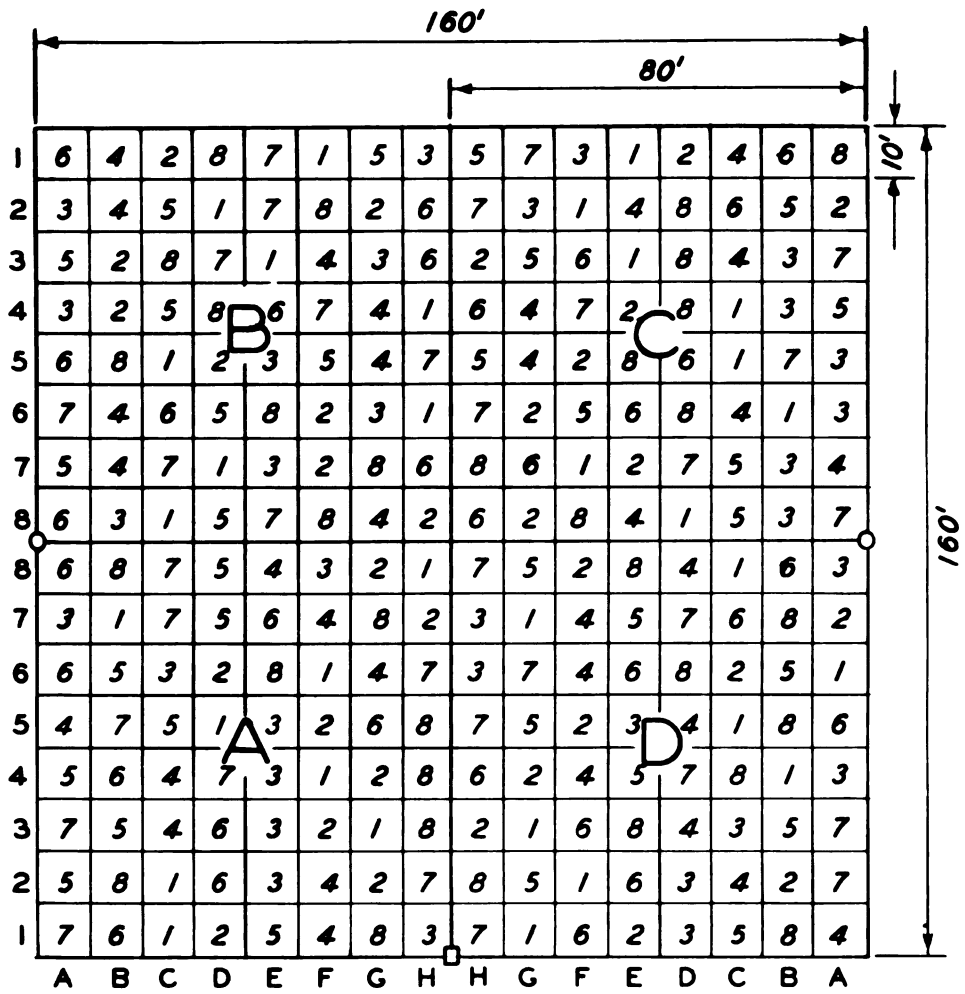

Figure 10. Plot diagram and sampling sequence for all plots

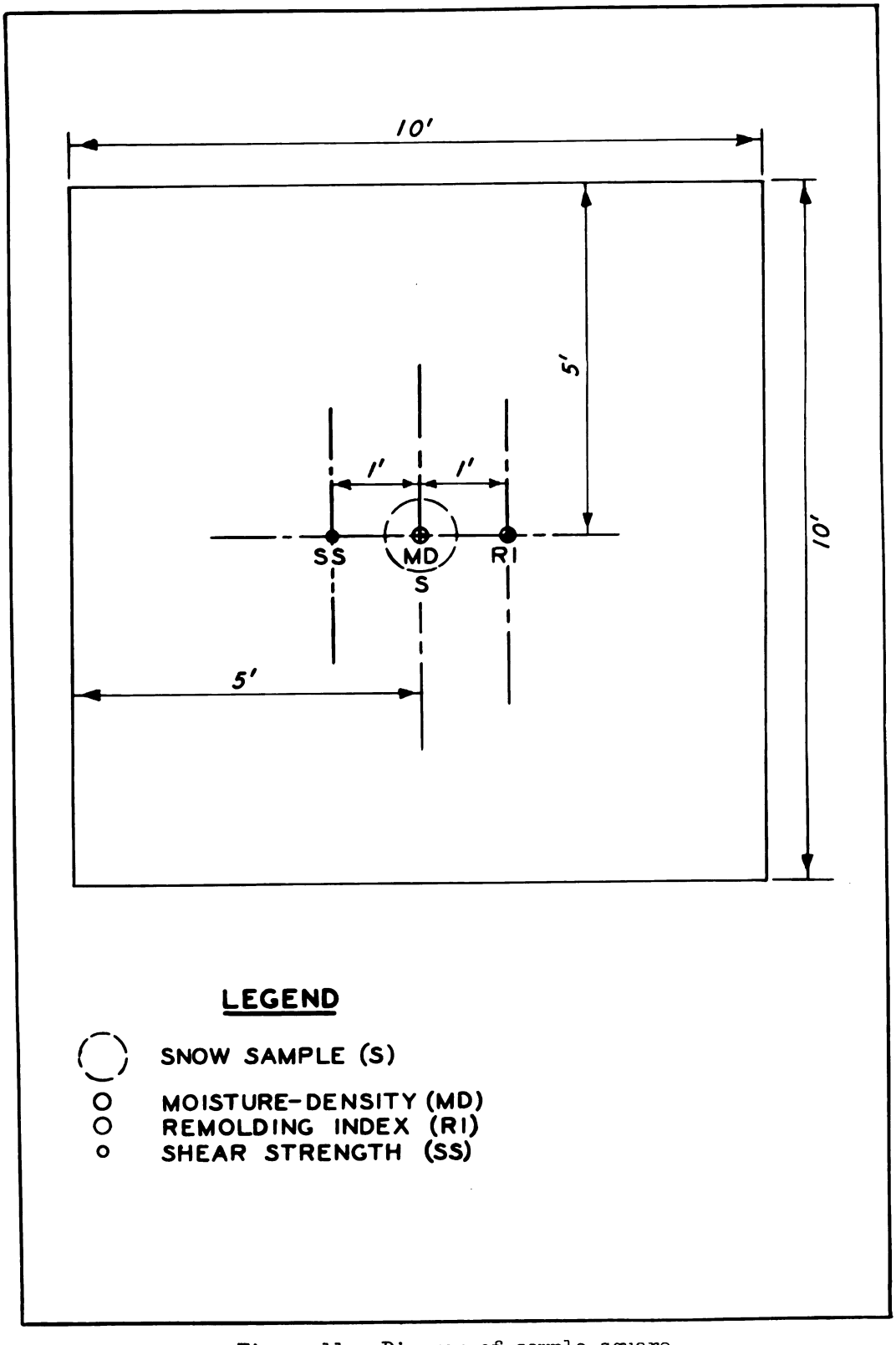

Figure 11. Diagram of sample square

block above it. The block was installed in its hole, the wire led across the pit, the soil was packed into the level at which the next block was to be installed.

The mechanics of thermocouple installation were similar. A pit for the thermocouples was dug about 2 ft deep; a post hole auger (5-in. diameter) was used to extend the hole to 48 in.

Thermocouples were installed in the hole by bending the end of the wire 90 degrees to the lead-in wire, and lowering this portion to the proper depth. Between depths the soil was tamped by a 2-in. by 2-in. by 2-in. stake, or a round (4-in. diameter) iron tamp, to the level of the next depth. In the pit, the end of the wire was pushed about 3 in. into the side.

Sampling Procedures

Modified Scheme of Randomization

The requirement to eliminate trampling on unsampled squares precluded complete randomization of sampling. Instead, a modified scheme of sampling was used to insure that trampling would occur only on plots already sampled. The scheme provided that an outermost row be sampled before the next inner row was begun. Details of the procedure are discussed in the next section.

Selecting Sample Squares

Each sampling quadrant contained eight columns of sample squares labeled A through H, and eight rows numbered 1 through 8 (Figure 10). The nine squares within each row were assigned random numbers. Each of the 256 squares could be identified by a combination of letters and a number to indicate quadrant, row, and column, in that order. For

example, the four squares occupying the four corners of the sample plot are designated as A1A, B1A, C1A, and D1A.

A sample schedule was prepared in advance. The numbers 1 to 8 were drawn at random for each square of each quadrant, and assigned to the columns in the order they were drawn. Thus, on the first drawing the numbers 7, 6, 1, 2, 5, 4, 8, and 3 were drawn in that order, and assigned to sample squares A1A, A1B, A1C, A1D, A1E, A1F, A1G, and A1H, respectively. The numbers 6, 4, 2, 8, 7, 1, 5, and 3 were drawn for the respective columns in row 1, quadrant B.

On the first sampling day the squares used were A1C, B1F, C1E, and D1G. On the eighth sampling day the squares were A1G, B1D, C1A, and D1B. On the ninth sampling day the sample squares were A2C, B2G, C2A, and D2E.

For a given visit, the same designated squares were sampled in all three plots first in one county, then in the other.

Adequacy of Number of Samples

Four squares, one from each quadrant, comprised a sample. This number was chosen for two reasons. At least four observations per sample are necessary to permit a "t" test sensitive enough to detect differences between means in the parameters estimated. Four plots per sampling were all that could reasonably be scheduled for a two-man crew. Each days sampling normally required 48 soil temperature readings, 36 resistance readings, 12 snow samples, 60 moisture-density samples, 12 series of shear strength readings, plus travel time.

Collection of Data

Properties may be grouped under the general headings of

vegetation, weather, static soil properties, and dynamic soil properties.

Vegetation

Herbaceous plots. Vegetation was enumerated by species, and the relative proportion of each species over the plot was estimated.

Hardwood plots. Basal area of trees 2 in. in diameter or over was measured and totaled as an estimate of the cover. Herbaceous vegetation was listed.

Weather Factors

Precipitation and air temperature. Precipitation was measured with a recording rain gage on the Kent County Herbaceous plot. Standard rain gages were used on the other plots. Records from the weather station nearest each set of plots were used for air temperature data.

Snow mantle. Snow was measured both for its effect as an insulator, and as a potential source of soil moisture. Four snow samples were taken on each sample day (one in each sample square). Snow depth, density, and water equivalent were determined from these samples. Each 4-in.-diameter core was taken in the center of a sample square, directly over the position for the moisture-density core (Figure 11).

Static Soil Properties[6/]

Static soil properties are those which would not be expected to change over a short period. They include soil texture, organic matter content, specific gravity, and Atterberg limits.

Texture. After the last freeze of 1960, bulk samples were taken

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6/ Soil texture, specific gravity, Atterberg limits, and organic matter (loss-on-ignition) were determined by procedures described in Soil Laboratory Manual, Lower Mississippi Valley Division, U. S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

on three occasions. The three random samples from each depth of each quadrant were composited. Mechanical analyses were run on the composite samples by quadrant and depth.

Organic matter. Organic matter was determined by the "loss-on-ignition" method (Wilde and Voight, 1955). A composite sample of the plot for each depth was used.

Specific gravity. To help characterize the soil on each plot, and to provide a basis for total pore space determinations, specific gravity determinations were made for each depth on a composite of the spring samples.

Dynamic Soil Properties

Dynamic soil properties are those that would be expected to change from day to day such as soil temperature, depth of freezing, bulk density, and soil moisture.

Soil temperature records for Michigan indicated that soil could freeze to a depth of 42 in. (USDA, 1941). In this study, physical observations of soil freezing were made to 15 in. It was hoped that by correlating observed temperatures with observed freezing in the upper 15 in., greater depth of freezing could be estimated through temperature observations alone.

Thermocouples were installed at the specific depths below the soil surface to represent the soil layers designated in the tabulation below.

Layer in.	Depth of Unit in.	Layer in.	Depth of Unit in.	Layer in.	Depth of Unit in.	Layer in.	Depth of Unit in.
0	0	9-12	10.5	21-24	22.5	33-36	34.5
0-3	1.5	12-15	13.5	24-27	25.5	36-39	37.5
3-6	4.5	15-18	16.5	27-30	28.5	39-42	40.5
6-9	7.5	18-21	19.5	30-33	31.5	42-48	45.0

Frost depth. Frozen depths were determined from moisture-density cores.

It was found that the difference between a frozen and unfrozen portion of a core could readily be determined using the point of a jackknife. The frozen portion of a core was always extremely hard, and the unfrozen portion soft.

Bouyoucos resistance blocks were placed at 1.5, 4.5, 7.5, 10.5, 13.5, and 16.5 in. below the soil surface to indicate the successive 3-in. intervals to 18 in. A meter reading of 10% or less of available moisture was a strong indication that the soil around the block was frozen.

Soil moisture and bulk density. The Hvorslev sampler[7] and a mechanical boring tool were used to take moisture-density cores. The Hvorslev sampler, used when the soil was frozen less than 2 in. from the surface, took cores up to 6 in. long. With mechanical boring tool frozen cores to 18 in. long could be obtained. In either case, the cores were cut into 3-in. lengths. Both samplers used a stainless steel sample tube with an inside diameter of 1.87 in.

A moisture-density core was taken in the center of the sample square (Figure 11).

The soil cores were extruded, by the piston from the Hvorslev sampler, and by a wooden block fitted into the tube from the mechanical sampler, into a special cutting box 18 in. long (Figure 12). The cores were then cut into 3-in. lengths with a thin butcher knife, or a

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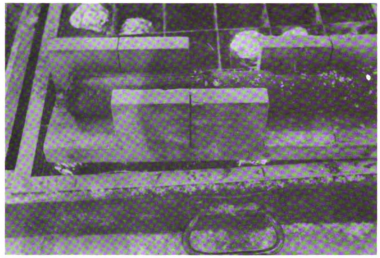
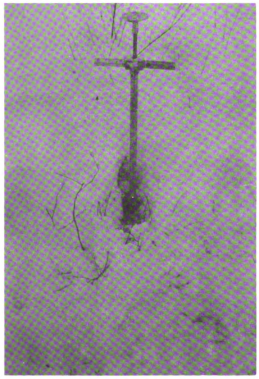
7/ For complete details on construction and use of the Hvorslev sampler see Waterways Experiment Station (1948).



Frozen core in cutting box. Box divided into 3-in. sections on each side to permit cutting to even lengths



Hvorslev sampler in ground under 10 in. of snow, Kent County Herbaceous plot

Figure 12. Core cutting board and Hvorslev soil sampler

piano-wire cutter, or, in the case of frozen cores, a hack saw.

When the line of separation between the frozen and unfrozen portion of the core did not fall at a 3-in. division line, the 3-in. core was divided into frozen and unfrozen portions. Each portion was measured and moisture and density determined separately. Frozen portions less than 1/8 in. long were noted as frozen, but were not separated from the unfrozen portion of the sample.

The soil tube on the mechanical sampler (Figure 13) was connected to a flexible drive shaft. The shaft in turn was driven by a 2-1/2-hp, 2-cycle gasoline engine. The soil tube turned at approximately 300 rpm when not under load. When the tube was inserted into the soil the turning rate varied from a dead stop to a maximum of 300 rpm.

Frequently a good sample could not be obtained with the first boring with the mechanical sampler. However, cores were extracted until a 15-in. core was obtained. The three major causes for difficulty are listed in order of frequency of occurrence: (1) stones in the profile, (2) excessive melting of the frozen core during drilling, (3) breaking of the core in the sample tube.

60-cm tension values. Samples for tension values were taken on one occasion before freezing. Tension cores were taken in lieu of the moisture-density core for that day.

Shearing strength. Measurements were made at frequent intervals even while the soil was frozen whenever, with reasonable effort, the instruments could be inserted into the ground. Measurements were made at 3-in. intervals from the surface to 18 in.

Taking frozen core under 3 in. of snow on Clinton County Bare plot. One man holds sled to prevent jumping while engine is running

Machine at rest. Note flexible drive shaft leading to sample shaft housing. Reduction gear connects flexible shaft to sample shaft. Mercury clutch connects flexible shaft to engine

Taking frozen core under 14 in. of snow, Clinton County Herbaceous plot

Figure 13. Mechanical sampler

Shear strength readings were taken 1 ft to the left of the moisture-density core. A 12-in. core was removed 1 ft to the right of the moisture-density sample for a special remold test (Figure 11).

Static Soil Properties

Detailed knowledge of static soil properties is essential to intelligent interpretation of the phenomena associated with moisture, bulk density, and shear strength. These properties are described here for each plot.

Soil Texture

Moisture-density sampling revealed considerable variation in texture over each plot. To obtain an accurate estimate of soil properties composite samples were obtained in the spring for each quadrant of each plot. Each depth was represented by a sample composited from three points in the quadrant; 12 samples to a depth. Soil texture classes are shown in Table 5.

Table 5. Soil texture classes of each plot

Depth	Kent County					Clinton County				
	Plot	Quadrant				Plot	Quadrant			
in.	Avg	A	B	C	D	Avg	A	B	C	D
					Bare					
0-3	SL	SL	SL	SL	SL	L	L	SL	L	SiL
3-6	SL	SL	SL	SL	SL	SL	L	SL	SL	SL
6-9	SL	SL	SL	SL	SL	L	L	L	SL	L
9-12	SL	SCL	SL	SL	SL	L	L	L	L	L
12-15	SL	SCL	SL	SL	SL	L	L	L	L	L
					Herbaceous					
0-3	SL	SL	SL	SL	SL	SL	L	L	SL	SL
3-6	SL	SL	SL	SL	SL	L	L	L	SL	L
6-9	SL	L	SL	SL	SL	L	L	L	L	SL
9-12	SL	L	SL	SL	SL	L	L	L	SL	L
12-15	SL	L	SL	L	SL	L	L	L	L	L

Note: SL - sandy loam; L - loam; SiL - silt loam; SCL - sandy clay loam; CL - clay loam.

(Continued)

Table 5. (Concluded)

Depth in.	Kent County Plot Avg	Kent County Quadrant A	Kent County Quadrant B	Kent County Quadrant C	Kent County Quadrant D	Clinton County Plot Avg	Clinton County Quadrant A	Clinton County Quadrant B	Clinton County Quadrant C	Clinton County Quadrant D
				Hardwood						
0-3	SL	SL	SL	SL	SL	L	SL	L	SiL	SiL
3-6	L	SL	L	L	L	L	L	L	SiL	SiL
6-9	SL	SL	SL	L	L	L	L	L	SiL	CL
9-12	SL	SL	SL	SL	SL	L	L	L	CL	CL
12-15	SL	SL	SL	SL	SL	L	L	L	CL	CL

Kent County plots. These plots were all sandy loams with the exception of the 3- to 6-in. depth of the hardwood plot. This depth was classified as loam.

Clinton County plots. Except for 3- to 6-in. depth in the bare plot and the 3- to 6-in. depth in the herbaceous plot, the soils in Clinton County were classified as loams.

Organic Matter

As the modified potassium dichromate method may give low values with high organic matter contents (Wilde and Voigt, 1955), this method was not used in the upper two depths of the hardwood plots. The loss-on-ignition method was used. Thus the surface to 3- and 3- to 6-in. depths in the wooded plots could not legitimately be compared with other depths.

The surface 3 in. of both hardwood plots proved to contain over 8% organic matter by weight (Table 6). The surface to 3-in. depth of the Kent County Bare plot had 2.87%, probably as a result of the manure applied the previous winter. The other surface to 3-in. layers fell between 1 and 2% organic matter content.

Table 6. Organic matter contents by modified potassium dichromate method (loss-on-ignition method used in top two depths of hardwood plots)

Depth, in.	Kent County	Clinton County
	Bare	
0-3	2.87	1.88
3-6	2.23	1.93
6-9	0.91	0.62
9-12	0.55	0.51
12-15	0.51	0.62
	Herbaceous	
0-3	1.45	1.98
3-6	1.45	1.88
6-9	0.35	0.78
9-12	0.42	0.70
12-15	1.05	0.59
	Hardwood	
0-3	8.26	8.70
3-6	2.35	4.56
6-9	0.70	1.29
9-12	0.59	0.62
12-15	0.42	0.59

The lower three depths were below 1% in all but the Clinton County Hardwood plot, while the 3- to 6-in. depths were above 2% in the Kent County Hardwood and Bare plots, and between 1 and 2% in the other plots.

Specific Gravity

Specific gravity determinations (Table 7) generally fall within

Table 7. Specific gravity

Depth in.	g/cc					
	Kent County			Clinton County		
	Bare	Herbaceous	Hardwood	Bare	Herbaceous	Hardwood
0-3	2.63	2.63	2.55	2.65	2.65	2.57
3-6	2.63	2.65	2.64	2.64	2.65	2.65
6-9	2.65	2.65	2.65	2.66	2.67	2.68
9-12	2.66	2.66	2.66	2.68	2.68	2.69
12-15	2.66	2.67	2.66	2.69	2.70	2.69

the range expected for mineral soils, i.e. 2.6 to 2.7 g/cc (Lutz, 1951). Organic matter was not removed from the soil in the analysis, and is reflected in the relatively low specific gravities of the surface to 3-in. layers of the Kent and Clinton County Hardwood plots, 2.55 and 2.57 g/cc, respectively.

Atterberg Limits

Atterberg limits are shown in Table 8. Sample treatment, soil colloid content, mineral composition of the colloids, and organic matter all affect Atterberg limits (Baver, 1956).

The liquid and plastic limits in the surface to 3-in. depth of the bare plots and the surface to 3- and 3- to 6-in. depth of the hardwood plots were higher in Clinton than in Kent County. This was to be expected from the higher organic matter content of these depths in Clinton County. Other variation in values is not susceptible of simple explanation.

Table 8. Atterberg limits for each plot

County	Depth in.	Per Cent Moisture by Weight: Liquid Limit	Plastic Limit	Plasticity Index
		Bare		
Kent	0-3	23	18	3
	3-6	21	17	4
	6-9	14	14	0
	9-12	14	13	1
	12-15	22	12	10
Clinton	0-3	20	17	3
	3-6	21	17	4
	6-9	21	13	8
	9-12	24	13	11
	12-15	28	14	14
		Herbaceous		
Kent	0-3	18	17	1
	3-6	16	15	1
	6-9	21	13	8
	9-12	18	13	5
	12-15	18	14	4
Clinton	0-3	22	17	5
	3-6	21	17	4
	6-9	20	13	7
	9-12	19	13	6
	12-15	24	13	11
		Hardwood		
Kent	0-3	41	31	10
	3-6	20	18	2
	6-9	18	15	3
	9-12	17	14	3
	12-15	20	14	6
Clinton	0-3	51	36	15
	3-6	40	29	11
	6-9	24	17	7
	9-12	24	15	9
	12-15	26	15	11

Soil Freezing and Thawing

Temperature Conditions Influencing Freezing Opportunity

Air temperature. The daily plot of air temperature for both counties is shown in Figure 14. Temperature changes follow a similar pattern with the high and low extremes usually greatest for Clinton County. Periods above and below 32 F are of about the same duration for each weather station.

Monthly mean air temperatures for the two counties summarize the major differences. Data were taken from Greenville Weather Station, Montcalm County, and Lansing (Capitol City) Airport, Clinton County; stations nearest the Kent and Clinton County plots, respectively.

	1959-60 Monthly Mean Air Temperatures, °F						
	Nov	Dec	Jan	Feb	Mar	Apr	Mean
Kent County	33.8	32.3	25.7	25.5	24.8	49.8	32.0
Clinton County	32.7	32.7	26.0	23.0	22.0	48.7	30.8

On the average the Clinton County area was 1.2 F colder than the Kent County area. In Clinton County February and March were 2.5 and 2.8 degrees colder, respectively, than in Kent County. The majority of soil freezing occurred during these months.

Degree-days. Table 9 lists the periods when air temperatures were below 32 F. The period in one county may have been one to three days longer or shorter than a period in the other, but in every case, one overlapped the other. There were 104 days in which air temperatures were below freezing in Kent County, and 110 days in Clinton County.

Degree-days were calculated using the mean temperature in relation to a base of 32 F. As degree-days are considered here as a measure of the freezing opportunity, those days on which the air temperature

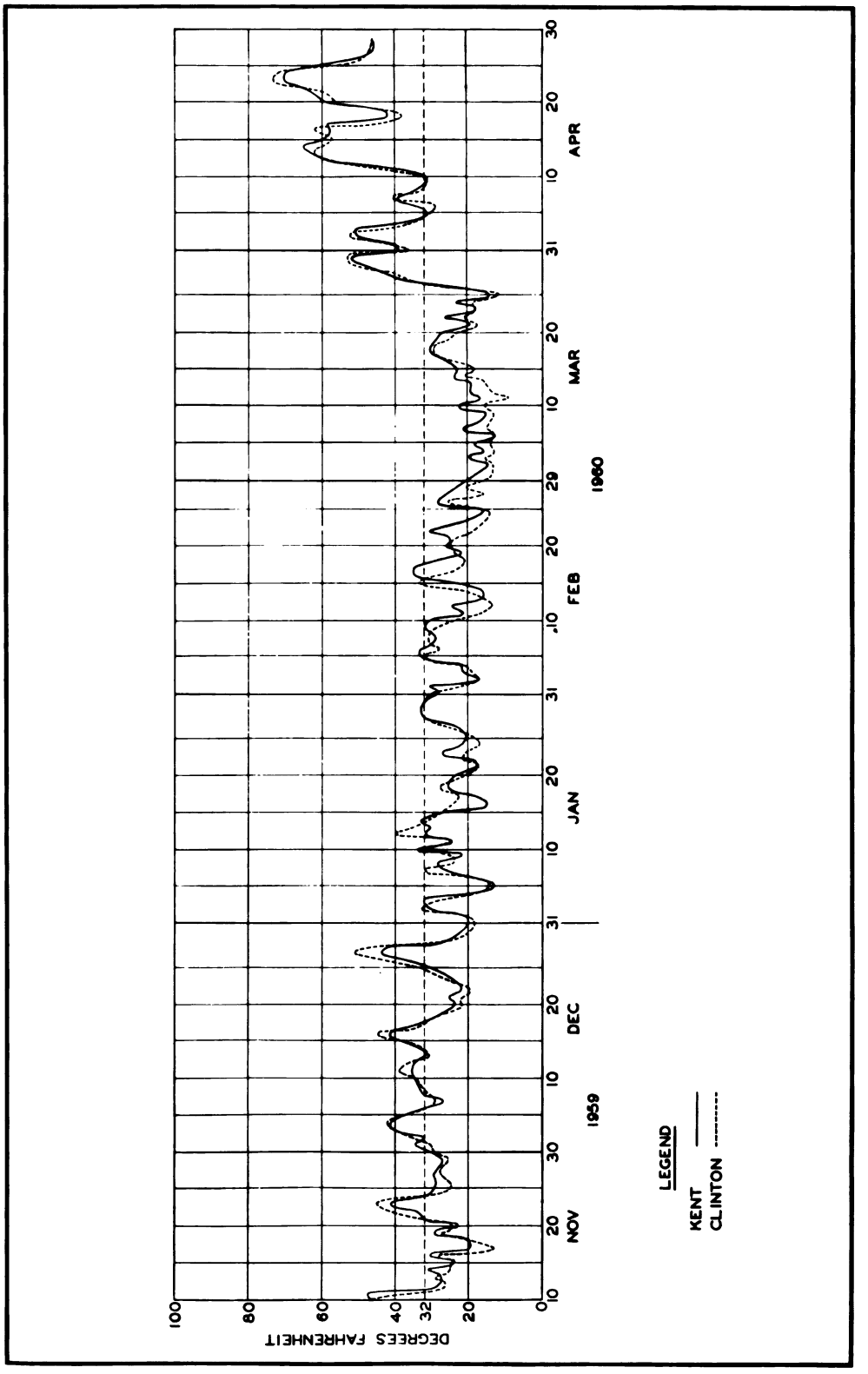


Figure 14. Mean air temperatures, Kent and Clinton Counties

Table 9. Degree-days for each plot grouped by freezing periods*

Period No.	Freezing Period Dates (Inclusive) Kent County First Day	Kent County Last Day	Kent County Total Days	Clinton County First Day	Clinton County Last Day	Clinton County Total Days	Cumulative Degree-days Kent County First Day	Kent County Last Day	Kent County Degree-days for Period	Clinton County First Day	Clinton County Last Day	Clinton County Degree-days for Period
1				6 Nov	7 Nov	2	-73.0	-74.0	-1.0	-63.5	-62.0	+1.5
2	12 Nov	20 Nov	9	12 Nov	21 Nov	10	-112.0	-58.5	+53.5	-93.0	-27.0	+66.0
3	25 Nov	30 Nov	6	25 Nov	30 Nov	6	-74.0	-55.0	+19.0	-53.0	-25.0	+28.0
4	6 Dec	7 Dec	2	6 Dec	7 Dec	2	-83.5	-78.5	+5.0	-56.5	-53.0	+3.5
5	13 Dec	13 Dec	1	13 Dec	14 Dec	2	-92.0	-92.0	0.0	-71.0	-70.0	+1.0
6	18 Dec	26 Dec	9	18 Dec	24 Dec	7	-114.5	-66.0	+48.5	-91.5	-42.0	+49.5
7	29 Dec	2 Jan	5	29 Dec	1 Jan	4	-87.0	-47.5	+39.5	-80.5	-34.0	+46.5
8	4 Jan	9 Jan	6	3 Jan	11 Jan	9	-48.0	+16.0	+64.0	-35.0	+32.0	+67.0
9	11 Jan	12 Jan	2				+14.0	+21.5	+7.5			
10	15 Jan	27 Jan	13				+17.0	+131.5	+114.5			
11	31 Jan	4 Feb	5	15 Jan	4 Feb	21	+129.5	+170.5	+41.0	+25.5	+179.0	+153.5
12	7 Feb	15 Feb	9	6 Feb	15 Feb	10	+168.5	+234.0	+65.5	+174.5	+252.5	+78.0
13	18 Feb	26 Mar	39	17 Feb	26 Mar	40	+229.0	-605.5	+376.5	+251.0	+760.0	+509.0
14	5 Apr	5 Apr	1	5 Apr	6 Apr	2	+494.5	+495.0	+0.5	+672.0	+676.5	+4.5
15	8 Apr	10 Apr	3	9 Apr	9 Apr	1	+485.5	+487.0	+1.5	+678.5	+678.5	0.0
		Total	104		Total	110		Total	+847.0		Total	+944.0
								Avg	+8.4		Avg	8.9

* Based on °F below 32 F, beginning with 1 Nov 59.

averaged over 32 F were given negative values, and those with an average below 32 F, plus values. Thus, a day with a mean temperature of 40 F would have a degree-day value of -8, and a day with a mean of 24 F would have a value of +8.

Comparison of periods of equal duration revealed that the Clinton County plots had slightly higher freezing opportunity than Kent County. Only during the period from February 17 to March 26 was opportunity appreciably different (Period number 13, Table 9). Clinton County had a total of 509 degree-days, and Kent County, 376.5.

Average degree-day values were 8.4 and 8.9 for Kent and Clinton Counties, respectively.

Soil temperature. Thermocouples were installed to indicate soil temperature and suggest when the soil should be sampled. Since frozen cores could not be taken in the immediate neighborhood of the thermocouples, the supposed utility of temperature readings to indicate soil condition (i.e. frozen or unfrozen) soon proved to be invalid.[8/]

However, comparison of frost and soil temperature data suggests several relationships (Table 10).

The highest recorded soil temperatures when the soil was frozen were 40.0 and 45.4 F in the surface (0 to 3-in.) layers of the Kent County Bare and Clinton County Hardwood plots (Table 10). Other maximum readings were below 37.7 F (3- to 6-in. reading in the Kent County Bare plot). Thus, though frozen ground is found on a given plot, temperatures well above freezing can be found elsewhere in the same plot.

8/ Soil temperature data is on file (VB 34.2) with the Trafficability Section of the Army Mobility Research Center, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Table 10. Minimum and maximum temperatures in frozen soil; number of frozen cores; and minimum temperature of unfrozen soil, deg F

Reading	Depth, in. 0 to 3	3 to 6	6 to 9	9 to 12	12 to 15
		Kent Bare			
Maximum	45.0 (1)*	37.7 (2)			
Minimum	22.1 (3)	30.1 (1)			
Minimum unfrozen	37.3	25.9			
		Kent Herbaceous			
Maximum	37.0 (4)	36.5 (1)			
Minimum	29.0 (4)	32.0 (2)			
Minimum unfrozen	31.2	29.2			
		Kent Hardwood			
Maximum	34.0 (1)				
Minimum	29.6 (1)				
Minimum unfrozen	29.3				
		Clinton Bare			
Maximum	33.9 (4)	33.6 (4)	34.8 (4)	35.2 (1)	34.4 (1)
Minimum	19.3 (4)	22.4 (4)	20.7 (4)	27.7 (4)	29.3 (3)
Minimum unfrozen	32.3	28.8	28.0	21.6	22.2
		Clinton Herbaceous			
Maximum	33.9 (4)	36.0 (1)	33.2 (1)		
Minimum	22.3 (4)	23.4 (2)	23.1 (2)		
Minimum unfrozen	28.5	24.1	26.6		
		Clinton Hardwood			
Maximum	45.4 (2)				
Minimum	28.8 (2)				
Minimum unfrozen	22.5				

* Numbers in parentheses are numbers of frozen cores in four soil samples. Depths are shown only if some freezing was noted.

In each county, the lowest temperatures when the soil was frozen were in the bare plots, the next lowest in the herbaceous, and the highest in the woods.

For plots with the same cover, depth by depth, the lower temperatures occurred in Clinton County. These plots had appreciably less snow cover than those in Kent County.

The surface layer on each plot had the lowest minimum temperature, reflecting the fact that this layer is more subject to daily temperature drops. Deeper layers would reflect the daily temperature fluctuation to a lesser degree. This agrees with the findings of Serova (1958).

Minimum temperatures occurring when the soil was not frozen are also revealing. In every case, other than the surface to 3-in. layers in the bare and herbaceous plots, the temperatures range from 2.8 to 10.4 degrees lower than 32 F, ample, it would seem, for soil freezing. Again this indicates that soil temperature at one point on a plot does not necessarily reflect the temperature elsewhere on a plot, nor can it take into account the solute concentration of the soil solution or the moisture tension levels prevailing elsewhere.

Soil Regime (Frozen and Thawed)

The first sampling of all three plots was made December 2 in Kent County, and December 9 in Clinton County.

Kent County Bare plot (Table 11). Frozen ground was first found on this plot December 10. There was frozen ground thereafter to March 30 (Figure 15), though there were as many as five days in a row when freezing air temperatures did not occur (e.g. December 13 to 18, Figure 14). Heat increments during these periods were not enough to remove all frost from the ground.

Table 11. Mean frost depths, Kent and Clinton Counties

Kent County				Clinton County			
	Frost Depth, in.				Frost Depth, in.		
Date	Bare	Herbaceous	Hardwood	Date	Bare	Herbaceous	Hardwood
1959				1959			
12 Nov	0.00	No data		10 Nov	0.00	No data	
17 Nov	0.00	No data		11 Nov	No data	0.00	No data
27 Nov	No data	0.00	No data	19 Nov	No data		1.82
30 Nov	No data		0.00	25 Nov	0.00	No data	
2 Dec	0.00	0.00	0.00	9 Dec	0.00	0.00	0.00
4 Dec	0.00	0.00	0.00	14 Dec	1.55	0.00	0.00
10 Dec	1.17	0.00	0.00	18 Dec	0.72	0.00	0.00
16 Dec	0.24	0.00	0.00	23 Dec	9.00*	1.54	0.64
21 Dec	2.18	1.56	0.60	28 Dec	0.00	0.00	0.00
30 Dec	0.60	0.00	0.00	31 Dec	0.24	0.00	0.00
1960				1960			
2 Jan	0.81	0.30	0.00	5 Jan	4.37	1.31	0.36
7 Jan	1.20	1.32	0.00	9 Jan	8.42	4.12	0.60
11 Jan	1.62	2.34	0.36	16 Jan	4.04	1.11	0.00
14 Jan	1.80	1.98	0.00	20 Jan	8.32	3.54	0.00
19 Jan	2.04	No data		23 Jan	6.85	2.84	0.00
21 Jan	0.36	0.57	0.00	28 Jan	7.95	3.02	0.00
26 Jan	0.93	0.72	0.00	2 Feb	8.40	4.38	0.00
30 Jan	1.23	0.61	0.00	4 Feb	9.12	2.25	0.00
3 Feb	0.30	0.24	0.00	9 Feb	9.24	2.40	0.00
6 Feb	1.12	0.00	0.00	13 Feb	10.92	1.71	0.00
12 Feb	0.99	0.12	0.00	17 Feb	8.71	2.04	0.00
16 Feb	1.32	0.48	0.12	24 Feb	11.04	3.00	0.48
20 Feb	0.93	1.41	0.00	1 Mar	10.50	3.00	0.48
25 Feb	0.39	1.17	0.80	8 Mar	15.00+	4.17	No data
5 Mar	0.54	1.32	0.00	11 Mar	12.50	4.05	1.47
10 Mar	1.17	1.50	0.84	15 Mar	10.18	5.49	0.17
14 Mar	3.00	1.56	0.84	21 Mar	15.00+	2.69	0.24
17 Mar	1.51	2.11	0.00	25 Mar	10.20	3.90	0.72
23 Mar	2.19	1.96	0.36	29 Mar	5.76	3.03	0.00
28 Mar	0.24	3.12	0.60	31 Mar	5.40	3.24	0.00
30 Mar	0.72	2.21	0.72	3 Apr	4.08	0.00	0.00
1 Apr	0.00	0.00	0.00	6 Apr	1.92	0.00	0.00
				9 Apr	1.32	0.00	0.00

* Only two cores taken.

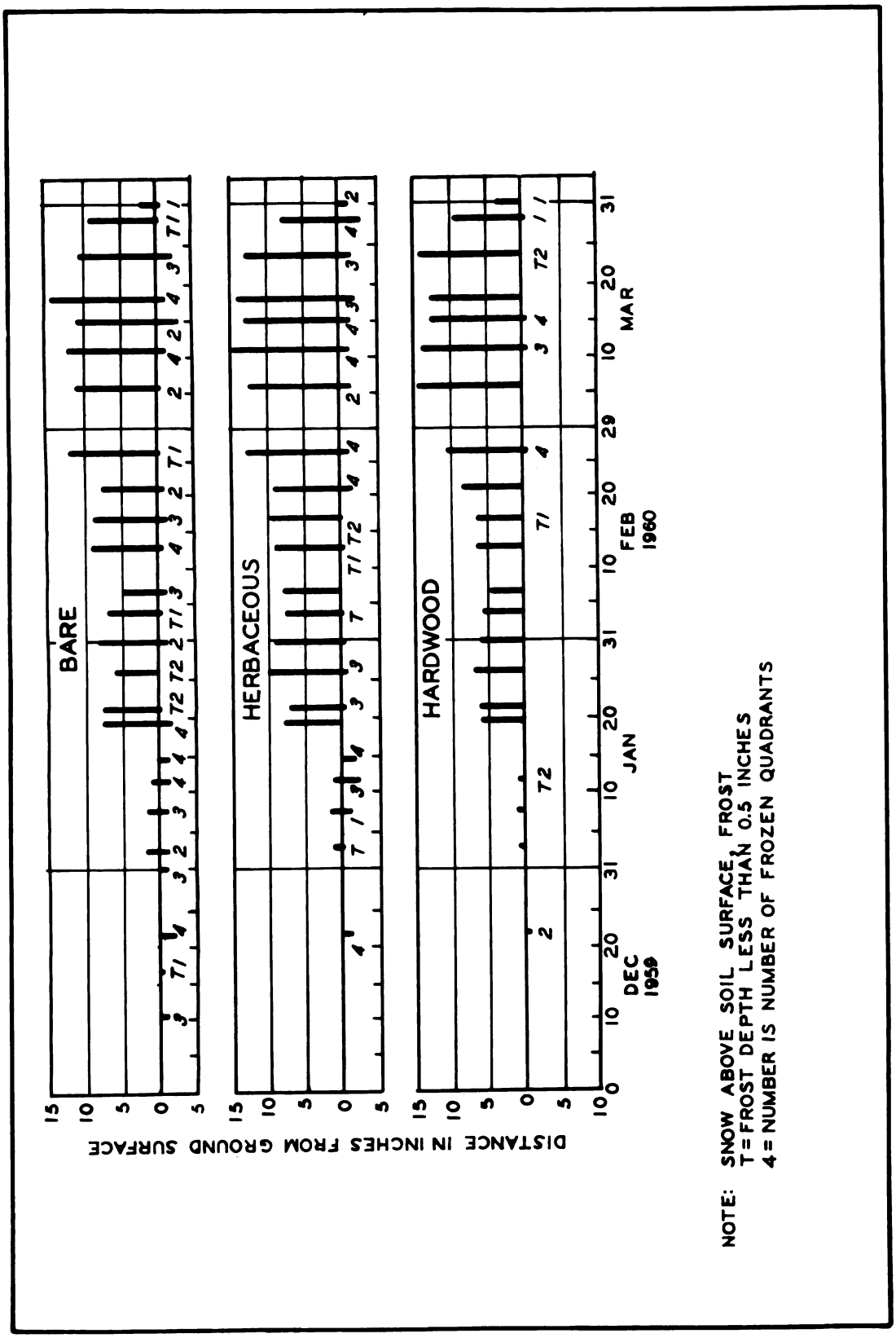


Figure 15. Mean snow and frost depths, Kent County

Kent County Herbaceous plot. December 21 was the first day when frozen ground was found. On the December 30 and February 6 samplings, the ground was thawed. Both dates occurred during periods when air temperature was well above freezing, Figure 14. Frozen ground was observed thereafter to March 30.

Kent County Hardwood plot. December 21 also marked the first day of frozen ground on this plot. Frozen ground was found once in December and January, twice in February, and five times in March, a total of nine frozen dates in comparison to the 25 dates when frozen soil was observed in the Kent County Bare plot. On each of the first seven times when frozen ground was found in this plot, three or more days of continuous freezing had preceded the sample date. Frozen ground was also found on the 28th and 30th of March, following a prolonged (39-day) freezing period, coupled with rapid snow disappearance (Tables 11 and 14).

Clinton County Bare plot. Frozen ground was not encountered until the 14th of December (Table 11). Subsequently, frozen ground was encountered at every sampling until the 9th of April with one exception. On December 28, the third day of a thawing period, air temperatures were 40 F and above, and rain had removed the frost.

Clinton County Herbaceous plot. Frozen ground was first observed on the 23d of December. The next two sample dates, December 28 and 31, revealed no frozen ground, but from then to the 30th of March, frozen soil was observed on every occasion. Frost disappeared 15 days before frost in the bare plot.

Clinton County Hardwood plot. Frozen ground was first observed on the 19th of November. No other plots were sampled on this date (Table 11). Frozen ground was observed after this date once in December, twice

in January and February, and four times in March. A period of five or more freezing days preceded each of these dates. Frozen soil was observed on every sample date from February 17 to March 28.

Frequency and Occurrence of Frozen Ground

Comparisons were made for the number of sample dates when frost was found (occurrence), and for the number of frozen cores observed of the four taken on each plot per sample date (frequency). Comparisons are based on the period from the first to the last time frozen ground was found in the bare plot in each county, Tables 12 and 13.

Table 12. Frost occurrence and frequency*

County	Visits			Frozen Cores			
	Total	No. with Frost	% with Frost	Total	Avg No. per Visit	Avg per Visit with Frost	% of Total Taken
			Bare				
Kent	28	25	89.3	66	2.3	2.6	58.0
Clinton	28	26	92.8	89	3.2	3.4	79.5
			Herbaceous				
Kent	27	20	74.1	59	2.2	2.9	54.5
Clinton	28	20	71.4	72	2.6	3.6	64.3
			Hardwood				
Kent	27	9	33.3	21	0.8	2.1	19.4
Clinton	28	10	35.7	21	0.7	2.1	18.7

* Between dates of first and last occurrence of frost on bare plot in each county.

Table 13. Per cent of time when 0, 1, 2, 3, and 4 cores were frozen* (based on all samples)

County	Frozen Cores per Plot, %				
	0	1	2	3	4
		Bare			
Kent	10.7	17.9	25.0	21.4	25.0
Clinton	3.6	7.1	7.1	10.7	71.4
		Herbaceous			
Kent	25.9	7.4	18.5	18.5	29.6
Clinton	28.5	3.6	3.6	10.7	53.6
		Hardwood			
Kent	63.0	14.8	11.1	3.7	7.4
Clinton	64.3	10.7	14.3	7.1	3.6

* Between dates of first and last occurrence of frost on bare plot in each county.

Twenty-eight visits were made to all Clinton County plots and to the Kent County Bare plot; the other two plots were visited 27 times. Frost occurrence by cover type was similar in each county, about 90, 72, and 34% for the bare, herbaceous, and hardwood plots, respectively (Table 12).

More frozen cores were found on the bare than herbaceous, and the herbaceous than hardwood plot in each county. In the bare and herbaceous plots the percentage of the total cores frozen was higher for the Clinton than for the Kent County plots. The hardwood plots were about equal (Table 12).

On only one visit to a plot the number of frozen cores could vary from zero to four. In Clinton County four frozen cores were obtained from the bare plot 71.4% of the time, from the herbaceous plot 53.6% of

the time, and from the hardwood plot 3.6% (Table 13). Corresponding values in Kent County were 25.0, 29.6, and 7.4%, respectively. The inference here is that meltwater from the snow pack could infiltrate the soil most of the time on all the Kent County plots, but less frequently in Clinton County. On the hardwood plots fewer than four frozen cores occurred on 92.6 and 96.4% of the sample dates in Kent and Clinton Counties, respectively. Thus, in the woods infiltration could take place most of the time.

Frost Depth Comparisons

The tabulation below shows mean frost depth for each plot, for visits when frost was present.

	Mean Frost Depth in Inches		
	Bare	Herbaceous	Hardwood
Kent County	1.20	1.32	0.60
Clinton County	6.36	2.88	0.48

Freezing in Clinton County was five times deeper in the bare plot, over twice as deep in the herbaceous plot, and about the same in the hardwood plot as in the Kent County counterparts. Greater snow depths in Kent County may account for these differences (page 87). Bare and herbaceous plots in Kent County had similar frost depths; in Clinton County frost was 2.2 times deeper in the bare than herbaceous plot. Differences in snow depths between Clinton County plots may account for frost depth differences. These differences did not occur in Kent County.

Effects of Vegetation and Snow on Soil Freezing and Thawing

Accumulated snow on the ground is of primary importance to the soil frost regime. Amounts of snowfall are not. Figures 15 and 16

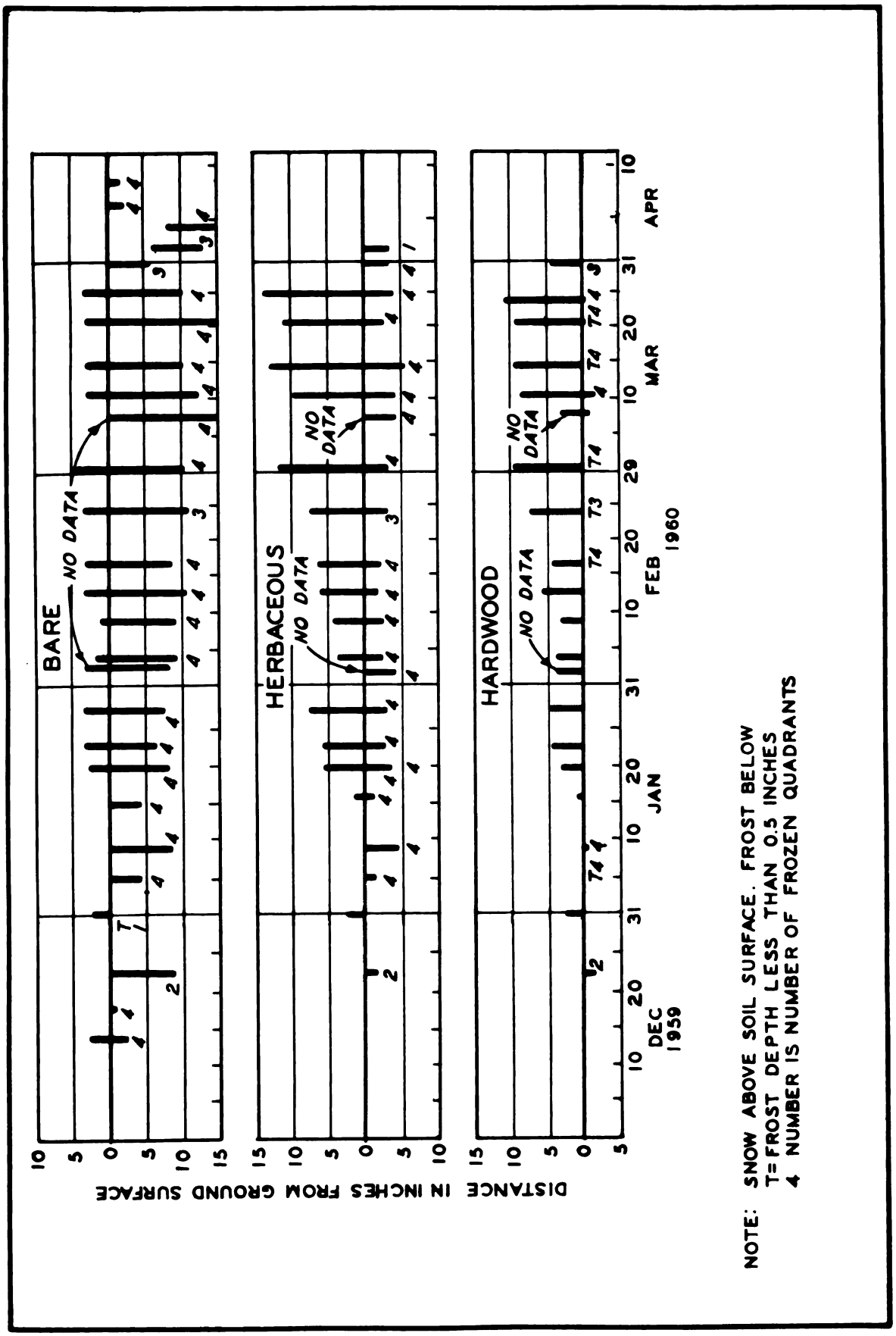


Figure 16. Mean snow and frost depths, Clinton County

illustrate the relationship of snow on the ground to frost. On these plots vegetation directly affected the relative amount of snow present.

In Kent County snow accumulation did not begin until January 18 (Figure 15). The maximum snow accumulated prior to this time was 2.61 in., and on the last sampling day before January 18, all snow had disappeared (Table 14). Mean snow depths per plot are shown below (based on the average snow depths from January 19 to March 30).

Mean Measured Snow Depth in Inches, Kent County

	January	February	March
Bare	7.24	8.03	9.96
Herbaceous	8.51	9.35	10.64
Hardwood	6.24	7.42	11.51

Mean snow depth increased on each plot from January to March. Except for March when snow in the woods was deepest, snow depth decreased from herbaceous to bare and bare to hardwood plots (Table 14).

Snow had disappeared from the bare and wooded plots on March 29, one to two days after it left the herbaceous plot.

In Clinton County snow accumulation began on the 16th of January on the herbaceous and wooded plots, and on the 20th of January for the bare plot, Figure 16, Table 14. Mean monthly snow depths are shown below.

Mean Monthly Snow Depths in Inches, Clinton County

	December	January	February	March
Bare	2.15	2.99	2.53	3.36
Herbaceous	2.61	5.17	5.66	10.22
Hardwood	2.40	3.22	4.92	9.71

Snow accumulation increased from January to March; the herbaceous

Table 14. Mean snow depth, density, and water equivalent

Date	Bare			Herbaceous			Hardwood		
	Depth in.	Density g/cc	Water Equiv in.	Depth in.	Density g/cc	Water Equiv in.	Depth in.	Density g/cc	Water Equiv in.
Kent County									
17 Nov-10 Dec	Intermittent snow < 1/4 in. and/or patches								
16, 21, 30 Dec	No snow on any plot								
2 Jan 60	1.70	0.08	0.13	1.14	0.07	0.08	0.78	0.12	0.09
7 Jan 60	1.47	0.06	0.09	1.59	0.06	0.09	1.21	0.12	0.14
11 Jan 60	0.95			0.91			0.90		
14 Jan 60	No snow			1-2 in. in patches			1-2 in. in patches		
19 Jan 60	7.67	0.07	0.57	7.95	0.05	0.43	6.00	0.06	0.38
21 Jan 60	7.54	0.07	0.54	7.09	0.06	0.41	6.00	0.07	0.41
26 Jan 60	5.80	0.10	0.59	9.94	0.08	0.79	6.94	0.09	0.65
30 Jan 60	7.97	0.13	1.00	9.06	0.09	0.84	6.03	0.12	0.70
3 Feb 60	6.70	0.12	0.83	7.78	0.11	0.84	5.50	0.13	0.70
6 Feb 60	4.67	0.18	0.33	7.92	0.12	0.94	3.70	0.15	0.84
12 Feb 60	8.96	0.17	1.55	9.06	0.15	1.96	7.37	0.14	1.01
16 Feb 60	8.58	0.17	1.44	9.64	0.18	2.04	7.37	0.16	1.20
20 Feb 60	7.44	0.18	1.38	9.26	0.22	1.96	8.22	0.16	1.32
25 Feb 60	11.84	0.18	2.12	12.44	0.16	1.90	10.34	0.15	1.54
5 Mar 60	10.96	0.18	1.88	12.34	0.17	2.08	14.38	0.13	1.91
10 Mar 60	12.12	0.20	2.46	14.34	0.15	1.95	13.89	0.11	1.61
14 Mar 60	10.78	0.17	1.84	12.93	0.17	2.22	12.81	0.12	1.53
17 Mar 60	14.14	0.17	2.32	14.38	0.17	2.46	12.75	0.14	1.76
23 Mar 60	10.72	0.21	2.23	12.87	0.20	2.60	14.12	0.16	2.28
28 Mar 60	9.03	0.24	2.17	7.68	0.22	1.64	9.28	0.19	1.72
30 Mar 60	1.94	0.25	0.54	No snow			3.40	0.14	0.65
Clinton County									
23 Dec 59	< 1/4 in. snow			< 1/4 in. snow			< 1/4 in. snow		
28 Dec 59	Rain			Rain			Rain		
31 Dec 59	2.15	0.06	0.12	2.61	0.03	0.07	2.40	0.03	0.09
5 Jan 60	No snow			1/2 to 3/4 in. snow			Thin snow crust		
9 Jan 60	No snow			No snow			No snow		
16 Jan 60	No snow			1.65	0.03	0.05	0.69	0.06	0.04
20 Jan 60	2.68	0.04	0.18	5.86	0.03	0.20	3.09	0.07	0.23
23 Jan 60	3.23	0.08	0.30	5.61	0.05	0.29	4.40	0.06	0.25
28 Jan 60	3.05	0.02	0.05	7.55	0.01	0.07	4.72	0.09	0.43
4 Feb 60	1.71	0.17	0.29	4.54	0.09	0.42	3.79	0.09	0.37
9 Feb 60	1.20	0.14	0.17	4.12	0.11	0.45	3.06	0.16	0.50
13 Feb 60	3.22	0.21	0.69	6.04	0.10	0.61	5.61	0.14	0.77
17 Feb 60	3.17	0.16	0.51	6.25	0.10	0.62	4.47	0.19	0.85
24 Feb 60	3.37	0.15	0.49	7.33	0.11	0.81	7.69	0.14	1.10
1 Mar 60	4.11	0.15	0.59	11.61	0.09	1.09	9.98	0.11	1.08
11 Mar 60	3.02	0.13	0.44	9.97	0.11	1.14	8.61	0.13	1.14
15 Mar 60	3.33	0.13	0.48	12.93	0.12	1.49	9.43	0.15	0.42
21 Mar 60	3.11	0.11	0.35	11.03	0.15	1.63	9.28	0.16	1.48
24 Mar 60	3.40	0.15	0.54	14.00	0.13	1.85	10.81	0.14	1.52
25 Mar 60	3.18	0.21	0.58	12.12	0.13	1.57	10.15	0.15	1.56
29 Mar 60							4.23	0.18	0.76

plot showed more snow than the woods or bare plot each month. Table 14 reveals that this same relationship held true on a sample to sample basis.

Snow disappeared on the Clinton County Bare and Herbaceous plots between the 25th and 29th of March, and from the Clinton County Hardwood plot between the 29th and 31st.

The month to month relationship of snow depths between the two counties is summarized below. With the exception of December when no snow was measured in Kent County, snow on the ground was generally higher, plot for plot, in Kent than in Clinton County.

Difference in Mean Monthly Snow Depth, Kent County over Clinton County

Plot	December	January	February	March	Mean
Bare	-2.15	4.25	5.50	6.60	3.55
Herbaceous	-2.61	3.34	3.69	0.42	1.21
Hardwood	-2.40	3.02	2.50	1.80	1.23

Daily air temperature and degree-day data revealed that the freezing opportunity was somewhat greater in Clinton than Kent County. In addition, the Kent County plots generally had deeper snow on the ground than the Clinton County plots.

Frost regime before snowfall. From the standpoint of its effect on soil freezing, it is assumed that there was no snow until the samplings of January 19 in Kent County, and January 20 in Clinton County. Cumulative degree-days from November 1 were 51.5 and 52.5 for these areas, respectively--essentially the same. All three plots in the county were sampled on the same day; nine times in Clinton County, and eight times in Kent County. Mean frost depths up to the beginning of continuous snowfall are shown on the next page.

Mean Frost Depth Before Snowfall in Inches			
	Bare	Herbaceous	Hardwood
Kent County	2.98	0.94	0.16
Clinton County	2.62	0.85	0.12

The mean depths do not vary greatly for plots under similar cover. However, in each county the effects of cover are evident; the bare plots had the deepest frost; the herbaceous plots the next deepest; and the hardwood plots the least.

Frost regime under continuous snow cover. Considerable effort was spent in an attempt to develop quantitative relationships between measured factors (snow depth, snow density or water equivalent, air temperature, degree-days) and frost depth. Systems which have been evolved previously require detailed knowledge of many factors such as volumetric heat capacity and latent heat of soil, thermal gradients of frozen and unfrozen soil, etc. (Aldrech and Paynter, 1953, Beskow, 1947).

Any system in which readily measured factors could be used would have great utility. The following independent variables were tested with frost depth:

1. Average degree-day[9/] from Nov 1 + $\frac{\text{average degree-day from Nov 1}}{\text{sample water equivalent}}$.
2. Same as 1. but with average degree-day from first day of frost.
3. Same as 1. but degree-days from first snowfall.
4. Total degree-days since last sample + $\frac{\text{total degree-days since last sample}}{\text{change in water equivalent from last sample}}$.

9/ An average degree-day is the sum or the daily degrees above or below 32 F on a sample date, divided by the total days from Nov 1, or from first day of frost, etc., to the sample date.

5. Average daily change in degree-days from last sample - (average change water equivalent) × (average daily change in degree-days since last sample).

6. $\frac{\text{Average degree-days from first frost}}{\text{Average water equivalent from first frost}}$.

7. (Average degree-day from first snow) × (average water equivalent from first snow).

8. Total degree-days since last sample - (total degree-days since last sample) × $\left(\sqrt{\text{change in water equivalent since last sample}}\right)$.

9. $\frac{\text{30-day accumulated degree-days + 3-day accum. degree-day values}}{\text{30-day accumulated snow depths + 3-day accum. snow depth}}$.

10. $\frac{\text{30-day accumulated degree-days + 4-day accum. degree-day values}}{\text{30-day accumulated snow depths + 3-day accum. snow depth}}$.

11. 4-day accumulated degree-days (including sample day).

12. 8-day accumulated degree-days (including sample day).

The last four independent variables were tested on the basis that there could be a long-term heat effect and a short-term heat effect resulting in the frost depth on any given day.

As can be readily realized, an indeterminable number of long- and short-day combinations could be used. The eight-day accumulated degree-day value proved significant in relation to frost depth for the Clinton County plots. All other combinations could not be related. This variable did not correlate with frost in the Kent County plots, primarily because of the greater amounts of snow on these plots.

As stated earlier, degree-day values are positive if the accumulated temperatures were below 32 F (indicating freezing opportunity) and negative if above 32 F (indicating thawing opportunity).

Frost depths for each sample day in Clinton County are plotted

against the eight degree-day sums in Figure 18. Statistics for the regressions of degree-days on frost depth are:

Plot	No. of Samples	Regression Coefficient	Correlation Coefficient	Standard Deviation y on x
Bare	19	Y = 4.7700 + 0.0511X	0.66	2.18
Herbaceous	19	Y = 1.2210 + 0.0236X	0.72	0.93
Hardwood	19	Y = 0.2102 + 0.0068X	0.67	0.03

These regressions were developed only for the time when snow was on the ground and were all highly significant. On the bare plot, samples 18 and 21 (number in symbols in Figure 18) were not included in the regressions. A frost depth of 15 in. was measured but may have been deeper, and so did not truly represent the actual depth of frozen ground.

Vegetation-snow interactions are reflected in slopes of the regression lines. The slope for the bare plot was 2.2 times that for the herbaceous plot, and that for the herbaceous plot 3.5 times that for the hardwood plot. In other words, in reducing frost depth the combination of snow and vegetation (herbaceous plot) was more effective than snow alone (bare plot), and the combination of snow, vegetation, and litter (hardwood plot) was most effective.

The variation in frost depths (standard deviation of y on x) was greater for the bare than the herbaceous plot, and greater for the herbaceous than the hardwood plot. This is paralleled by corresponding variation in snow depths observed on the bare plot.

The relationships for Kent County were not so clear as for Clinton County (Figure 17). However, the hardwood plot always had less frost than either of the other two plots on every sample day. Here again

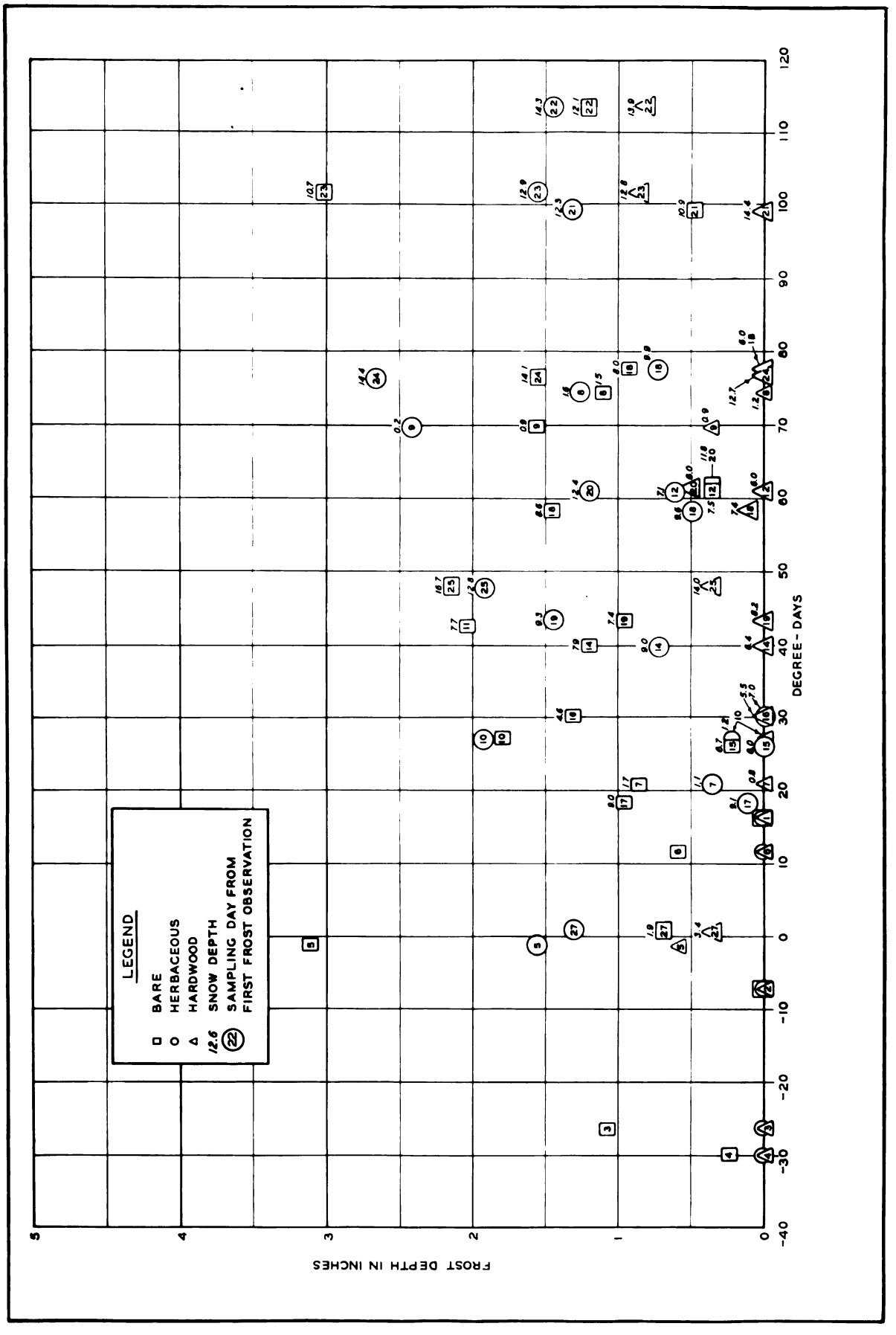


Figure 17. Frost depth versus eight degree-day sum, Kent County plots

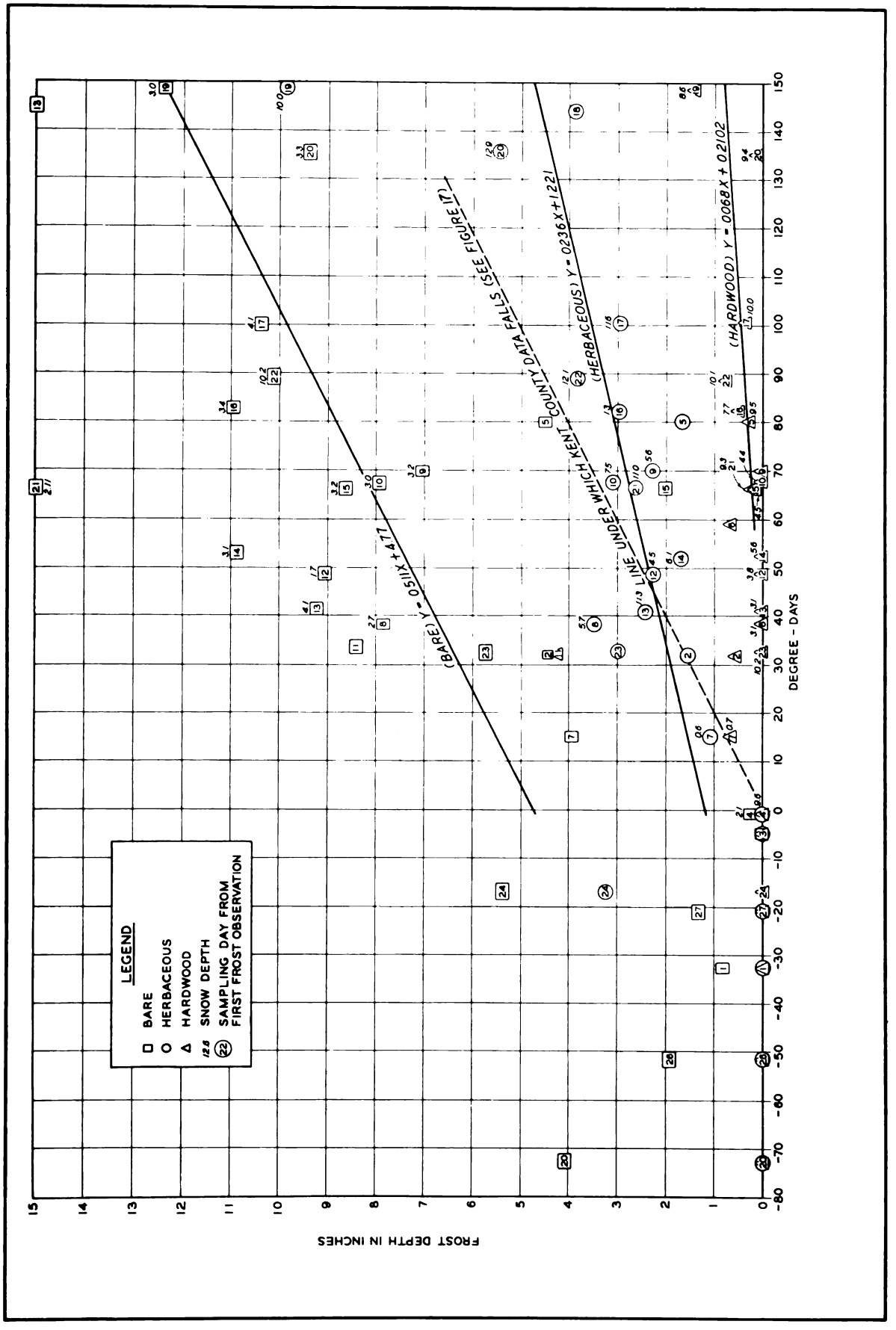


Figure 18. Frost depth versus eight degree-day sum, Clinton County plots

the snow-litter-vegetation complex was highly effective in reducing freezing.

In most cases, when snow depth was less than 6 in. on the Kent County Bare plot, an increase in degree-days (increase in heat loss) resulted in an increase in frost depth (samples 7, 8, 9, 13, 16, and 27, Figure 17). There was no consistent relation between heat loss and frozen depth when snow depths were from 6 to 9 in. (samples 11, 14, 15, 18, and 19).

With less than 6 in. of snow on the Kent County Herbaceous plot (samples 7, 8, and 9), frost depth increased with increasing heat loss. Sample 27 was an exception. On this day all snow had disappeared, and the soil had no insulation from the thawing temperatures of the preceding days.

On the Kent County Herbaceous plot, when snow depths averaged more than 12 in. and the eight degree-day sum was 76.5 or over, frozen depths increased with heat loss (samples 20, 21, 22, 23, 24, and 25). Frost depths decreased in three occasions when snow depths were between 7 and 8 in. (samples 12, 15, and 16). On another occasion (sample 27) there was a substantial increase from 1.92 in. in depth to 3.48 in. For the first three samples at least one thawing day occurred in the week before the sample date; while in contrast, sample 27 had been preceded by 33 days of continuous freezing.

The maximum frost depth in the Kent County Hardwood plot was 0.84 in. (samples 22 and 23). The first time soil freezing occurred with any appreciable snow cover (5.5 in. in sample 16) was when the eight degree-day sum was 32.5.

In the Kent County Herbaceous and Bare plots, freezing was found

with shallower snow as well as fewer degree-days than in the woods, a testimony to the effective combination of litter-vegetative canopy.

Comparative effects of snow on the plots in each county. On Figure 18 a line was drawn from the zero degree-day point on the abscissa through the point below which all the Kent County samples with snow would fall.

The result is striking. With three exceptions (samples 8, 19, and 22), the area under the line includes all the Clinton County data which had more than 5.6 in. of snow at the time of sampling.

Hence, it appears that with the freezing opportunity provided, it was impossible for the Kent County plots to have deeper frost due to their deep snow cover. The deeply frozen plots in Clinton County, those falling above the line, generally had less than 4.1 in. of snow.

The area under the line includes all but seven samples in the herbaceous and hardwood plots in Clinton County. Thus, the over-all effect of snow on the Kent County plots was similar to the effect of vegetation on the Clinton County plots.

On the whole, during the period of continuous snow cover the bare and herbaceous plots in Kent County had far less frost than their counterparts in Clinton County. Frost depth was about equal in the hardwood plots.

Frost regime after final snow disappearance. Figures 15 and 16 illustrate the frozen ground pattern after the snow mantle had disappeared.

On March 30 snow had disappeared from the herbaceous plot in Kent County since the last sampling, March 28, and mean air temperatures (Figure 14) had been 42 and 48 F on March 28 and 29, respectively.

Lack of snow cover resulted in a decrease in frost depth from 3.48 to 1.32 in. in the herbaceous plot without this insulation. The bare and hardwood plots, which still had 1.94 and 3.40 in. of snow had slight increases in frost depth (Table 14).

Snow disappeared from all Kent County plots by April 1, and on the preceding two days, air temperatures of 52 and 40 F helped to remove all frost.

On the sampling of March 29, when snow had disappeared from the Clinton County Bare and Herbaceous plots, they averaged 5.76 and 3.00 in. of frost, respectively. The woods had no frost, but had an average snow mantle of 4.23 in.

Frost depths in Clinton County had all decreased since the last sampling, March 25: 4.44 in. for the bare, 0.84 in. for the herbaceous, and 0.72 in. for the hardwood plot. By March 31, snow was gone from the hardwood plot and no frost was found. The preceding two days mean air temperatures had been 53 and 36.5 F.

In the Clinton County Bare plot on March 31 frost had disappeared from the surface to 3-in. soil depth, but was found from 5.59 to 13.9 in. below the surface, Figure 16. Three days later, April 3, frost was from 7.31 to over 15 in. below the soil surface. The preceding three days average temperatures had been 37, 41, and 52 F.

From April 3 to April 6, average air temperatures were 42, 34, 30.5, and 29 F, respectively. Frost was found from 12 to 15 in. below the surface in one quadrant of the bare plot, and in all four quadrants in the surface to 3-in. depth.

Last frost in the Clinton County Bare plot was found on April 9 in the surface depth. The average was 1.31 in. This followed three days

with average air temperatures of 29, 40.5, and 35 F, respectively, followed by 30.5 F on the sample date. Thereafter air temperatures were above freezing.

In the Clinton County Herbaceous plot the thawing air temperatures of the two days preceding March 31 had removed frost from the immediate soil surface. Frost was found in two quadrants, in one from 3 to 4.9 in. below the soil surface, and in the other from 1.75 to 3.0 in., Figure 16. After March 31 frozen soil was not found again in the Clinton County Herbaceous plot. Subsequent freezing air temperatures did not induce frost as in the bare plot, reflecting the influence of the herbaceous cover.

Resistance Block Readings
as Indicators of Frost Depth

Rowland, Lewis, and Crabb (1955) suggested that resistance blocks might be used for determining the time at which soil moisture crystallized and began to freeze.

It was planned to use the blocks to supplement visual observation of frozen soil cores. Table 15 lists the ranges in available moisture recorded during the study when 4, 3, 2, 1, and 0 frozen cores were observed on a plot. In the majority of cases the range was very wide.

For example, available moisture when four frozen cores were taken ranged from 0 to 60%. In the Clinton County Herbaceous plot, a range from 0 to 100% was observed.

This lack of consistency was soon apparent in the field. Readings were continued through the study, but were not relied upon to indicate the presence of frozen ground.

Table 15. Minimum and maximum available moisture readings (from Bouyoucos blocks)

No. of Frozen Cores	Meter Readings, Per Cent Available Moisture — Soil Depth, in.									
	0 to 3		3 to 6		6 to 9		9 to 12		12 to 15	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Kent Bare										
4	10	64	--	--						
3	0	77	--	--						
2	10	76	12	65						
1	15	82	18	76						
0	57	100	12	100						
Kent Herbaceous										
4	10	65								
3	19	69								
2	58	69								
1	62	63								
0	48	89								
Kent Hardwood										
4	50	61								
3	5	60								
2	10	65								
1	10	72								
0	0	90								
Clinton Bare										
4	0	68	0	63	0	54	0	39	0	6
3	10	10	0	33	15	81	0	68	10	12.5
2	70	81	0	12	0	78	52	60	--	--
1	0	67	79	85	0	0	0	63	0	75
0	75	85	61	89	61	88	55	83	58	93
Clinton Herbaceous										
4	0	100	0	59						
3	10	65	0	74						
2	10	10	10	80						
1	80	90	10	100	0	58				
0	62	96	58	90	29	100				
Clinton Hardwood										
4	0	60								
3	69	71								
2	38	66								
1	68	70								
0	5	95								

Crawford (1955), commenting on the work of Rowland, et al., stated,

> "A further disadvantage to the use of moisture meters for locating the frost line is that continuous readings are required to establish time of initial crystallization."

Crystallization could take place over a range of about 100,000 ohms, equivalent to 25 to 85% available moisture. Sampling visits were too infrequent to use resistance to establish time of freezing.

The same restrictions held true with the resistance blocks as with the thermocouples; the resistance of the block is not necessarily indicative of moisture or frost conditions elsewhere on the plot.

Frozen Cores and Frost Type

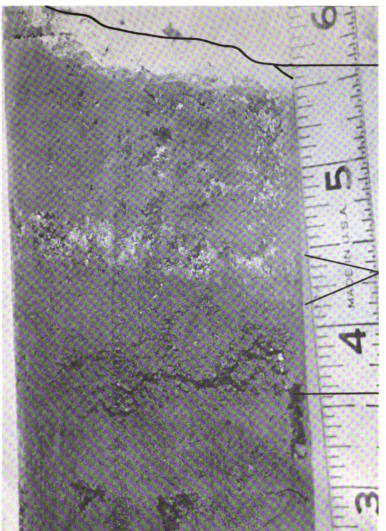
Photographs were made of 151 frozen cores to illustrate soil, ice, and pore relationships. In each case the cores were 1.87 in. in diameter (see Figures 19 through 29). Distance from the camera lens to the core was generally 5 in. or less, and the depth of field on the core was generally 1/4 in. or less.

Physical Condition of Frozen Cores

Figure 19 illustrates the typical condition of sample cores as they were removed from the sample tube. Most cores could be extracted without distortion or fracture.

Trials were made to determine the physical conditions of the cores, and to develop suitable techniques for core extraction. Frozen cores could be pushed out of the tube readily, because the slightly thawed outer space of the frozen soil core provided lubrication and permitted easy extrusion. Unfrozen soil tended to bind the soil core in the tube.

On exceptionally cold days cores froze in the tube. When this happened, it was necessary to warm the whole tube using the exhaust from



Top of core; thin snow cover

Litter

3/16 to 1-3/8 in. honeycomb frost in F and H layers

5/16-in.-thick stalactite and granular frost

Frozen-unfrozen boundary; coarse above, finer below

Figure 19. Frozen cores, Kent County Bare plot (left), Clinton County Hardwood plot (right)

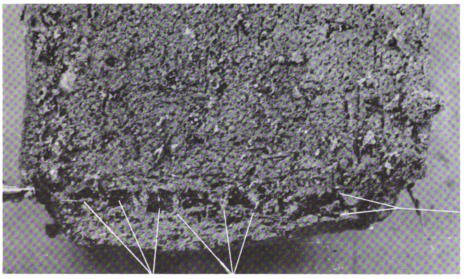


Figure 20. Lower 1-1/4 in. of 3-1/4-in.-deep frozen core, Clinton County Bare plot

Light, opaque areas are granular frost

Dark, irregular areas are open spaces in soil

Horizontally oriented dark lines (< 1/16 in. thick) are ice lenses

Note: Area in rectangle has beginnings of stalactite frost.

Figure 21. Frozen core, Kent County Bare plot

Figure 22. Frozen core, Clinton County Bare plot

Figure 23. Frozen core, Clinton County Bare plot

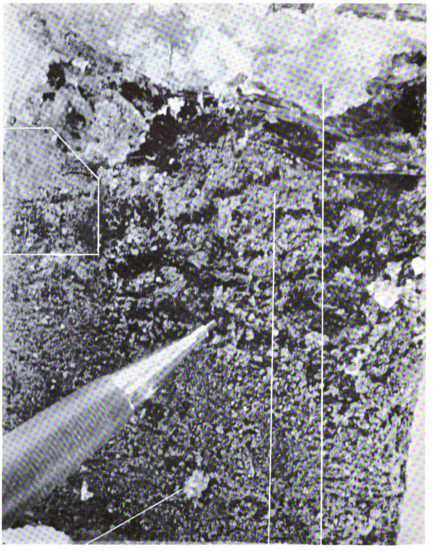


Figure 24. 2-1/2-in. frozen core, Kent County Herbaceous plot

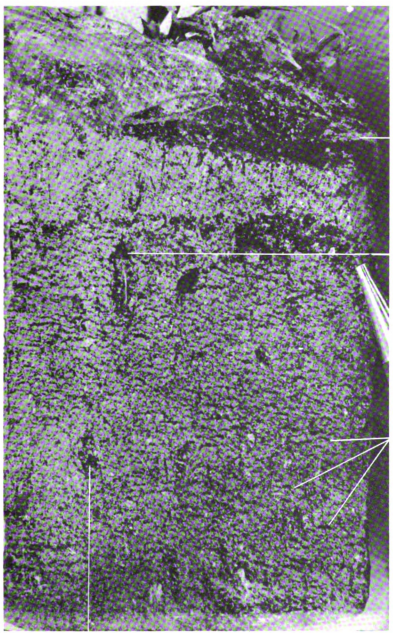
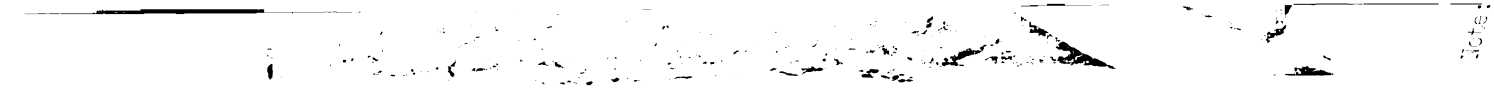
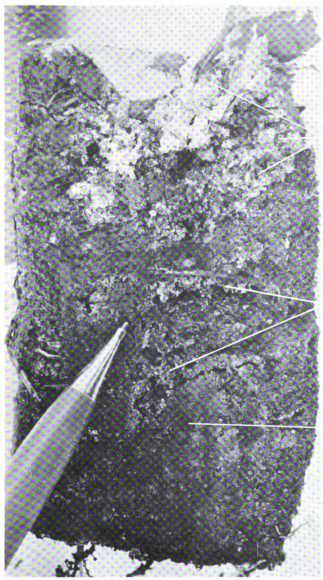


Figure 25. 3-1/2-in. frozen core, Clinton County Herbaceous plot

Figure 26. 1-1/8-in. frozen bottom of core, Kent County Herbaceous plot


Note



Note: General admixture of porous, crumblike soil into solid concrete frost.

Figure 27. 3-1/4-in. frozen core, Kent County Hardwood plot

Stalactite crest; between

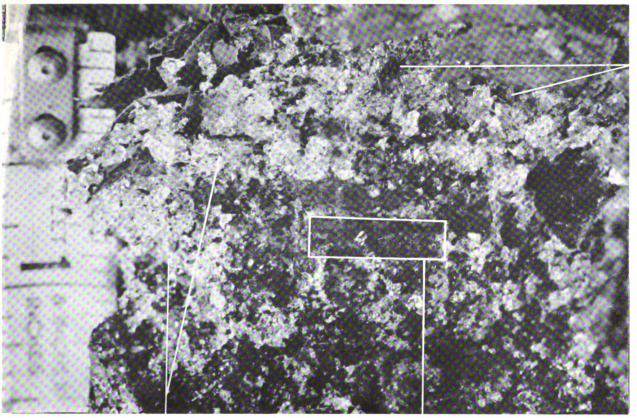
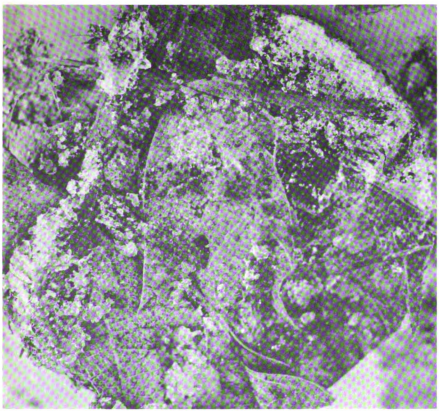
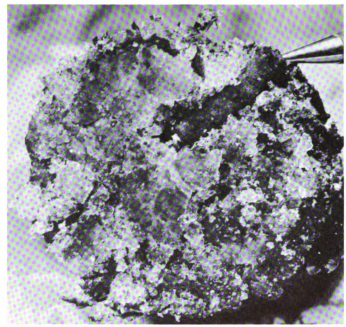


Figure 28. Frozen upper portion of core, Clinton County Hardwood plot



Most of litter removed, showing granular ice into humus layer. Core has up to 1/2 in. of clear ice over leaves and granular-honeycomb ice shown



All of litter layer removed showing fused granular-honeycomb frost. Note porous nature of ice. Pencil points to cutoff portion of twig

Figure 29. Looking down on two Clinton County Hardwood cores

the jeep. As soon as surface melting began, the core could be extruded into the cutting board. This technique was used extensively from the middle of January to the last week in March.

After March 28 the manual Hvorslev sampler was adequate to remove the frozen cores. However, it was often necessary to hammer the sampler into the frozen ground.

Porosity of Frozen Cores and Frost Type

Porosity. The literature implies that concrete frost is impermeable. However, in the concrete frost zone of almost every core, few to many open pores were observed. These varied in size from barely visible up to about 1/2 in. in diameter. Many study cores were broken open to scrutinize these pores. It was concluded that most cores were porous and that there was a reasonable possibility that moisture movement could occur through concrete frost.

Frost type. Each photograph is annotated with specific comments on frost type. Frequently several frost types occurred in close association in the cores. This was particularly noticeable in the case of concrete and granular types. In some cases granular cleavage lines were noted in areas of "solid" ice; in these instances the frost is termed "granular-concrete," Figures 25 and 26.

There were evidences of columnar structure in some areas of solid ice, and in some cores, stalactite frost was noted contiguous to concrete frost, Figure 20. A combined term was not given to these frost types, but there seems to be ample evidence that concrete frost may develop from stalactite.

Concrete frost predominated in the Clinton County Bare plot.

Many horizontal ice lenses of varying length and up to 1/32 in. wide were present (Figure 22). Frequently solid ice up to 1/2 in. thick was found across cores between 3 to 7 in. below the surface. Vegetative material was sometimes included in the ice band (Figure 20).

On the Kent County Bare plot ice lenses were generally thicker, to about 3/16 in. No ice bands were found (Figure 21). However, granular frost mixed with concrete was frequently found in the upper 1-1/2 in. of the cores.

In the herbaceous plots concrete frost was general from 1 in. below the soil downward. A definite line separated this from the more porous frost above (Figures 24 and 25). Frost in the upper portion was a mixture of granular and honeycomb with some concrete frost.

Open pores were noted in the lower concrete zone as in the bare plots. The upper porous zone generally coincided with the dense root mass, but the few roots in the concrete zone (Figure 26) were often surrounded by granular-concrete, granular, or concrete ice with contiguous open spaces. As with the bare plots, ice lenses were thinner in Clinton than in Kent County.

Ice lenses in concrete frost may be important from the standpoint of percolation observed during freezing (page 141). Impermeable when frozen, these lenses might melt during periods of rising temperature allowing meltwater from the snowpack, as well as from the lenses themselves, to percolate to lower horizons.

Under undisturbed snow on the hardwood plots, freezing was not sufficient to produce a long frozen core. Hence pictures of frozen cores in the hardwood plots are of cores taken where the snow has been trampled, and the soil was frozen more deeply.

Frozen soil of the crumb type was found in the upper 1/2 to 1 in. of the hardwood cores. This layer generally contained granular frost, and often some honeycomb and stalactite frost (Figures 27 and 28). Cores from the hardwood plots were more porous than cores from the herbaceous or bare plots.

In hardwood cores the lower concrete zone was not distinctly divided from the upper as in the herbaceous cores. There was a greater admixture of porous, crumblike soil grading and intruding into the lower concrete zone (Figure 27).

The concrete frost zone itself was more porous in cores from the wooded cores than elsewhere. There was a geater root mass in this zone, and the area around visible roots, and worm channels were lined with granular-concrete, concrete, or granular frost.

Two pictures have been included to show the frozen litter that could be found at almost any time during freezing periods in the hardwood plots. Frost was of all types and combinations of types. Pure ice frequently held this mixture together, though most often the frost was granular or granular-concrete (Figure 29).

Soil Moisture and Bulk Density

There was a tendency toward an increase in moisture with increasing frost depth and a concurrent decrease in bulk density, Figures 32 through 37. As a preliminary step, the possibility that significant differences occurred from one sample day to the next was investigated.[10/]

10/ This analysis is on file (VB34.2) with the Trafficability Section of the Army Mobility Research Center, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Comparisons made from one sample day to the next proved inconclusive and contradictory; increases in moisture during the freezing period could not be consistently explained by moisture movement during freezing, by associated changes in bulk density, or even by a shift from the frozen to the nonfrozen state.

The comparisons did indicate that:

1. Significant day to day changes in bulk density and moisture could not be accounted for because of the relatively long interval (2 to 6 days) between samples.
2. Inherent variations in bulk density frequently masked daily changes in both moisture and bulk density.
3. Some soil moisture increases were attributable to losses of water from the snowpack.
4. A rise in air temperature to near or above freezing often preceded increase in soil moisture.

Likewise examination of the air temperature regime (i.e., were air temperatures directly related to freezing or thawing, to moisture release, or density changes?) provided no logical and consistent explanation for the changes in moisture and bulk density.

The analysis that follows developed from these preliminary investigations. A general picture of moisture movement was obtained from the entire upper 15 in. of the soil and relationships of moisture and bulk density with frost depth were explored for each 3-in. layer.

Meaningful comparison of moisture and bulk density with frost depth required determination of the inherent variation in bulk density and in water holding capacity. Inherent variation in maximum moisture content determined when the soil was not frozen. The variation in

bulk density that might be expected to occur in the nonfrozen soil was determined from samples obtained prior to the first freeze.

Direct relationships between moisture and bulk density were also investigated; as was the possibility that snow meltwaters contributed to moisture in the frozen soil.

Moisture Movement in the 15-in. Depth

Kent County plots. Moisture contents were shown in Figure 30. Starting with initial moisture values of 4.68, 4.13, and 4.77 in. of water per 15 in. of soil, respectively, for the bare, herbaceous, and hardwood plots, moisture remained relatively constant during the study period. From the first freeze until the end of the freezing period, March 30, the variation from day to day was generally less than 0.5 in. of water. Standard deviations of 0.36, 0.23, and 0.21 in. of moisture per 15 in. of soil for the bare, herbaceous, and wooded plots respectively, substantiate the graphic evidence (Table 16).

Table 16. Mean moisture contents, standard deviations, and coefficients of variation for the upper 15 in. of soil

Plot	No. Samples	Mean in.	Standard Deviation in.	Coefficient of Variation %
		Kent		
Bare	25	4.71	0.36	7.60
Herbaceous	24	4.25	0.23	5.40
Hardwood	24	4.73	0.21	4.40
		Clinton		
Bare	19	4.97	0.53	10.70
Herbaceous	23	4.86	0.44	9.10
Hardwood	22	5.58	0.33	5.90

Moisture contents on the first and last day of freezing with

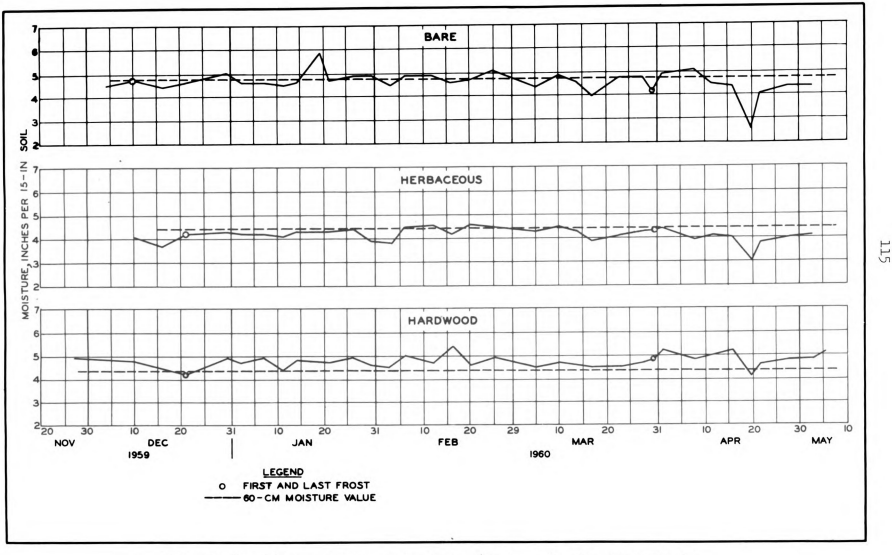


Figure 30. Mean moisture content, in./15 in. of soil, Kent County

estimated field maximum moisture contents for comparison are shown below.

	Bare	Herbaceous	Hardwood
December 10	4.68	4.13	4.77
March 30	4.23	4.29	4.79
Field maximum	4.74	4.41	4.36

These data indicate no noteworthy increase in moisture over the winter period. Examination of moisture content in the light of the estimated field maximum moisture reveals that moisture was near the field maximum both before and after freezing.

Linear relationships were tested between moisture content and frost depth, but none proved significant.

Clinton County plots. Freezing was first observed on the bare plot December 14. Moisture contents on that day were 4.78, 4.58, and 5.27, for the bare, herbaceous, and hardwood plots, respectively, each value being somewhat higher than the respective Kent County plots. Variation, too, was greater than in Kent County with standard deviations of 0.53, 0.44, and 0.33 in. of moisture for the bare, herbaceous, and hardwood plots (Table 16).

In Clinton County there was a general increase in soil moisture as the freezing season progressed (Figure 31); however, moisture dropped rapidly in late March and by the last day of freezing had dropped 1.31 in. (in the bare plot) and 0.43 in. (in the herbaceous plot) below moisture content on the first day of freezing. The wooded plot gained 0.78 in. (tabulation on page 118).

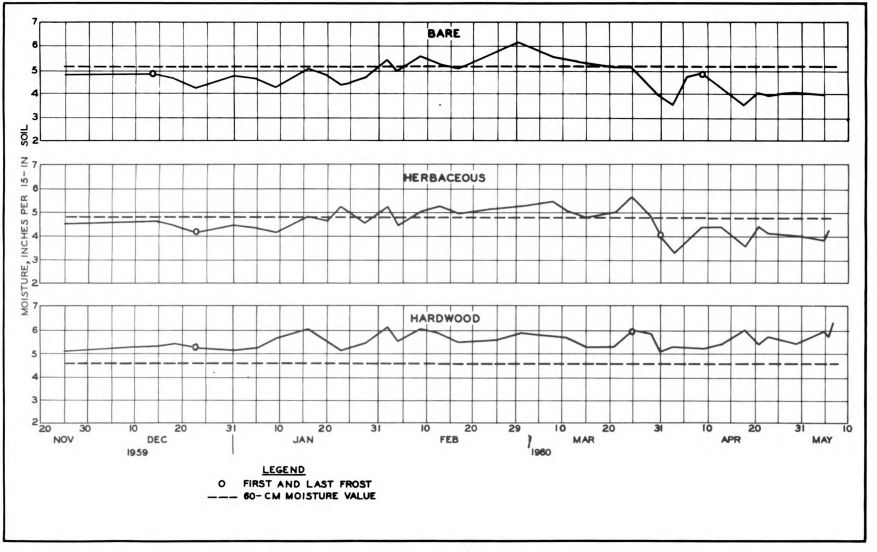


Figure 31. Mean moisture content, in./15 in. of soil, Clinton County

	Bare	Herbaceous	Hardwood
December 14	4.78	4.58	5.27
Last day of freezing	3.47 (April 3)	4.15 (March 31)	6.05 (March 25)
Field maximum	5.14	4.79	4.58

Gain in moisture by the hardwood plot in Clinton County may be explained by its poor drainage resulting (in many sectors) from an impending horizon about 20 in. below the soil surface.

The herbaceous and hardwood plots had been covered with an appreciable snow mantle in each county. On the Clinton County Bare plot which had very little snow (none on March 29), moisture loss was appreciable. In Kent County, the bare plot had 1.94 in. of snow on the last day of freezing and moisture loss was less than in the Clinton County Bare plot on the last day of freezing.

Again, in Clinton County, linear relationships between moisture and frost depth were tested without significant results.

Relation of Soil Moisture Content to Frost Depth and Pore Space

Soil moisture plotted with frost depth, Figures 32 through 37, indicated that in some plots there was a general increase in moisture in the frozen layers as freezing progressed (see Appendix A). Frost depth also tended to increase during the freezing season.

Kent County plots. Moisture content, in inches per three inches of soil, was plotted with frost depth (Figures 32 to 34). On all three plots, moisture contents remained within the range of 0.9 to 1.5 in. of moisture per 3 in. of soil regardless of frost depth (Figures 32 to 34).

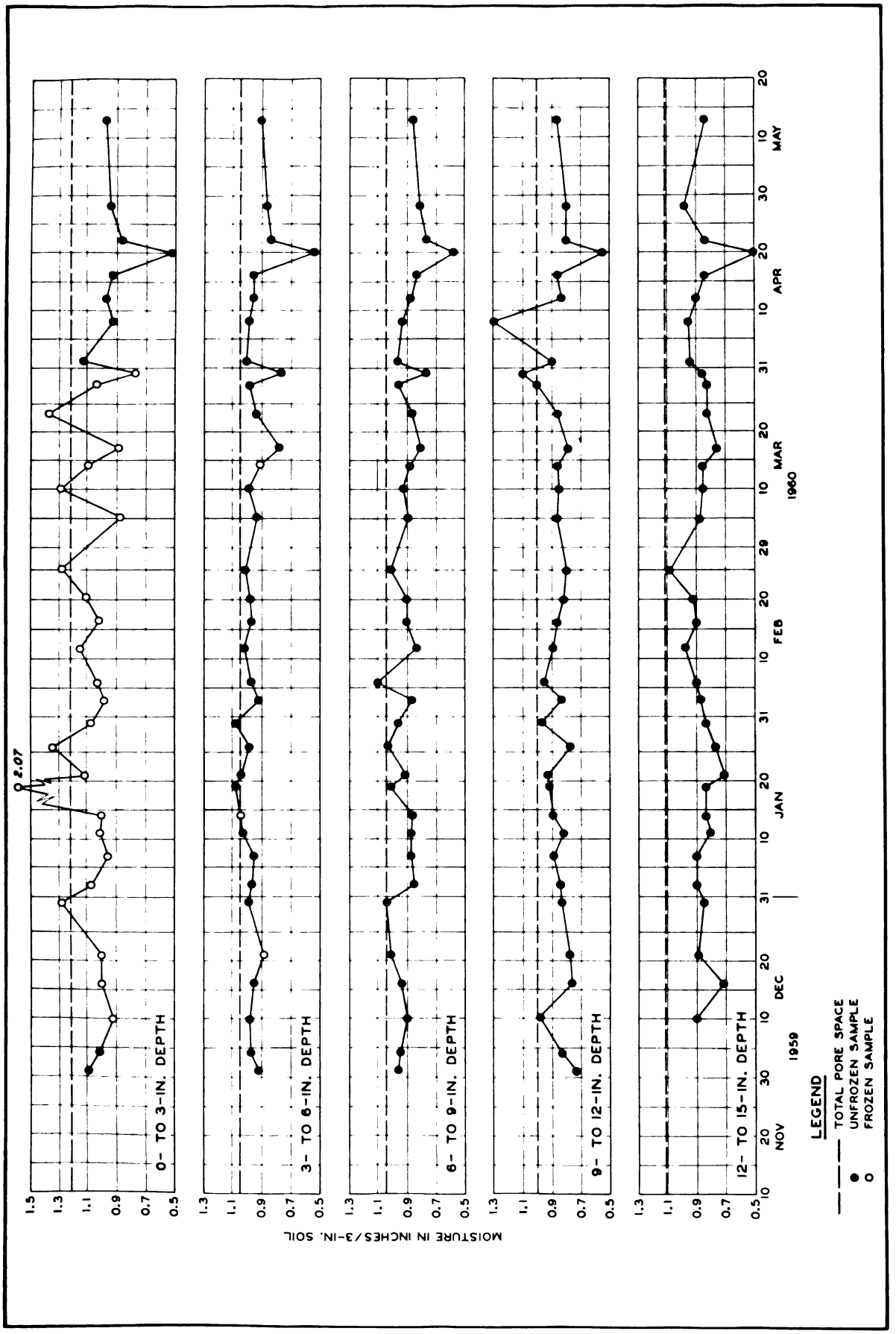


Figure 32. Mean moisture contents by 3-in. depths, Kent County Bare plot

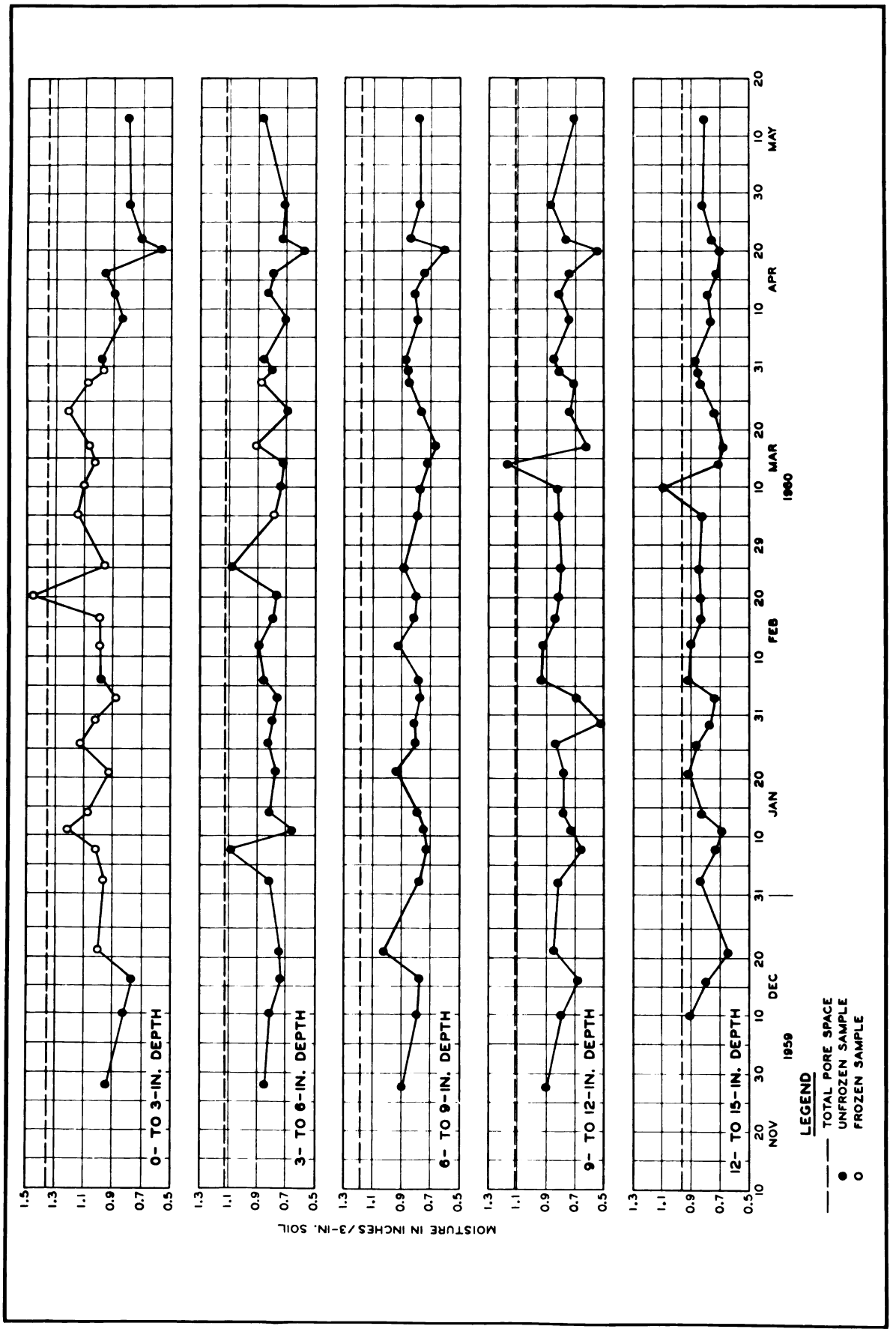


Figure 33. Mean moisture contents by 3-in. depths, Kent County Herbaceous plot

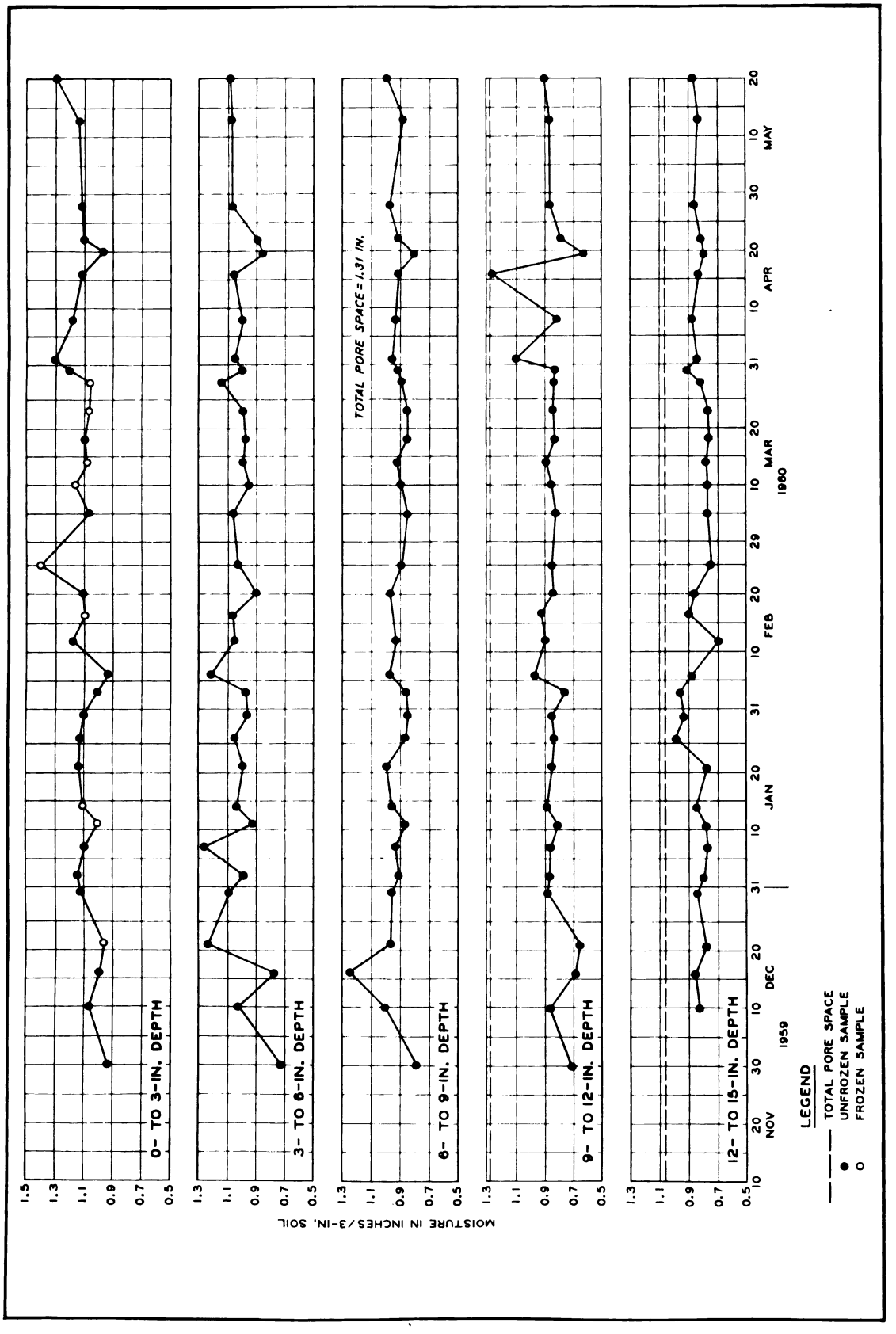


Figure 34. Mean moisture contents by 3-in. depths, Kent County Hardwood plot

On the herbaceous and hardwood plots all moisture contents were between the 60-in. tension value and the total pore space of the soil before freezing. Moisture contents during freezing in the bare plot showed a wide range, some falling both above and below total pore space and 60-cm values, Figure 35, Table 17.

Clinton County plots. Moisture was again plotted with frost depth (Figures 35 through 37). The bare plot data are presented for all five depths, as freezing occurred in all. Freezing occurred in the herbaceous plot in the surface to 3-in. and 3- to 6-in. depths and hardwood plot data in the surface depth only.

Moisture was significantly related to frost depth only in the surface to 3-in. depth of the bare plot. The regression equation, $Y = 0.0322X + 0.14$, where Y is moisture content and X is frost depth, evidenced a significant correlation coefficient of 0.470.

Table 17. 60-cm tension values and total pore space before freezing period

Plot	Depth in.	Kent County 60-cm Tension Values, in.	Kent County Total Pore Space, in.	Clinton County 60-cm Tension Values, in.	Clinton County Total Pore Space, in.
Bare	0-3	1.03	1.22	1.09	1.20
	3-6	0.93	1.15	0.98	1.16
	6-9	0.93	1.04	0.99	1.05
	9-12	0.90	1.00	0.99	1.05
	12-15	0.93	1.12	1.09	1.02
Herbaceous	0-3	0.83	1.36	0.83	1.25
	3-6	0.94	1.11	0.98	1.18
	6-9	0.86	1.18	0.86	1.10
	9-12	0.91	1.11	1.01	1.19
	12-15	0.87	0.96	0.97	1.07
Hardwood	0-3	0.87	1.87	0.67	1.73
	3-6	0.80	1.66	0.84	1.57
	6-9	0.89	1.31	1.00	1.28
	9-12	0.83	1.28	1.03	1.28
	12-15	0.97	1.06	1.04	1.17

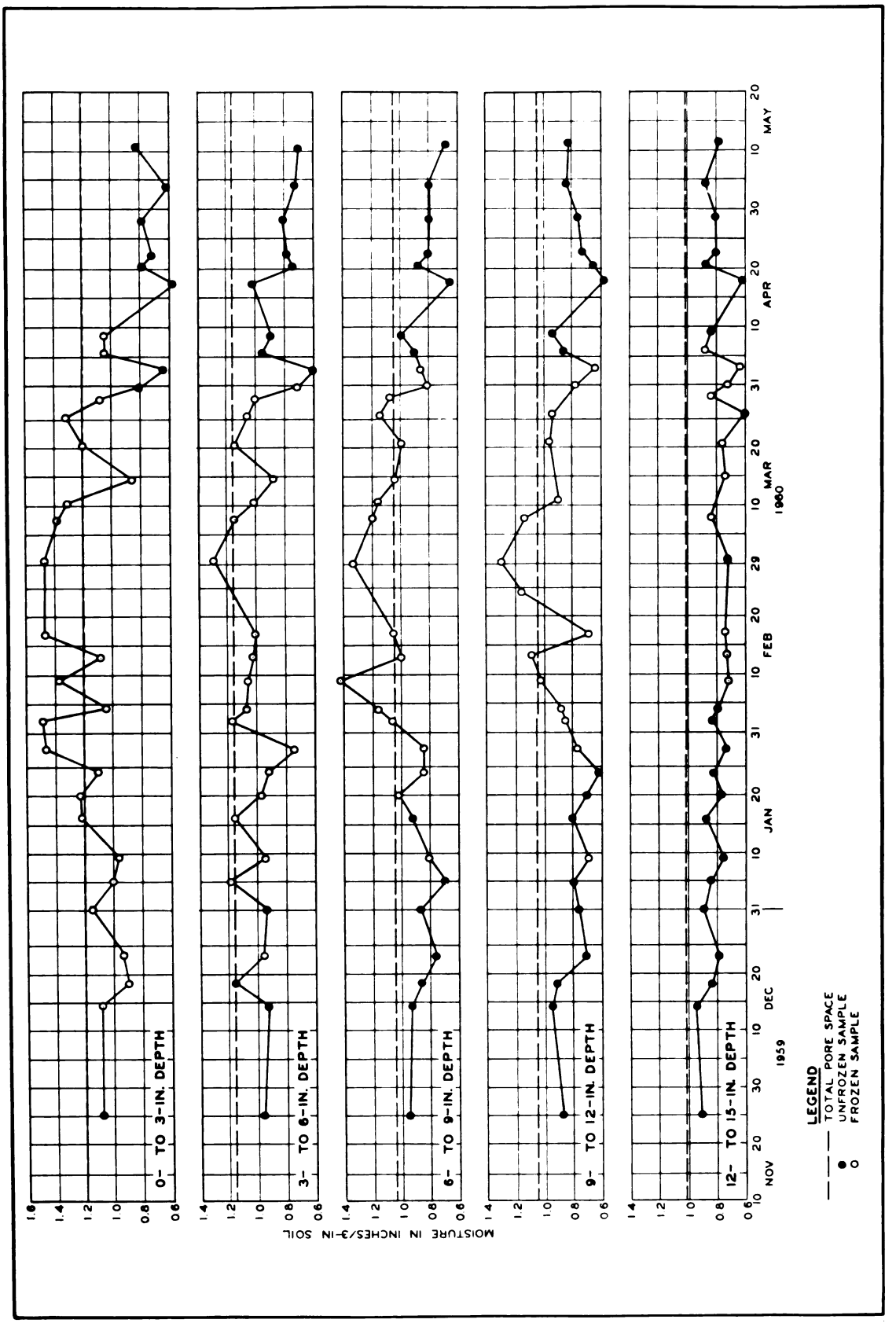


Figure 35. Mean moisture contents by 3-in. depths, Clinton County Bare plot

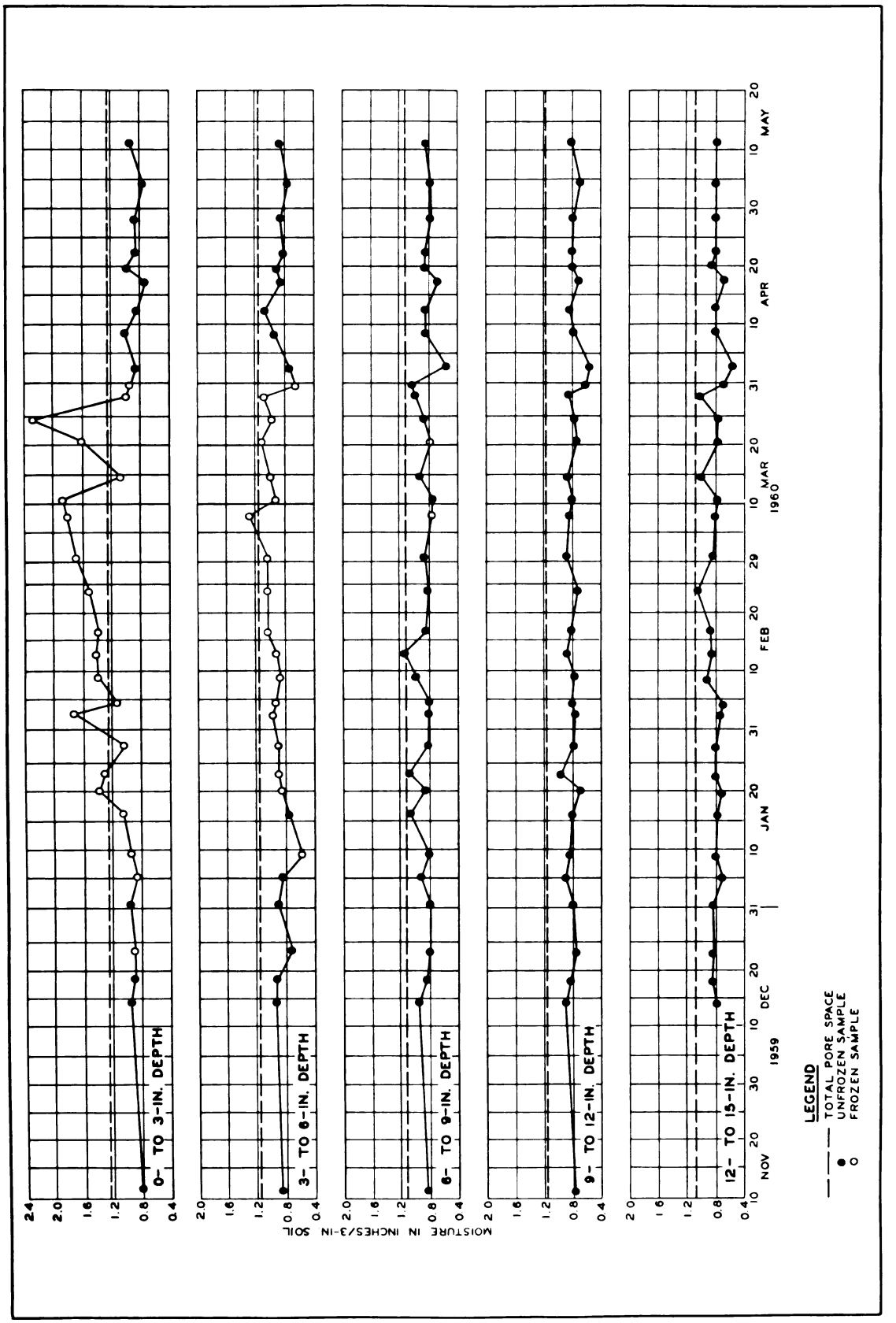
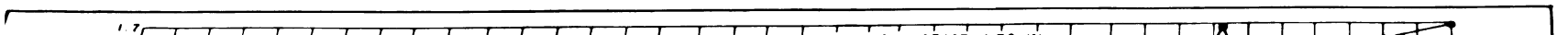


Figure 36. Mean moisture contents by 3-in. depths, Clinton County Herbaceous plot



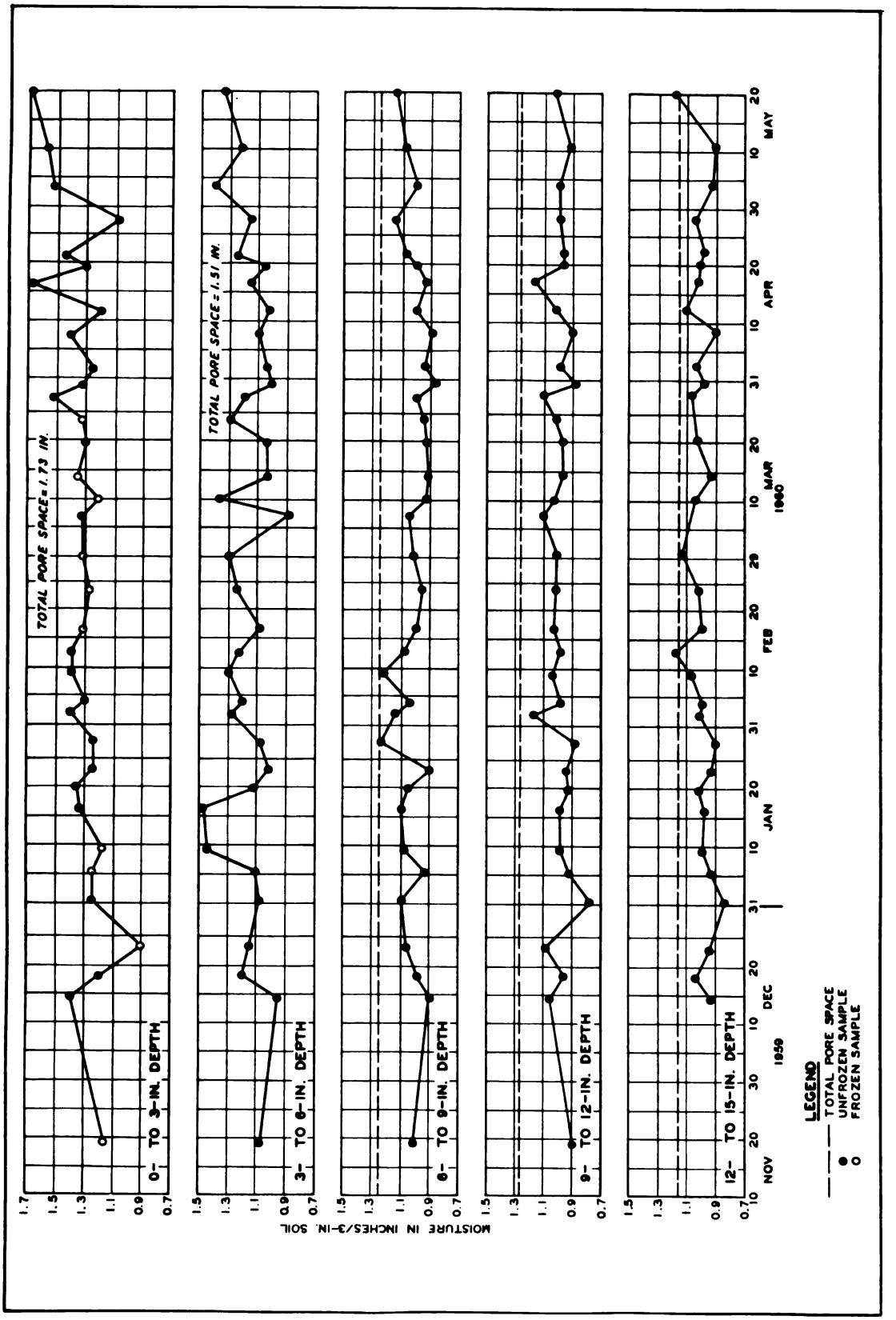


Figure 37. Mean moisture contents by 3-in. depths, Clinton County Hardwood plot

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In the Clinton County plots moisture during freezing exceeded the total pore space value except in the hardwood plot and the 12- to 15-in. layer of the bare plot. In these two exceptions the frost was never deeper than the layer for which the moisture contents were plotted; i.e. lower than 3 in. in the hardwood plot, or 15 in. in the bare plot.

On 6 of the 12 days when the moisture contents exceeded total pore space (calculated before the soil was frozen) the entire 15-in. layer increased in moisture content. On three of these six days the 15-in. moisture content had not changed from the last sampling date.

Examination of the moisture patterns on each plot, Figures 32 to 37, revealed that when the moisture content in a given depth increased, a decrease in moisture did not necessarily occur in the depths below. This clearly infers that moisture need not have moved up from the lower soil depths to cause the increase.

On certain dates the moisture content in each depth increased over that of the previous sampling, again suggesting a source of moisture other than upward movement. The source of this moisture may have been the snowpack. This possibility is considered in the section "Snowfall and Peak Moisture Contents," page 140.

Moisture content varies for a given frost depth. For example, when the frost line was about 1.2 in. deep in the Kent County Bare plot, moisture contents of 0.92, 0.96, 1.07, and 1.28 in. were recorded. (These occurred on December 10, January 7 and 30, and March 10.) In every plot more than one moisture content per frost depth was noted.

Discussion. There are ample indications of moisture movement into the frozen layer, a phenomenon previously noted by other workers (e.g. Domby and Kohnke, 1955). Moisture movement due to capillarity

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undoubtedly takes place; the presence of ice induces very high tension gradients between it and the unfrozen soil.

Though there is much disagreement as to the quantities of water that can be moved by vapor transfer, such movement must also be considered as a potential source. No published work on direct experimentation with moisture movement from unfrozen to frozen soil layers was found. Several investigators, notably Bouyoucos (1915) and Smith (1943), have reported moisture movement in the vapor phase when temperature gradients were established in unfrozen soil. With the extreme temperature differentials between frozen soil and unfrozen soil, vapor movement into the frozen zone would be expected. Vapor movement, plus water added by capillary rise might well explain some of the higher moisture content. Water movement in the liquid or gaseous phase may also explain why moisture contents could not be related, linearly, to frost depth. Only moisture present as ice influences frost depth as observed in the field. That is, the frozen core determined visually depends on frozen soil moisture, while liquid water or water vapor may or may not be present in this core.

Bulk Density Versus Frost Depth and Limit of Bulk Density Variation

In testing relationships between bulk density and frost depth, consideration was limited to depths with frequent freezing. These data are plotted in Figures 38, 39, and 40 (see Appendix Table A6 for bulk densities of each depth).

Confidence intervals were developed for bulk density based on the number of unfrozen cores obtained in each depth to the time of first

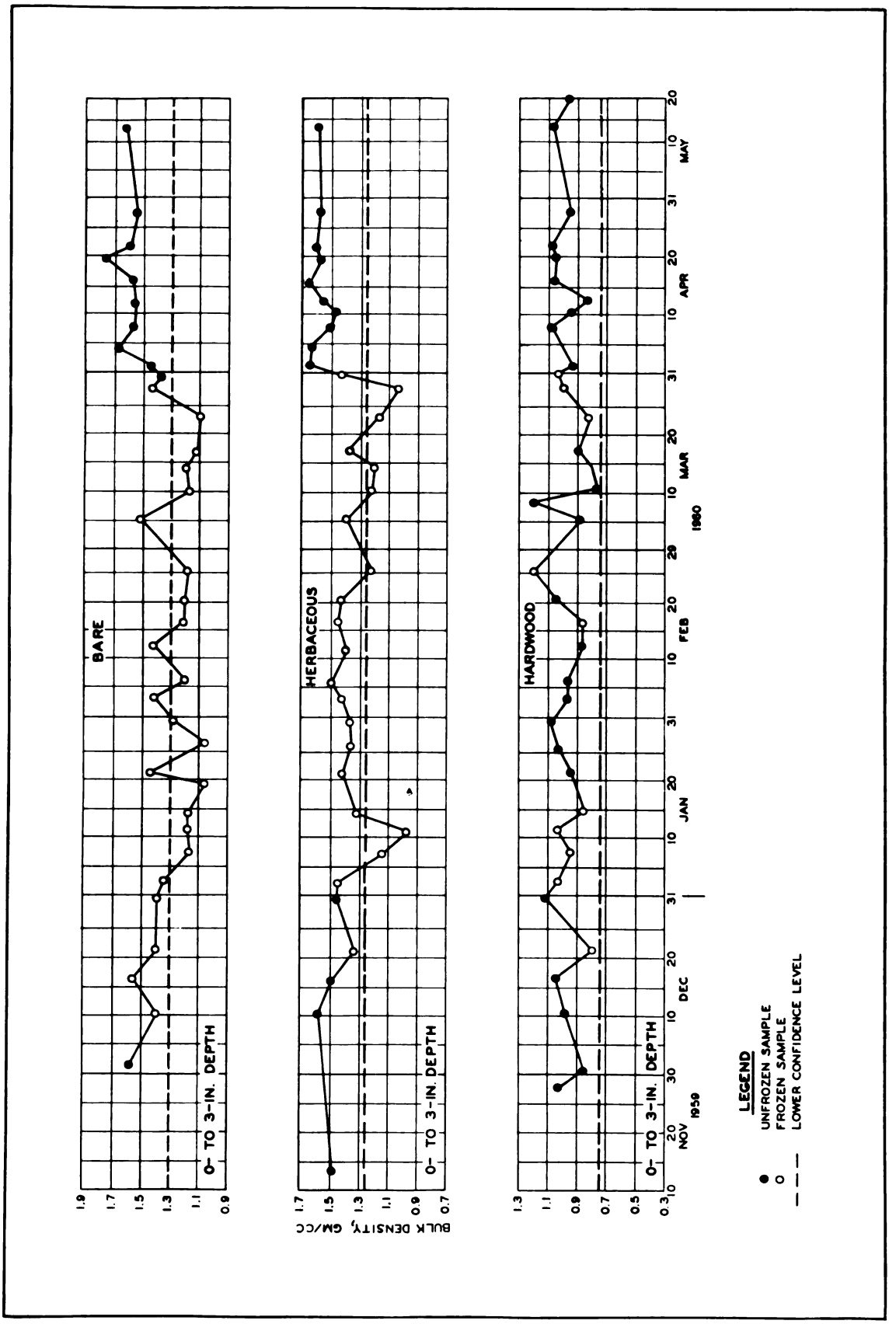
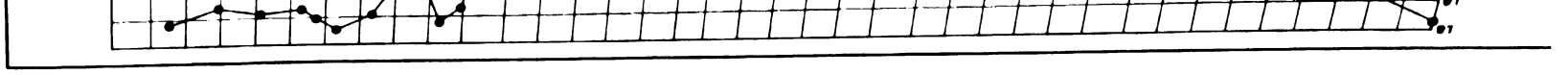


Figure 38. Mean bulk density in frozen depths (surface to 3-in. depth), Kent County



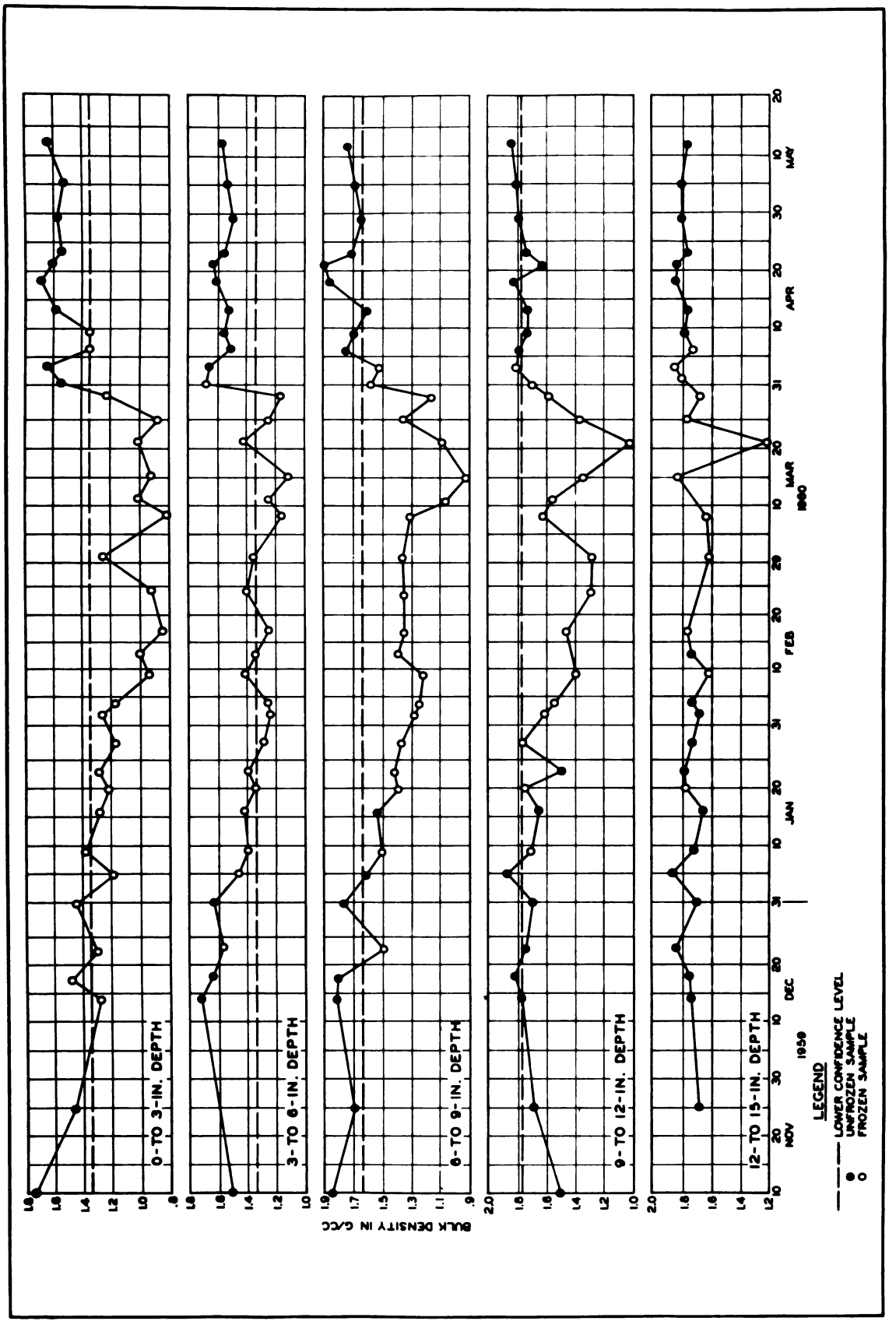


Figure 39. Mean bulk density by 3-in. depths, Clinton County Bare plot

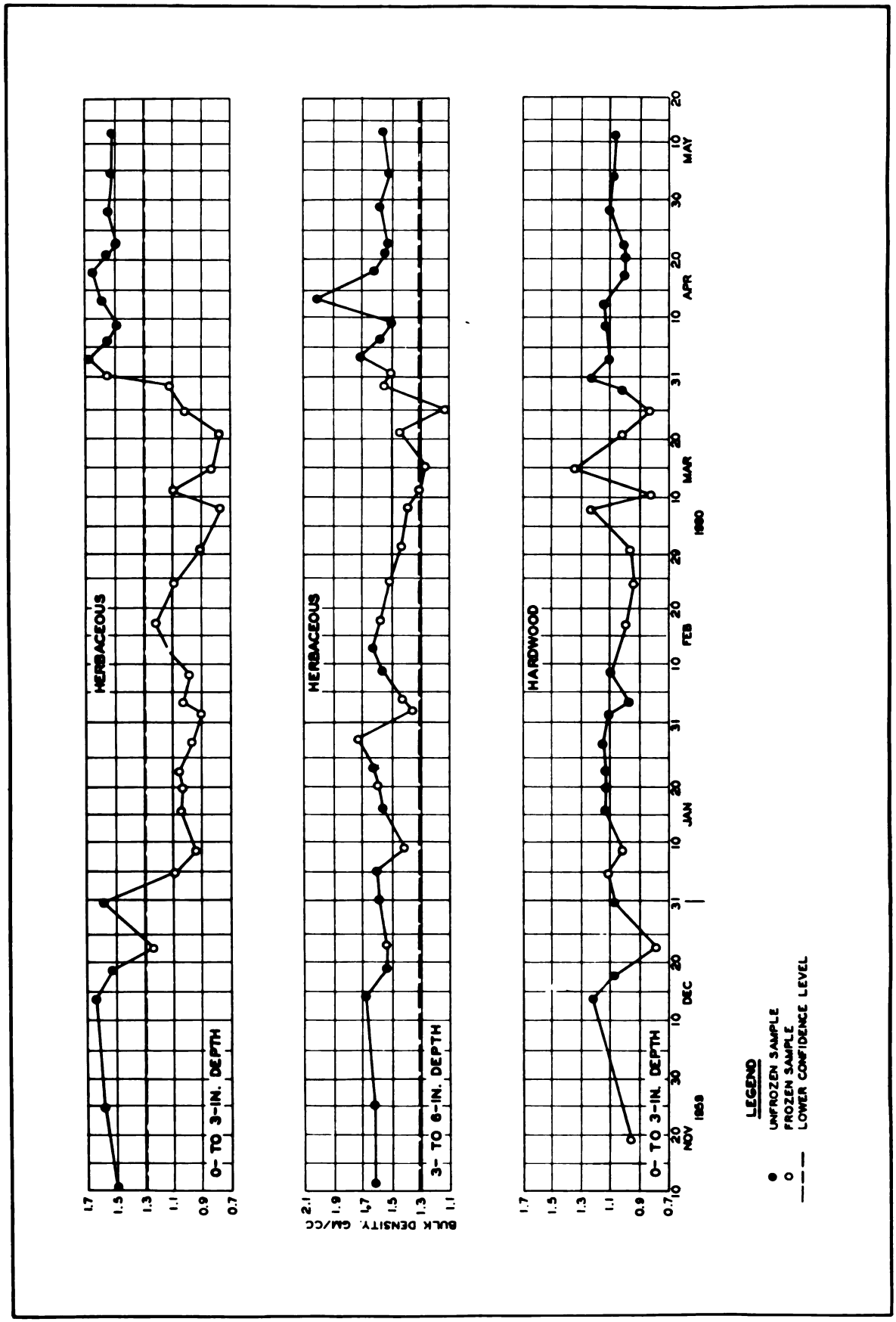


Figure 40. Mean bulk density in frozen depths, Clinton County Herbaceous and Hardwood plots

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freezing. Bulk densities during freezing which were below the lower confidence level were assumed to be a result of moisture movement and freezing. The 99% confidence level was used to provide a stringent test (Table 18).

Intercept values of the regression equations generally reflect bulk density values of the several soil depths, Table 19. The Kent County Hardwood plot, which had the lowest bulk density, had the lowest intercept value; while the Clinton County Bare plot, 9- to 12-in. depth with the highest mean bulk density, had the highest intercept. Deviations from the regression varied from 0.14 g/cc to 0.10 g/cc and showed no relation to depth, vegetation, or mean bulk density.

The hardwood plots showed no significant relation between frost depth and bulk density. There were only 10 frozen samples in the Kent County plot, and 9 in the Clinton County plot. In the Clinton County plot, none of the bulk density data fell below the lower confidence level, and only four points did so in the Kent County plot.

In all other frozen depths a significant or highly significant linear regression was developed between bulk density and frost depth (Figure 41). In all but two depths where significant regressions were determined, a majority of the points were below the lower confidence level, Figures 38, 39, and 40.

Discussion. Results of the bulk density-frost analysis suggest that bulk density of specific soils can be predicted from frost depth. If moisture contents could be determined from bulk density, a useful procedure might be evolved for estimating soil moisture contents at any time during the winter period, and a prognosis might be made as to the soil moisture status during thaw.

Table 18. Means, standard deviations, and confidence intervals for bulk density before freezing*

Depth in.	No. of Samples	Bulk Density, g/cc $\bar{x}$	Standard Deviation	Confidence Interval (99 %)
		Kent Bare		
0-3	24	1.62	0.11	1.31 - 1.93
3-6	32	1.59	0.14	1.20 - 1.98
6-9	87	1.65	0.30	0.82 - 2.48
9-12	167	1.73	0.10	1.46 - 1.99
12-15	133	1.75	0.05	1.62 - 1.88
		Kent Herbaceous		
0-3	12	1.52	0.09	1.25 - 1.78
3-6	23	1.69	0.01	1.06 - 2.33
6-9	132	1.73	0.01	1.70 - 1.77
9-12	132	1.77	0.01	1.73 - 1.81
12-15	128	1.81	0.002	1.80 - 1.82
		Kent Hardwood		
0-3	12	0.96	0.07	0.73 - 1.18
3-6	132	1.38	0.01	1.34 - 1.42
6-9	129	1.57	0.007	1.55 - 1.59
9-12	129	1.68	0.02	1.63 - 1.72
12-15	121	1.76	0.01	1.73 - 1.79
		Clinton Bare		
0-3	26	1.61	0.00	1.35 - 1.87
3-6	10	1.71	0.11	1.36 - 2.06
6-9	10	1.82	0.06	1.64 - 2.00
9-12	35	1.79	0.003	1.78 - 1.79
12-15	43	1.75	0.09	1.50 - 2.01
		Clinton Herbaceous		
0-3	12	1.54	0.09	1.29 - 1.80
3-6	22	1.61	0.10	1.31 - 1.90
6-9	38	1.70	0.17	1.24 - 2.16
9-12	35	1.77	0.18	1.28 - 2.25
12-15	126	1.75	0.08	1.54 - 1.97
		Clinton Hardwood		
0-3	12	1.08	0.18	0.52 - 1.66
3-6	131	1.38	0.02	1.33 - 1.43
6-9	130	1.61	0.01	1.58 - 1.64
9-12	128	1.65	0.01	1.62 - 1.68
12-15	116	1.64	0.009	1.62 - 1.67

* Based on number of frozen cores before freezing.

Table 19. Statistics for the regressions of bulk density (Y) on frost depth (X)

Plot	Depth in.	Equation	Correlation Coefficient	Level of Significance	Standard Deviation from Regression	Mean Bulk Density (Y)	No. of Samples
			Kent County				
Bare	0-3	Y = 1.40 - 0.09X	-0.5050	*	0.12	1.18	25
Herbaceous	0-3	Y = 1.45 - 0.12X	-0.7250	**	0.10	1.29	20
Hardwood	0-3	Y = 0.96 - 0.10X	-0.1925	†	0.06	0.92	8
			Clinton County				
Bare	0-3	Y = 1.48 - 0.04X	-0.7600	**	0.12	1.17	19
Bare	3-6	Y = 1.55 - 0.03X	-0.5000	*	0.10	1.33	16
Bare	6-9	Y = 1.66 - 0.04X	-0.5250	*	0.14	1.32	16
Bare	9-12	Y = 2.04 - 0.06X	-0.7270	**	0.13	1.53	13
Herbaceous	0-3	Y = 1.30 - 0.07X	-0.6480	**	0.11	0.99	20
Herbaceous	3-6	Y = 1.71 - 0.09X	-0.6020	*	0.14	1.44	17
Hardwood	0-3	Y = 1.04 - 0.17X	-0.5800	†	0.12	0.94	17

* Significant at 95% level.
** Significant at 99% level.
† Not significant.

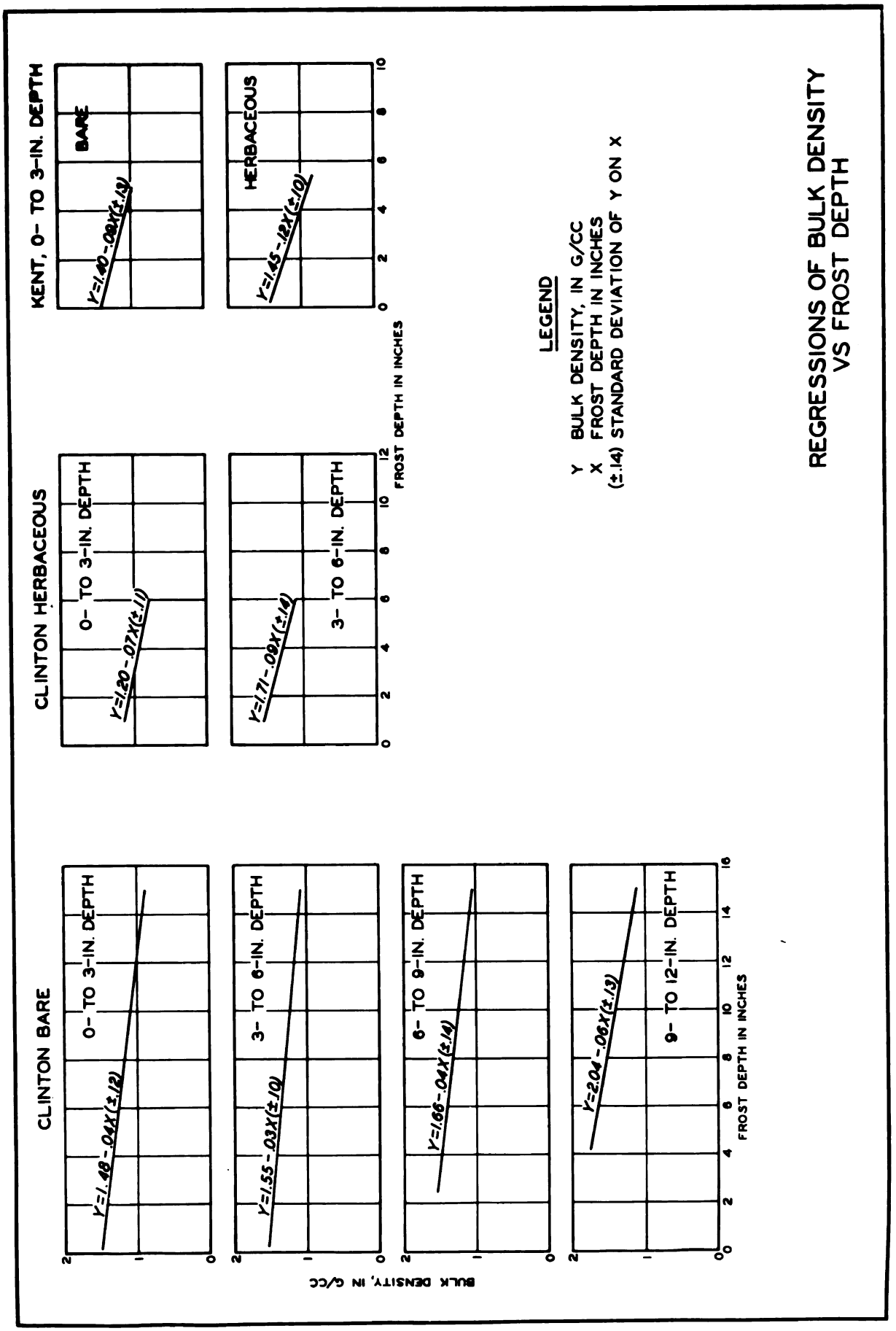

Figure 41. Regressions of bulk density versus frost depth

The presumption appears valid that bulk densities falling below the lower confidence level of the mean bulk density before freezing were a result of the process of moisture movement and freezing. In those depths in which significant relations between moisture and density are well developed, all or most of the bulk densities were below the lower confidence level.

In the surface 3 in. of the hardwood plots, where no significant relationships evolved, the bulk densities were exceedingly low at the start. During freezing bulk densities seldom were outside the range of normal variation (below the lower confidence level).

It is logical that bulk density change be related to frost depth. The low bulk densities observed are probably caused by moisture movement into the frozen zone, freezing and expanding, allowing room for more moisture movement, etc. Thus for a low bulk density to occur, the ground must be frozen. On the other hand, all moisture need not be frozen even when the soil appears frozen, thus moisture content need not correlate with frozen depth.

Relation of Bulk Density to Soil Moisture During Freezing

Regression of bulk density against soil moisture content for days when the soil was frozen are shown in Figure 42. Except for the wooded plots, the 12- to 15-in. depth of the Clinton County Bare plot, and the 3- to 6-in. depth of the Clinton County Herbaceous plot, bulk density proved to be significantly related to soil moisture content.

Statistics for these regressions are given in Table 20, page 137.

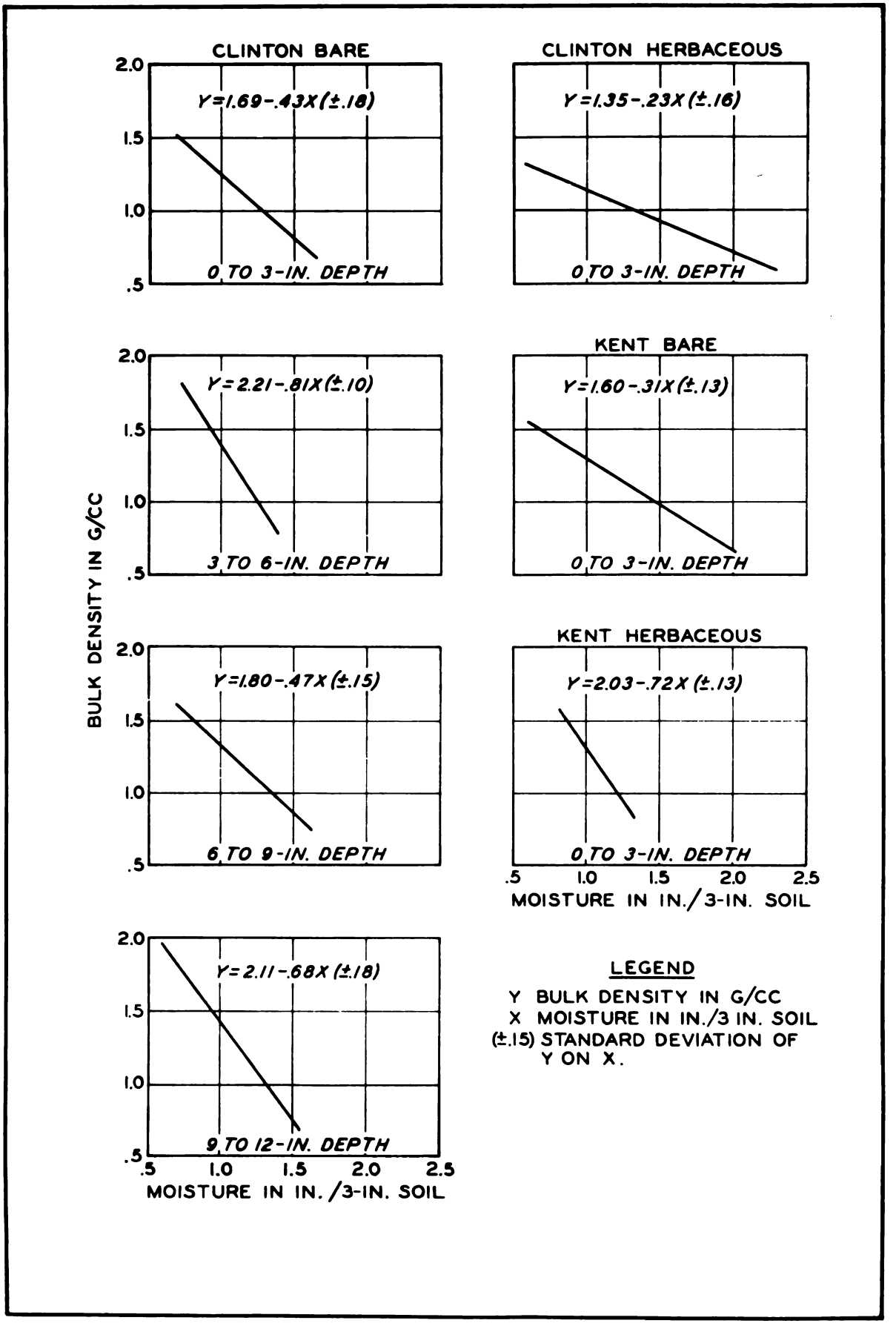

Figure 42. Regressions of bulk density on moisture during freezing

Table 20. Statistics for regression of bulk density (Y) on moisture (X)

Plot	Depth in.	No. of Samples	Regression Equation	Correlation Coefficient	Level of Significance	Std Deviation from Regression
			Kent County			
Bare	0-3	25	Y = 1.60 - 0.31X	-0.551	*	0.13
Herbaceous	0-3	19	Y = 2.03 - 0.72X	-0.501	**	0.13
			Clinton County			
Bare	0-3	25	Y = 1.69 - 0.43X	-0.420	**	0.18
	3-6	21	Y = 2.21 - 0.81X	-0.768	**	0.10
	6-9	19	Y = 1.80 - 0.47X	-0.503	**	0.15
	9-12	15	Y = 2.11 - 0.68X	-0.590	**	0.18
Herbaceous	0-3	19	Y = 1.35 - 0.23X	-0.490	**	0.16

* Significant at 95% level.
** Significant at 99% level.

In each case the standard deviations from the regression indicate that the chances are about two out of three that bulk densities as predicted from moisture will deviate by 0.2 g/cc or less from the actual bulk density.

To provide a uniform basis of comparison, the bulk densities at the saturation (total pore space) level were computed from the regression equations. The calculated bulk density for the frozen soil at saturation was then compared to the bulk density (measured) when the soil was not frozen (Table 21).

In the surface layers the bulk densities during freezing reached nearly the same value in bare plots, 1.22 g/cc in Kent County, and 1.17 g/cc in Clinton County, column 3, Table 21. Unfrozen bulk densities differed by only 0.01 g/cc.

Table 21. Estimation of change in bulk density with freezing at saturation (total pore space) and at maximum observed moisture content

Plot	Depth in.	(1) Total Pore Space in.	(2) Avg Bulk Density g/cc	(3) Calculated Bulk Density After Frozen Total Pore Space	(4) Difference in Bulk Density from Unfrozen g/cc	(5) Calculated Bulk Density at Maximum Observed Moisture g/cc	(6) Maximum Observed Moisture in.
				Kent County			
Bare	0-3	1.22	1.62	1.22	-0.40	1.18	1.36
Herbaceous	0-3	1.16	1.52	1.05	-0.47	1.16	1.21
				Clinton County			
Bare	0-3	1.21	1.61	1.17	-0.44	1.05	1.49
	3-6	1.16	1.71	1.28	-0.43	1.14	1.32
	6-9	1.05	1.82	1.33	-0.49	1.13	1.43
	9-12	1.05	1.79	1.40	-0.39	1.21	1.32
Herbaceous	0-3	1.25	1.54	1.06	-0.48	0.82	2.29

Frozen bulk density in the surface to 3-in. layer of the herbaceous plots was calculated to be 1.05 g/cc in Kent County and 1.06 g/cc in Clinton County. Before freezing bulk densities were 1.52 and 1.54, respectively, for the two plots.

The greater reduction in bulk density of the surface depths of the herbaceous plots than that of the bare plots reflects the greater influence of honeycomb and granular frost, as opposed to the concrete frost, on soil expansion.

Differences in bulk density at saturation both before and after freezing were computed, column 4, Table 21. The differences ranged from 0.39 to 0.49 g/cc.

Theoretical bulk densities were computed from the highest moisture contents observed in the field (column 5, Table 21). With one exception, the surface to 3-in. depth of the Kent County Herbaceous plot, the computed bulk densities were lower than those which would have occurred at saturation (total pore space) with freezing. This substantiates the fact that bulk density during freezing can and does go below the normal where the ground is thawed.

In every case where a significant regression was determined, some of the moisture contents were above the estimated total pore space (Figures 32 and 33, surface to 3-in. depth; Figures 35 and 36, surface to 3- and 3- to 6-in. depths; and Figure 37, surface to 3- and 3- to 6-in. depths). In most cases the values fell above the estimated field maximum moisture content (60-cm moisture tension value).

In those depths where moisture was not related to bulk density, moisture contents were near or below the field maximum moisture content, or bulk densities were within the range of variation. In all the

depths in which significant moisture-bulk density relations were evolved, except the 9- to 12-in. depth of the Clinton County Bare plot, all or most of the bulk densities were outside the range of normal variation.

Discussion. The relationship of moisture to bulk density brings together the findings on moisture and bulk density versus frost depth.

As noted, moisture was not related to frost depth, presumably because all the moisture in a frozen soil depth need not be frozen. However, bulk density changes during freezing were a result of very high moisture contents, which in turn caused an increase in pore space--moisture freezing to ice caused bulk density reductions. Thus bulk density could be related to frost depth.

When regressions of bulk density on moisture were significant some of the moisture contents were above total pore space. This indicates that the normal pore volume was exceeded and hence prior freezing must have resulted in a density reduction.

In the 12- to 15-in. depth of the Clinton County Bare plot and in the 3- to 6-in. depth of the Clinton County Herbaceous plot, most moisture contents during freezing were below the 60-cm tension level, and significant correlations with bulk density were not found (Figures 35 and 36). In the other plots, where most moisture contents during freezing were above the 60-cm tension level, significant relations were developed. It is possible that moisture in the noncapillary pores froze and expanded causing a reduction in bulk density, and that the total pore space value need not be exceeded.

Snowfall and Peak Moisture Contents

Soil moisture contents during "peak" days and water available

to the soil from snowfall and the snowpack appeared related.

"Peak" days were defined as those days when soil moisture content rose above the total pore space value indicated for each plot, Figures 32, 33, 35, and 36.

Table 22 lists the days when moisture contents of the surface layers of the bare and herbaceous plots were above total pore space. The sum of the moisture from snowfall during the period from the last sample plus the water in the snowpack at the sampling preceding the peak day is shown in column 2. Column 3 lists the measured water content of the snowpack on the peak day, and column 4 the difference between columns 2 and 3, i.e. the water unaccounted for. The last five columns are the cumulative changes in water content to 3, 6, 9, 12, and 15 in. below the soil surface since the last sampling before the peak day.

In every instance when water was lost from the snowpack the moisture content of the soil increased. Though the moisture lost from above the soil and that gained by the soil do not necessarily balance, the consistency of the loss-gain relationship may be considered strong evidence that moisture is moving down through the concrete frost.

The number of soil cores frozen, out of four possible per sample, was used as an indication of the areal extent of freezing (Table 13). The Clinton County Bare plot appeared frozen solid (concrete frost) on all but two occasions (February 17 and March 25), when peak moistures occurred. The Clinton County Herbaceous plot was also frozen completely on each peak moisture occasion, and the single "peak" moisture listed for the Kent County Herbaceous plot also coincided with complete freezing. The Kent County Bare plot was completely frozen only on January 11.

Table 22. Inches of water in snowfall, snowpack, and available to soil, with soil moisture changes from previous sample day to day of peak moisture contents

(1) Dates		(2)	(3)	(4)	Change in Moisture in Soil, in. Depth, in.				
Last Sample	Peak Sample	Water in Snowfall Plus Snowpack, in.	Water in Snowpack on Peak Day, in.	Water Lost from Snow Plus Snowpack, in.	0 to 3	0 to 6	0 to 9	0 to 12	0 to 15
				Kent County Bare					
21 Dec	30 Dec	0.66	0.00	0.66	0.28	0.39	0.42	0.47	0.43
7 Jan	11 Jan	0.09	0.00	0.09	0.05	0.13	0.13	0.06	-0.03
21 Jan	26 Jan	0.65	0.59	0.06	0.23	0.17	0.29	0.13	0.19
20 Feb	25 Feb	2.60	2.12	0.48	0.17	0.20	0.31	0.29	0.46
5 Mar	10 Mar	2.32	2.46	0.00	0.42	0.48	0.52	0.50	0.48
17 Mar	23 Mar	2.37	2.23	0.14	0.48	0.64	0.70	0.77	0.84
				Kent County Herbaceous					
16 Feb	20 Feb	2.21	1.90	0.78	0.47	0.44	0.42	0.40	0.40
				Clinton County Bare					
9 Jan	16 Jan	1.94	0.00	1.94	0.26	0.46	0.51	0.69	0.82
23 Jan	20 Jan	0.58	0.05	0.53	0.36	0.19	0.20	0.35	0.27
4 Feb	9 Feb	1.09	0.17	0.92	0.32	0.31	0.57	0.72	0.65
13 Feb	17 Feb	0.69	0.51	0.18	0.10	0.09	0.14	-0.26	-0.25
24 Feb	1 Mar	1.61	0.59	1.02	0.27	0.64	--	0.14	--
21 Mar	25 Mar	0.57	0.58	0.00	0.11	-0.04	0.19	0.17	0.01
				Clinton County Herbaceous					
16 Jan	20 Jan	0.44	0.20	0.24	0.32	0.24	0.05	0.07	0.09
4 Feb	9 Feb	1.22	0.45	0.77	0.24	0.18	0.38	0.33	0.54
1 Mar	11 Mar	1.32	1.14	0.18	0.19	0.07	0.04	-0.13	-0.19
21 Mar	25 Mar	1.85	1.57	0.28	0.68	0.53	0.61	0.63	0.64

Of equal importance is the decline in soil moisture between the peak days. On those plots where frost was of the concrete type, the bare and herbaceous plots, the obvious inference is that moisture is moving through the frozen soil. That this is possible was pointed out in reference to frozen cores in which it was evident that concrete frost was not necessarily nonporous.

Soil Shear Strength Before, During, and After Soil Freezing

Soil shear strength was measured with the cone penetrometer in pounds per square inch (Appendix B).

To make a measurement, the penetrometer was pushed to the top of each depth (i.e. 0, 3, 6, 9, and 12 in. below the soil surface), and the force required to push the cone past that level was recorded as shear strength. Concurrent moisture contents for the surface reading are those occurring in the surface to 3-in. depth; for the 3-in. strength reading, those in the 3- to 6-in. depth; etc. The range of the penetrometer was 0 to 300 psi. Readings of 300 may be over 300 psi, and are lumped as 300 psi or over. Readings were taken whenever time permitted and where the penetrometer could be pushed into the ground with reasonable effort. The degree of freezing determined whether or not readings were obtained.

Strength readings for each 3-in. depth are plotted in Figures 43 through 48. On the Kent County plots and the Clinton County Hardwood plot readings were relatively frequent. However, in the Clinton County Bare and Herbaceous plots, heavy frost prevented cone readings from January to the end of March.

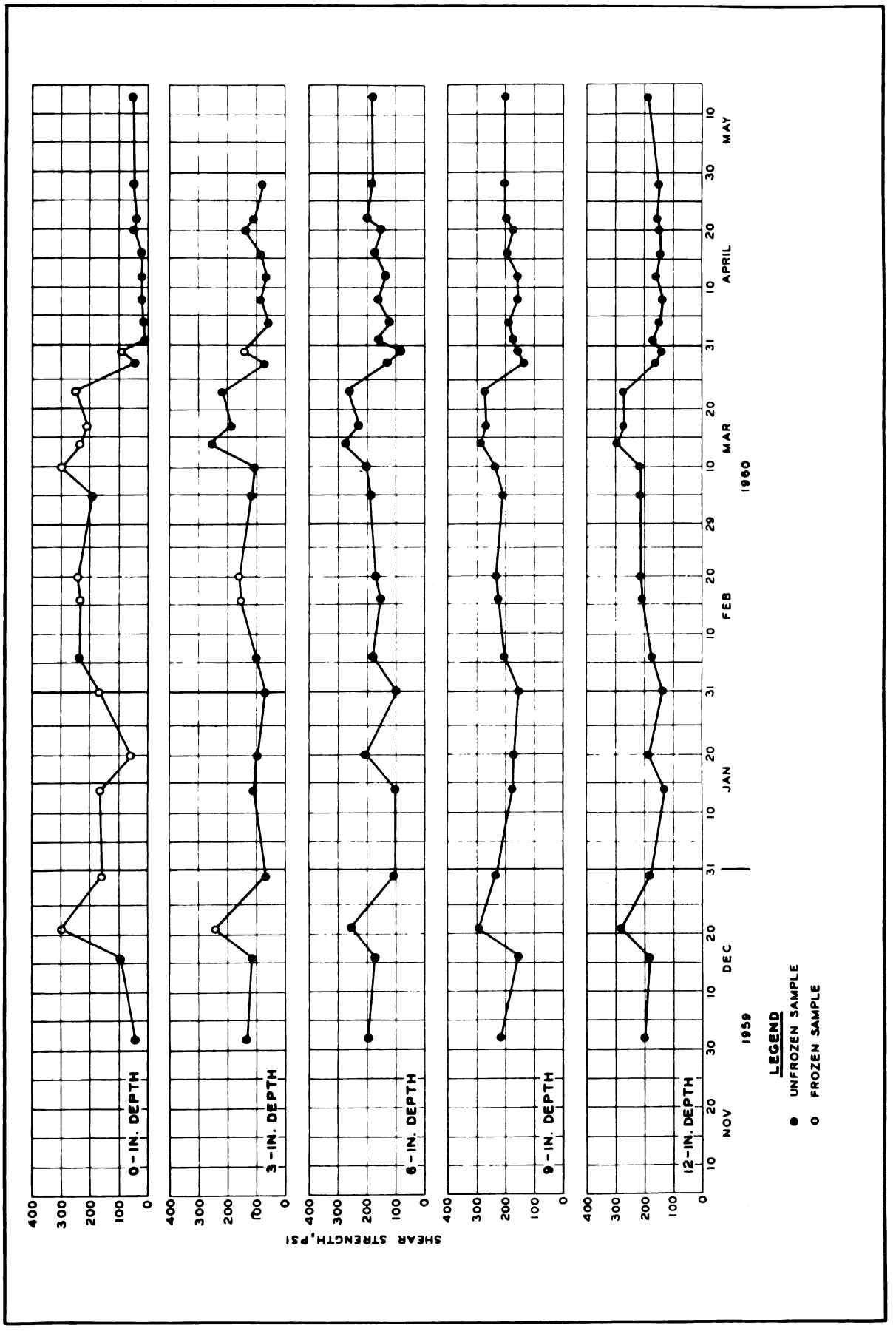

Figure 43. Mean shear strengths, Kent County Bare plot

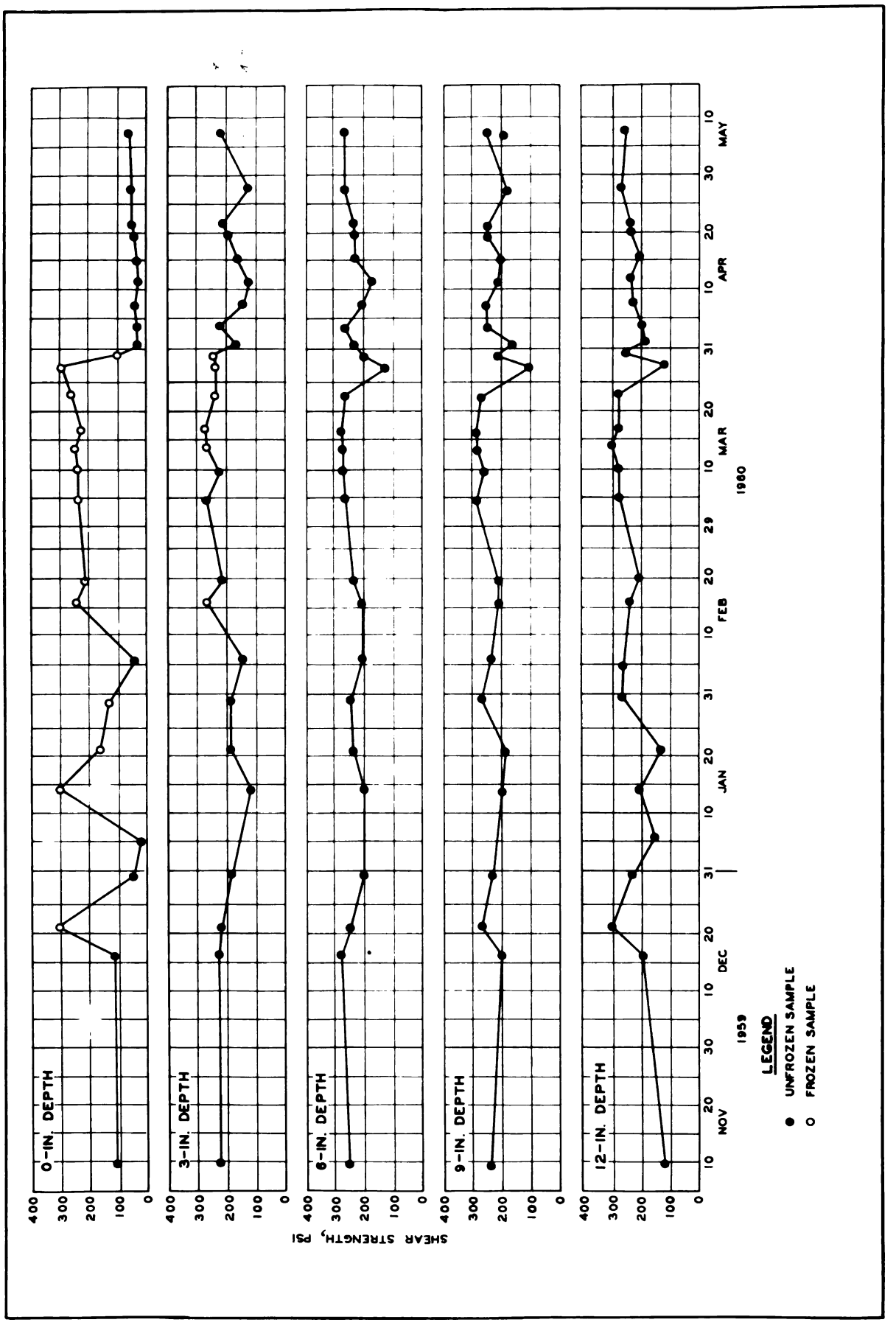

Figure 44. Mean shear strengths, Kent County Herbaceous plot

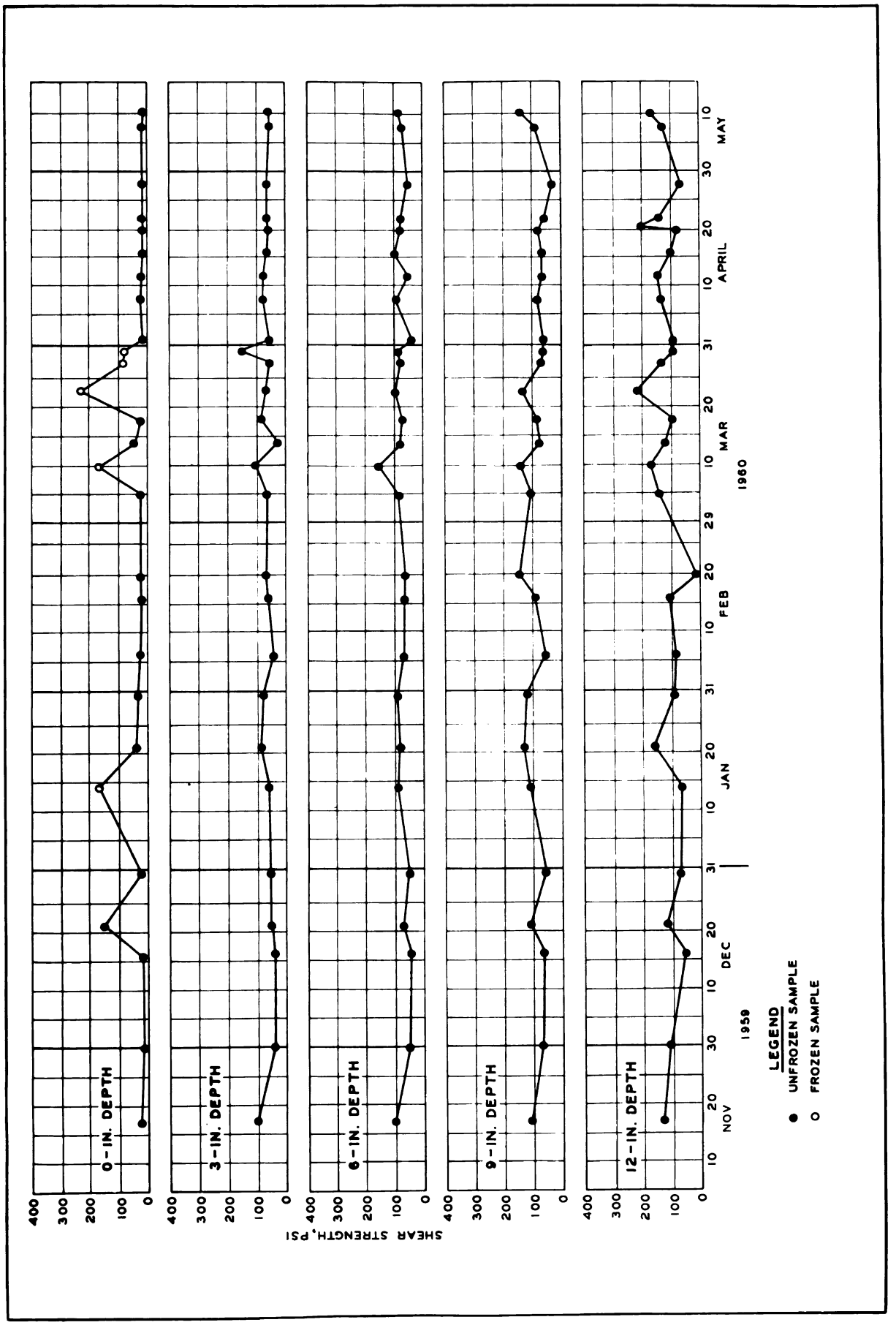

Figure 45. Mean shear strengths, Kent County Hardwood plot

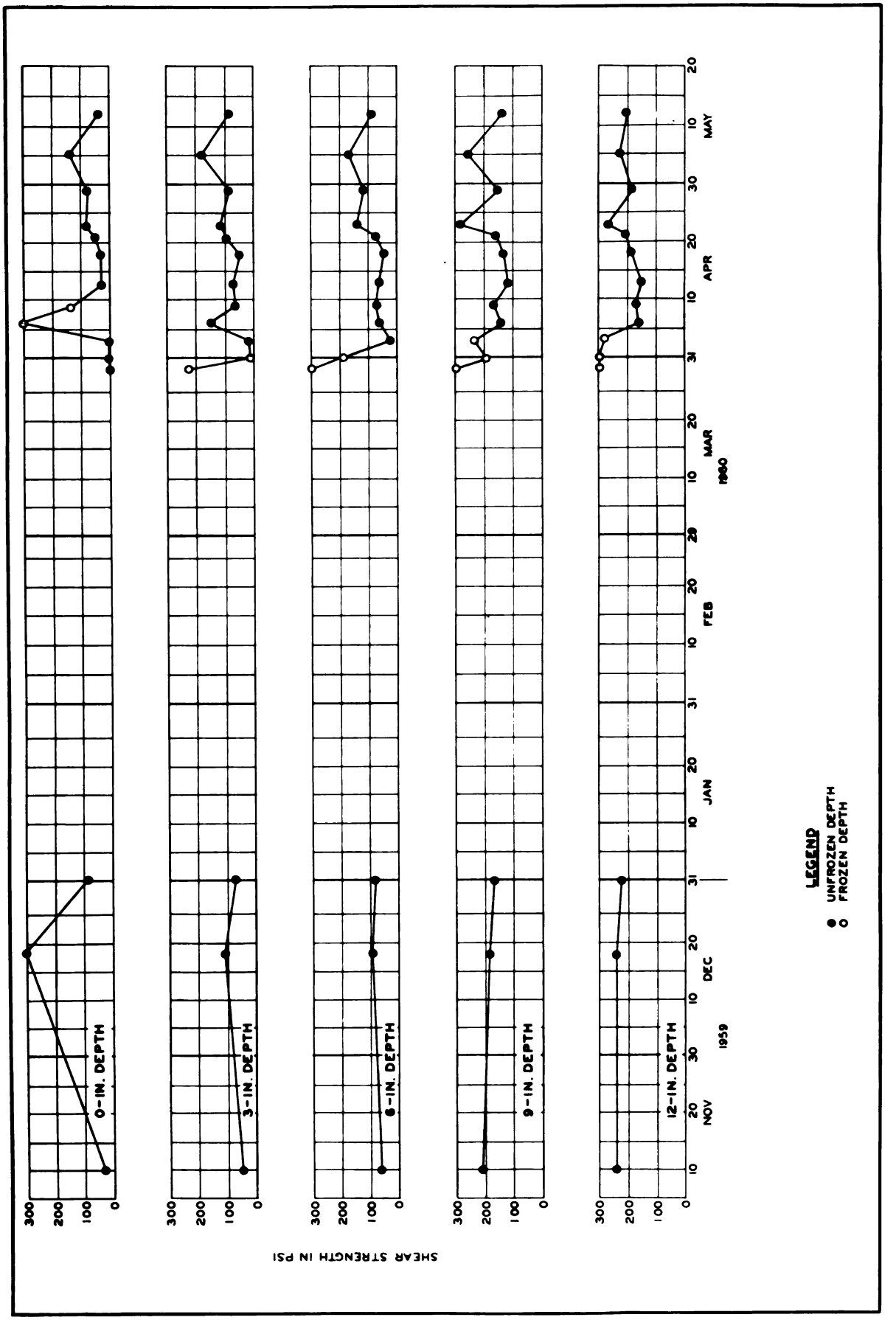

Figure 46. Mean shear strengths, Clinton County Bare plot

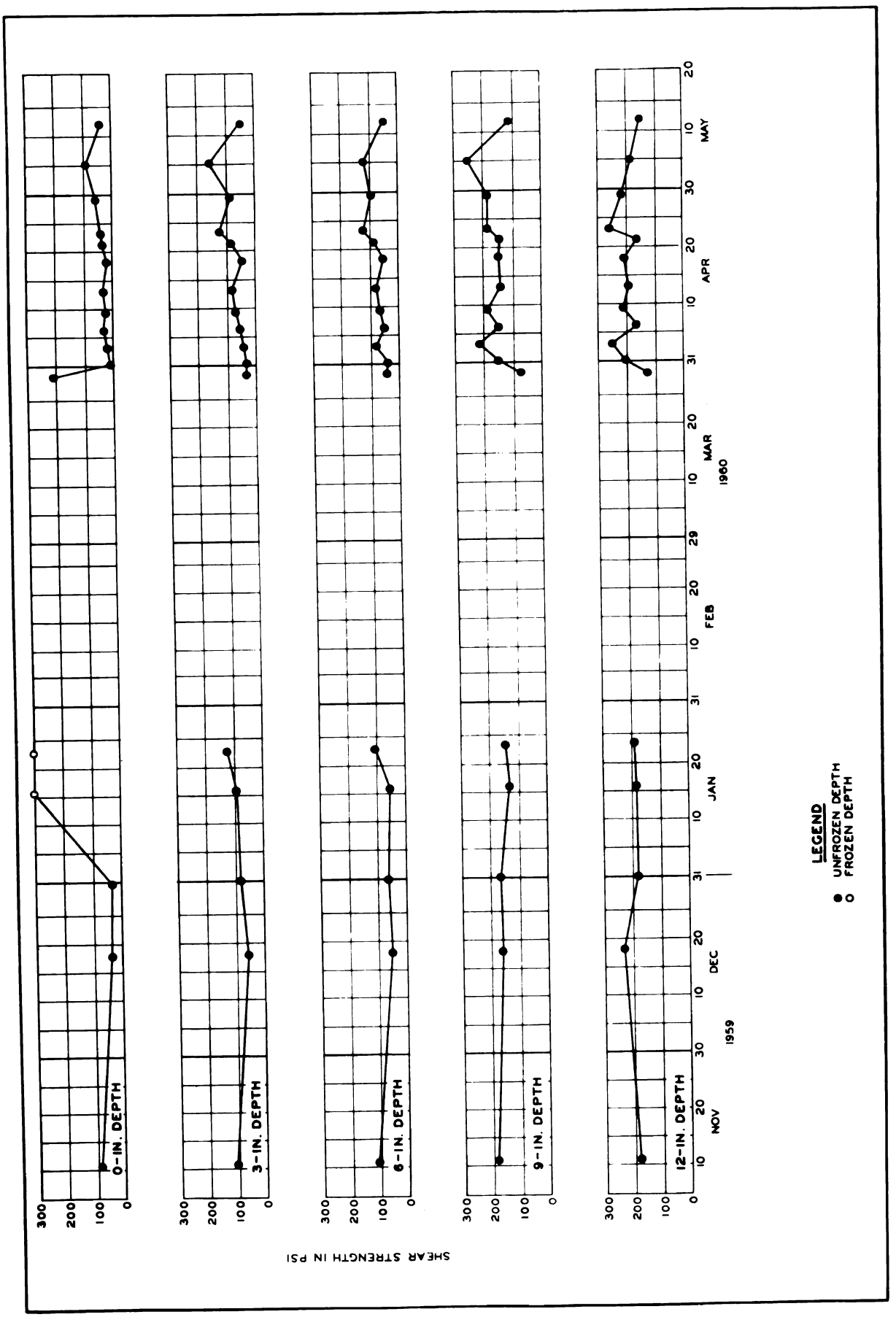

Figure 47. Mean shear strengths, Clinton County Herbaceous plot

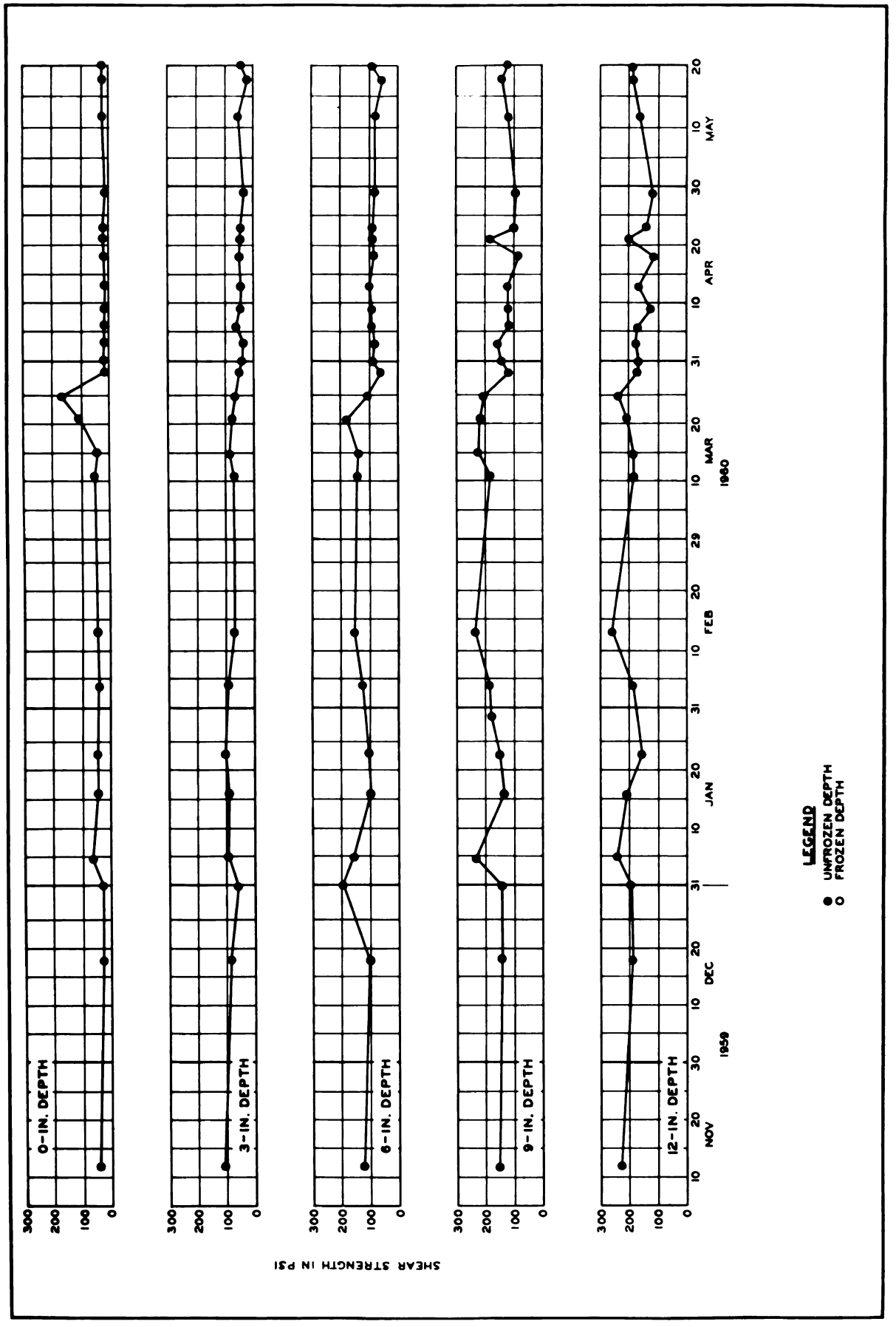

Figure 48. Mean shear strengths, Clinton County Hardwood plot

Rush and Kennedy[11] both found significant inverse linear relationships between shear strength (the measured average of readings in the 6-, 9-, and 12-in. depths) and moisture content for every soil textural class listed in the USDA classification. These relationships were inversely proportional.

In these studies, as in the analysis that follows, moisture content changes were necessarily considered when soil strength changed.

Shear Strength Before Freezing[12]

Kent County plots. Soil freezing was first encountered on December 21 in the herbaceous and bare plots. Freezing was not encountered in the woods until January 14 (Figures 43 and 45, mean data in Appendix A).

Mean soil strengths and corresponding moisture contents are listed in Table 23.

Table 23. Mean shear strengths and moisture contents, averaged for two samplings, before December 21, Kent County

Depth in.	Plot					
	Bare		Herbaceous		Hardwood	
	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.
0	69.70	1.00	105.00	0.79	16.80	1.03
3	126.40	0.95	226.30	0.77	44.30	0.89
6	185.40	0.93	271.30	0.78	50.60	1.12
9	187.10	0.85	220.00	0.74	67.50	0.76
12	190.20	0.90	159.60	0.85	82.50	0.83

11/ In separate office reports to the Army Mobility Research Center, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

12/ Frozen ground was not always found at the points of the shear strength observations on the same sample occasion that it may have been found in a moisture-density core.

Depth for depth the hardwood plot had the lowest strengths, but not necessarily the highest moisture contents; the herbaceous plot, the highest strengths, and except for the 12-in. depth, the lowest moisture contents.

When soil layers are of the same texture, and moisture contents are nearly equal, similar shear strengths would be expected. A comparison of plots in which the depths were alike in moisture content indicated that the hardwood plot always had the lowest strength. This relationship has occurred in other studies at Vicksburg, Mississippi. In general, wooded soils are subject to less use by man and animals, show less compaction, and hence have lower strengths than cultivated soils of the same texture.

Clinton County plots. First freezing in this area was recorded December 18 on the bare plot. The bare, herbaceous, and hardwood plots had been sampled on November 10, 11, and 19, respectively. Corresponding strength and moisture contents appear in Table 24.

Table 24. Mean shear strengths and moisture contents in Clinton County before December 18 (averaged for two samplings)

Depth in.	Plot					
	Bare		Herbaceous		Hardwood	
	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.
0	33.70	1.08	87.50	0.81	43.70	1.17
3	45.00	1.00	108.70	0.87	108.70	1.08
6	62.50	0.94	110.00	0.84	125.00	1.02
9	207.50	0.91	187.50	0.77	158.70	0.91
12	243.70	--	190.00	--	228.70	--

The inverse moisture-strength relation appeared in all plots with the exception of the surface depth of the herbaceous plot.

On December 31 all quadrants were thawed. Extended freezing in

Clinton County did not begin until January. Moisture contents and shear strength for December 31 are listed in Table 25.

Table 25. Mean shear strengths and moisture contents in Clinton County for December 31

Depth in.	Plot					
	Bare		Herbaceous		Hardwood	
	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.
0	88.70	1.15	31.20	1.00	27.50	1.25
3	72.50	0.95	80.00	0.94	62.50	1.09
6	85.00	0.88	60.00	0.83	196.20	1.11
9	170.00	0.78	168.70	0.82	140.00	0.79
12	223.70	0.90	180.00	0.85	201.20	0.85

In comparison with the readings before December 18, there were generally higher shear strengths associated with lower moisture contents. Both strength readings at 0, 3, and 6 in. and moisture contents of the bare plot had increased from the last thaw period (except for the 6-in. depth which had dropped only 0.05 in. of moisture). The bare plot had been plowed three weeks before the first readings, and was undoubtedly less compact on December 18 than when the December 31st measurements were made. Normal soil settling plus the fact that the soil was frozen to 9 in. on December 18 may have caused an increase in compaction yielding higher strengths.

Shear Strength During the Freezing Period

Frozen and thawed conditions did not necessarily coincide on all three plots in either county. Strength data were examined on the basis of the per cent of the plot which was frozen (five classes were used: 0, 25, 50, 75, or 100% frozen), based on the number of unfrozen

samples out of four taken on a sampling day.

Kent County plots. Frozen soil occurred from December 31 to March 30. Of 23 moisture-density samplings 15 strength samplings were made in this period (Table 26). It was assumed that with deep freezing strength readings could not be taken, and occurrence of frozen conditions was based on the 23 samples.

The surface was unfrozen 13.0, 8.7, and 78.3% of the time on the bare, herbaceous, and hardwood plots, respectively (Table 26). Below the surface layer, strength readings could be made about 50% of the time in the herbaceous and bare plots, and on every sampling in the hardwood plot. Complete freezing occurred 30.5% of the time on the bare plot, 43.6% of the time on the herbaceous plot, and never in the hardwood plot.

Generally as the proportion of the frozen area on each plot decreased the mean strength readings did also (Table 26).

Tilled soils (bare plot) and wooded soils are generally less compact in the upper layers than pasture and meadow soils with herbaceous cover. This is revealed in the higher strength readings of the herbaceous plot throughout the frozen season.

When 75% of the area was frozen, strength ranged from 233.7 psi for the surface depth in the hardwood plot to 256.5 psi in the 3-in. depth of the herbaceous plot. An equalizing effect of frost on soil strength is evident.

Although Kent County plots were similar in texture, moisture increased as strength decreased only in the hardwood plot when the soil was unfrozen.

In the hardwood plot the effects of frost on soil compaction,

Table 26. Mean shear strengths and moisture contents when various percentages of plot were frozen, Kent County

Depth in.	Per Cent of Area Frozen														
	100			75			50			25			0		
	Strength psi	Moist. in./ 3 in.	Occur-rence* %	Strength psi	Moist. in./ 3 in.	Occur-rence* %	Strength psi	Moist. in./ 3 in.	Occur-rence* %	Strength psi	Moist. in./ 3 in.	Occur-rence* %	Strength psi	Moist. in./ 3 in.	Occur-rence* %
							Bare								
0	300	1.14	30.5	240.7	1.13	21.7	177.2	1.06	17.4	93.7	1.03	17.4	66.3	1.00	13.0
3				247.5	0.89	8.7	157.9	0.95	13.0	165.6	0.77	8.7	99.7	1.01	39.1
6				240.8	0.94	8.7	261.2	0.86	4.3	230.0	0.78	8.7	154.3	0.93	43.5
9				289.1	0.81	8.7	272.5	0.85	4.3	270.0	0.78	4.3	195.5	0.92	47.8
12				293.7	0.87	8.7	275.0	0.75	4.3	275.0	0.82	4.3	180.7	0.85	47.8
							Herbaceous								
0	300	1.03	43.6	232.8	1.06	34.7	222.5	1.45	4.3	144.3	0.96	8.7	41.8	0.95	8.7
3				256.5	0.82	17.4	238.7	0.69	4.3	238.7	0.76	13.0	185.5	0.80	30.4
6							280.0	0.66	4.3	217.1	0.90	13.0	221.7	0.80	47.8
9							285.0	0.62	4.3	253.7	0.83	13.0	218.9	0.81	47.8
12							275.0	0.68	4.3	280.8	0.77	13.0	212.8	0.84	47.8
							Hardwood								
0				233.7	1.06	4.3	166.8	1.07	8.7	85.7	1.12	8.7	40.2	1.07	78.3
3													69.62	1.04	100.0
6													83.8	0.96	100.0
9													100.8	0.85	100.0
12													115.0	0.82	100.0

* Based on 23 sample occasions.

aggregation, and consistency undoubtedly influenced the strength relations. This is brought out in the surface depth, where strengths were lower during the freezing period (when no frost was in the ground) than before freezing began, although no large differences in moisture were evident.

Clinton County plots. The bare and herbaceous plots show considerable contrast to their Kent County counterparts. Because of frozen ground, no measurements were taken on the bare plot from December 31 to March 25 or on the herbaceous plot from January 28 to March 25. However, it was possible to make measurements through the winter on the hardwood plot.

Samplings were made January 16 and 23 in the herbaceous plot. Mean shear strengths and their respective moisture contents were:

Depth in.	Strength psi	Moisture in./3 in.
0	300.00	1.21
3	104.40	0.94
6	72.60	1.09
9	134.10	0.92
12	185.00	0.82

All quadrants were frozen in the surface depth, accounting for the 300-psi readings.

In the hardwood plot soil strength changed but little over the winter (Figure 48) and average strength and moisture content for January 16 and 23 were:

Depth in.	Strength psi	Moisture in./3 in.
0	42.50	1.30
3	96.70	1.36
6	103.10	0.95
9	143.70	0.97
12	185.00	0.97

Every depth had increased in strength from December 31, with attendant moisture increase, except in the 9-in. depth where both moisture and strength decreased appreciably. No explanation was found for these anomalies. The hardwood and herbaceous plots had similar strengths, except for the frozen surface of the herbaceous plot.

Six additional strength samplings were made when no soil was frozen in the woodlot, but the bare and herbaceous plots were frozen. On one of these occasions there was less than 1 in. of frost in one quadrant, March 21; on a second occasion about 2 in. of frost were found in two quadrants, March 25.

On these consecutive sampling days strength and moisture readings were:

	March 21 Reading		March 25 Reading	
Depth in.	Strength psi	Moisture in./3 in.	Strength psi	Moisture in./3 in.
0	107.50	1.31	168.70	1.34
3	77.50	1.05	70.00	1.30
6	183.70	0.94	110.00	0.96
9	212.50	0.99	211.20	1.04
12	212.50	1.05	243.70	1.41

Again moisture strength relations were obscure. However, the influence of one additional frozen quadrant (on March 25) in the surface depth raised the average shear strength from 107.5 to 168.7 psi.

Shear Strength
After the Freezing Period

The rate at which the soil returns to the strength condition approaching that before continuous freezing is of particular interest.

Kent County plots. In these plots the last day of observed frozen ground was on March 30. Strength values after March 30 to the final sampling dates are shown in Figures 44 to 46.

The bare plot reached its highest strength in the surface and 12-in. depths on May 13, the 3-in. depth on April 20, and the next two depths on April 22 and 28, respectively.

Depth in.	Strength psi
0	53.70
3	133.70
6	201.20
9	203.70
12	192.50

With the exception of the surface reading, the strengths were above that before freezing (before December 21). As noted, most of the high strengths did not occur until 20 days or more after frost left the ground.

The low surface strength may have been a result of reduction in consistency. Moisture had dropped below prefreeze level on April 8 (Figure 32), but the soil strength remained low until May 13. In the other depths strength increase to that before freezing and moisture reduction were closely related.

In the herbaceous plot soil strength never approached that before freezing in the surface depth but soil moisture dropped below prefreeze on April 20. The 3-in. strength value approached the before-freezing level on April 4, but the moisture did not drop below prefreeze content until April 9. In these upper two depths reduction in consistency may have delayed strength return.

The strength pattern in the hardwood plot was fairly uniform during the entire study period, and it is doubtful if soil freezing had any effect.

Clinton County plots. Figure 49 shows the shear strength on the

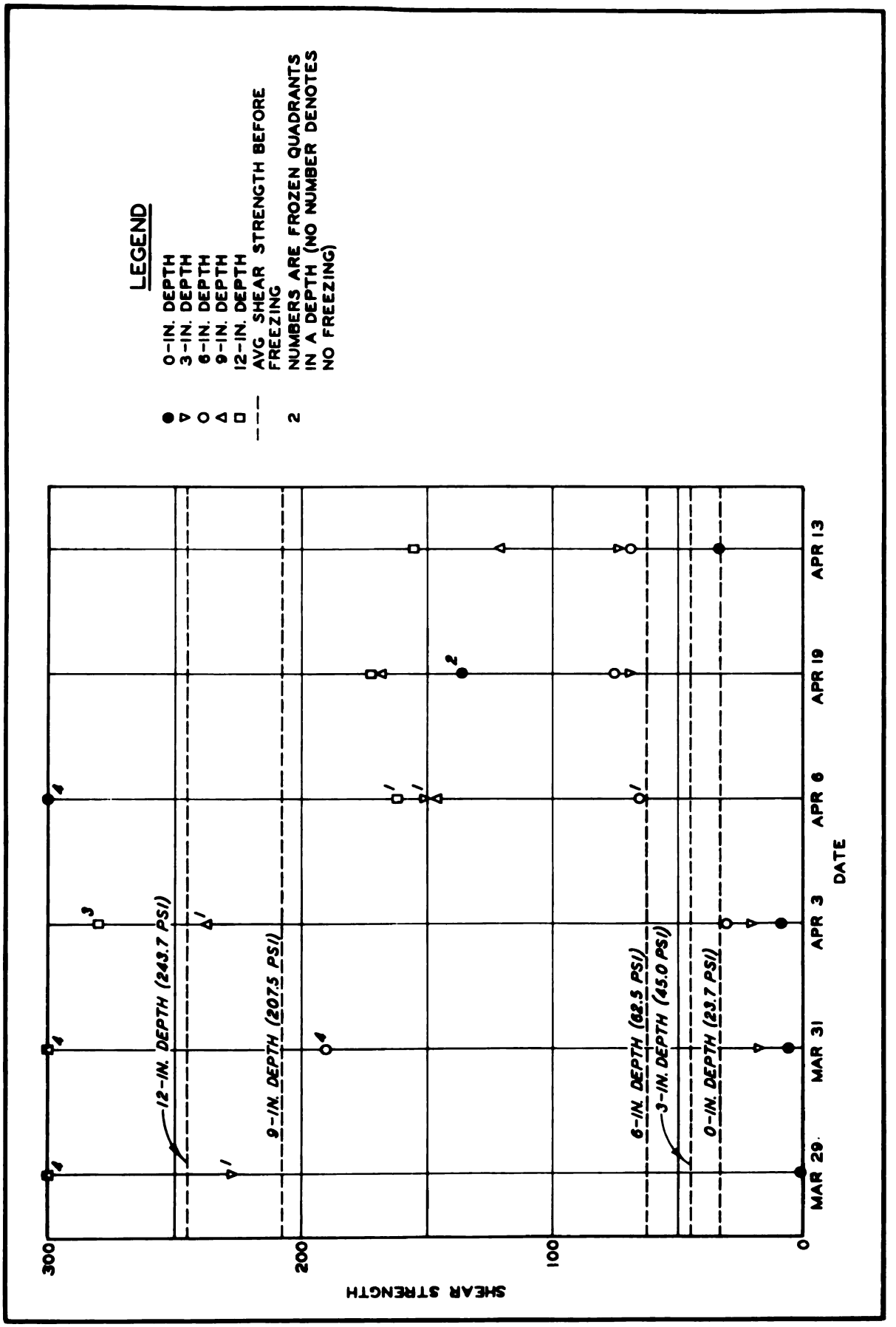

Figure 49. Shear strength pattern for each depth during final thaw, Clinton County Bare plot

bare plot from March 29 to April 13 as well as the strength levels before the first freeze. The effect of freezing can be noted depth for depth.

The surface and 3-in. readings dropped well below their original values (before freezing) until the freeze of April 6 when both went above the original strength. On April 9, when the 3-in. depth had thawed again, and on April 13, when the surface depth had thawed, each depth dropped to approximately the original value. This indicated that the short-term freezing was not as effective in reducing shear strength (soil consistency) as was the extended winter period.

Shear strength at 6, 9, and 12 in. in the bare plot behaved similarly to that at 0 and 3 in.; as soon as most frost disappeared they dropped well below the original strengths.

On the bare plot the return to original strength was almost simultaneous with the return to original moisture. The respective dates of return to prefreeze moisture and strength were:

Depth, in.	Strength	Moisture
0	Apr 13	Apr 18
3	Apr 6	Apr 3
6	Apr 6	Apr 3
9	Apr 23	Apr 23

(No moisture data were available for the 12-in. depth before freezing.)

Thus, in the 3- and 6-in. depths there may have been some reduction in consistency, but in the surface and 12-in. depths the relationship between strength and moisture appeared strong.

In the herbaceous plot the recovery of strength in the surface, 3-in., and 6-in. depths was preceded by the loss of moisture, and consistency was probably the answer. In the 9-in. depth both strength

and moisture returned to prefreeze levels on April 3. Again, no moisture data were available before freezing for the 12-in. depth.

In the hardwood plot there had been no frost since March 25. On this date the strength of each depth was appreciably greater than it was on December 31 (Figure 48). However, the snowpack had not disappeared with the beginning of thaw as it had on the other plots (Table 16). The addition of water from the snowpack (0.76 in. of water on March 29) plus the rain (April 11-20 and subsequently) had not yet permitted return of strength equal to that before freezing when the last sampling was made May 20.

Discussion. The lag in return of strength to the prefreeze level, though moisture contents had become low, has been ascribed to reduction in soil consistency. However, initially after thaw begins the distribution of soil moisture influences strength.

During freezing, water is drawn to ice crystals resulting in dehydration of the soil aggregates, and intimate contact of the soil particles, i.e. increased aggregation.

With thaw, moisture is not immediately distributed through the soil mass, but coats the surface of the aggregates lowering adhesion between them. This greatly reduces shear strength even at the low moisture contents observed.

SUMMARY AND CONCLUSIONS

Vegetation, snow cover, and soil type are known to influence occurrence and depth of frost penetration. In this investigation soil moisture, bulk density, and shear strength regimes were studied, with particular reference to changes occurring in these parameters during freezing and thawing periods.

Regimes were studied on wooded, herbaceous, and bare plots 160 ft square. All plots were located on medium textured soils derived from glacial till. One set of three plots was located in Kent County and one set in Clinton County. Kent County lies in a higher snowbelt.

Influence of Vegetation and Snow on Frozen Soil

Freezing opportunity based on air temperature was similar in both counties.

The ground froze on the bare plot 11 days before the wooded and herbaceous plots in Kent County, and similarly 9 days before in Clinton County. From the beginning to the end of the winter period, frost was found approximately 90% of the time on the bare plots, 72% of the time on the herbaceous plots, and 36% of the time in the woods. The combination of tree cover plus litter in the woods proved to be more effective in reducing frost occurrence than did the grass and legume cover on the herbaceous plots.

When frost was present in Clinton County, it was deeper in the bare than the herbaceous plot, and in the herbaceous than the wooded plot. Snow depths averaged 2.2 times deeper on the herbaceous than the bare plot. In Kent County there was less than 1.5 in. difference in snow

depth between the bare and herbaceous plots. In Kent County snow averaged 3.55 in. deeper on the bare plot, 1.21 in. deeper on the herbaceous plot, and 1.23 in. deeper on the hardwood plot than on the respective plots in Clinton County.

Before the period of continuous snow cover, there was less than 0.4 in. difference in frost depths between plots under similar cover.

Snow effects were manifest in the relations developed between freezing opportunity and frost depth. In Clinton County frost depth was closely correlated with freezing opportunity. Maximum snow depth on the Clinton County bare plot was 4.11 in., on the herbaceous plot 12.12 in., and in the woods 10.81 in.

In Clinton County the herbaceous cover-snow combination was 2.2 times more effective in reducing frost depth than was snow alone, while the vegetation-litter-snow combination was 3.5 times more effective than herbaceous cover and snow.

An over-all comparison of the Kent to Clinton County frost data indicated the effect of snow on the Kent County plots was similar to vegetation alone in Clinton County.

Soil Moisture in the 15-in. Depth

The moisture regime in Kent County did not change appreciably over the winter. Maximum freezing was generally less than 3 in. in any plot. The same relationships held for the Clinton County Hardwood plot.

More freezing occurred in the Clinton County Bare and Herbaceous plots and a general increase in moisture was noted over the freezing period.

On the day when frost left each plot, the moisture content

was highest on those plots with the most snow on the ground.

Soil Moisture and Bulk Density

Moisture-bulk density relationships were quantified and tested by linear regression technique. Bulk density was found to show a significant inverse relationship to frost depth while moisture was not significantly related to frost. However, significant inverse relationships were found between bulk density and moisture during freezing. This indicated a possibility of predicting soil moisture during the freezing period, and up to the time of soil thawing.

Study of soil and snow moisture regimes indicated that moisture moved into the frozen soil profile from the snowpack. Other investigators have demonstrated that water vapor may also move in the soil from warmer to colder regions, and that capillary water moves from unfrozen to frozen regions.

Thus, the movement of moisture into the frozen soil without freezing helps explain why moisture content bears no necessary relation to frost depth.

Bulk density reductions are a product of moisture movement to the frozen zone, freezing and expanding, allowing for more moisture movement, with subsequent freezing and expanding, etc. Reductions in bulk density occurred only in frozen soil, allowing the development of quantitative expressions between bulk density and moisture content, and bulk density and frost depth.

Shear Strength

In the wooded plots little variation occurred in soil shear

strength, presumably because no appreciable soil freezing occurred. In plots where freezing and thawing occurred, the soil showed lower strength during the thaws than had been measured before initial freezing set in.

Explanation for these low strengths is associated with soil moisture distribution. During freezing, water is drawn to ice crystals resulting in dehydration of the soil aggregates, and intimate contact of the soil particles, i.e. increased aggregation.

With thaw, moisture is not immediately distributed through the soil mass, but coats the surface of the aggregates lowering adhesion between them. This greatly reduces shear strength even at the low moisture contents observed.

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APPENDIX A: TABLES

Appendix Table A1. Basal area and number of stems by species (based on 50% cruise), Kent County Hardwood plot

Diameter Class, in.	Black Cherry		Red Oak		Soft Maple		White Ash		Hard Maple		Sassafras		Chinquapin Oak	
	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft
0-1.0														
1.1-2.0									1	0.046				
2.1-3.0	3	0.129	2	0.083	12	0.440	1	0.067						
3.1-4.0	7	0.497	3	0.185	8	0.508								
4.1-5.0	2	0.202	1	0.120	4	0.414			1	0.110				
5.1-6.0	2	0.338	-	-	1	0.190								
6.1-7.0	-	-	2	0.412	2	0.475								
7.1-8.0	1	0.282	2	0.607	1	0.290								
8.1-9.0	2	0.724	-	-	-	-								
9.1-10.0	1	0.461	2	1.109	2	1.015	1	0.562						
10.1-11.0	1	0.612	-	-	-	-					1	0.648		
11.1-12.0	1	0.684	1	0.772	1	0.772								
12.1-13.0			1	0.812	-	-	1	0.811						
13.1-14.0			2	1.990	1	0.979	1	1.023					1	1.040
14.1-15.0			1	1.178	-	-	1	1.620						
15.1-16.0			-	-	1	1.396								
16.1-17.0			3	4.488										
17.1-18.0			-	-										
18.1-19.0			1	1.906										
Total	20	3.929	21	13.662	33	6.479	5	4.083	2	0.156	1	0.648	1	1.040
Total/acre	68	13.371	71	46.493	112	22.049	17	13.895	7	0.531	3	2.205	3	3.539

Total basal area per acre - 102.083 sq ft
Total number stems per acre - 281
Average diameter - 8.2 in.

Appendix Table A2. Basal area and number of stems by species (based on 50% cruise), Clinton County Hardwood plot

Diameter Class, in.	Slippery Elm		Red Oak		Shagbark Hickory		Soft Maple		Basswood		Green Ash		Swamp White Oak	
	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft
0-1.0														
1.1-2.0														
2.1-3.0	7	0.302	2	0.089	5	0.169	7	0.258	6	0.221	1	0.046	2	0.080
3.1-4.0	5	0.361	4	0.304	4	0.320	1	0.067	2	0.119	2	0.143		
4.1-5.0	6	0.666	4	0.413	3	0.342	2	0.223			5	0.523	4	0.444
5.1-6.0	6	0.974	5	0.825			3	0.452	4	0.600				
6.1-7.0	3	0.698	6	1.342			3	0.715			2	0.446	1	0.216
7.1-8.0	1	0.275	5	1.496	1	0.323	2	0.573						
8.1-9.0			4	1.606	1	0.375								
9.1-10.0	1	0.534	1	0.513										
10.1-11.0														
11.1-12.0														
12.1-13.0														
13.1-14.0														
14.1-15.0														
15.1-16.0														
16.1-17.0														
17.1-18.0														
18.1-19.0														
Total	29	3.810	28	6.588	14	1.529	18	2.288	12	0.940	10	1.158	7	0.740
Total/acre	99	12.966	95	22.420	48	5.203	61	7.786	41	3.199	34	3.941	24	2.518

	Pignut Hickory		White Ash		Hard Maple		Big-Toothed Aspen		White Oak		Black Cherry	
	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft	No. Stems	BA sq ft
2.1-3.0	2	0.072	1	0.040	1	0.031						
3.1-4.0	3	0.175	1	0.056							1	0.079
4.1-5.0	2	0.207	2	0.207								
5.1-6.0	1	0.183	1	0.153							1	0.183
6.1-7.0			2	0.400								
7.1-8.0			1	0.283			1	0.283				
8.1-9.0												
9.1-10.0									1	0.442		
10.1-11.0												
11.1-12.0									1	0.759		
12.1-13.0												
13.1-14.0												
14.1-15.0												
15.1-16.0												
16.1-17.0												
17.1-18.0									1	1.707		
Total	8	0.637	8	1.139	1	0.031	1	0.283	3	2.908	2	0.267
Total/acre	27	2.168	27	3.876	3	0.105	3	0.963	10	9.896	7	0.909

Total basal area per acre - 76.010
Total number trees per acre - 479
Average diameter - 5.4 in.

Appendix Table A3. Daily mean air temperatures, deg F

	Kent County						Clinton County					
Day	Nov	Dec	Jan	Feb	Mar	Apr	Nov	Dec	Jan	Feb	Mar	Apr
1	47.0	34.5	21.0	30.5	18.0	40.5	46.5	35.0	20.5	23.0	13.5	40.0
2	38.0	32.5	30.5	17.5	14.5	50.0	33.5	35.5	33.0	17.0	13.0	52.0
3	42.0	41.0	32.5	21.5	19.5	51.0	37.5	40.5	28.5	19.5	15.5	42.0
4	45.5	42.0	19.5	21.5	16.0	37.5	51.0	42.5	18.5	21.0	13.0	35.0
5	51.0	38.5	13.0	32.0	18.0	31.5	53.0	38.0	14.5	36.5	14.5	30.5
6	39.5	32.0	19.0	34.0	13.0	34.0	32.0	31.5	17.0	31.5	13.0	29.0
7	31.0	27.0	26.0	29.5	21.0	39.5	30.5	29.0	31.5	28.0	15.0	40.5
8	35.0	33.0	29.0	29.0	16.5	36.0	34.0	32.5	24.5	31.0	14.0	34.5
9	36.5	34.0	31.5	32.0	16.0	32.0	38.0	34.0	25.5	31.0	13.0	32.0
10	47.0	35.0	34.0	30.5	22.5	31.5	48.0	35.0	30.5	29.0	15.5	32.5
11	47.5	36.0	24.5	21.5	16.5	37.5	39.0	39.5	25.0	23.5	9.0	43.0
12	28.5	35.5	32.0	24.5	19.0	53.5	26.5	37.0	39.5	16.5	14.0	53.5
13	27.5	32.0	35.0	16.0	19.0	61.5	29.5	31.0	35.5	13.5	15.0	61.5
14	31.5	33.0	33.5	16.5	24.0	65.0	25.5	32.0	32.5	17.0	21.5	60.0
15	24.0	39.0	27.5	23.0	23.0	57.5	25.0	38.5	27.0	21.5	18.5	57.0
16	30.5	42.0	15.0	34.0	26.0	57.5	28.5	45.0	24.5	33.5	24.5	61.5
17	20.0	36.5	16.5	35.0	29.5	58.0	13.5	34.0	22.5	31.0	29.5	48.0
18	21.0	30.5	25.5	30.5	30.5	42.0	19.0	31.5	27.5	22.5	29.5	38.5
19	29.5	27.0	26.0	22.0	29.0	43.5	27.5	26.5	26.5	21.0	26.0	43.0
20	23.0	23.5	23.5	26.0	27.0	58.0	25.0	22.0	21.5	23.5	23.0	57.5
21	33.0	25.5	18.0	25.0	20.5	61.5	32.0	22.0	17.5	25.0	18.0	58.0
22	34.0	22.0	19.0	30.5	26.5	64.5	41.5	19.5	21.5	19.0	22.0	64.5
23	41.5	23.0	27.0	24.5	18.5	70.5	45.5	23.5	21.5	17.0	18.0	73.0
24	35.0	27.0	23.0	18.5	23.5	69.5	35.0	29.5	17.5	14.5	19.0	72.0
25	29.5	29.5	20.5	16.0	14.5	62.5	25.5	32.5	18.0	16.0	12.0	56.5
26	29.0	35.0	21.5	28.0	22.5	50.5	26.0	43.0	22.0	26.0	25.5	48.5
27	29.5	44.0	26.5	26.5	38.5	46.0	28.5	51.0	29.0	21.5	36.0	47.5
28	28.0	41.0	32.5	23.0	42.0	46.5	28.5	40.0	32.0	21.0	39.5	47.0
29	27.5	27.0	33.0	20.5	48.0	53.5	26.0	23.5	32.0	16.0	51.5	52.5
30	30.0	22.0	32.5		52.0	51.5	29.5	20.0	32.0		53.0	49.5
31		20.0	28.0		39.5			18.5	31.5		36.5	

Appendix Table A4. Daily precipitation in inches of water*

Day	Kent County							Clinton County						
	Nov	Dec	Jan	Feb	Mar	Apr	May	Nov	Dec	Jan	Feb	Mar	Apr	May
1				0.27S	TS				0.17S				T	T
2			TS	0.30S	TS				T	0.04S	0.01	TS	T	0.04
3			TS	0.25S	0.04S					0.05S		0.16S		
4			0.1S	0.10S						0.01S	0.05	0.01S	TS	
5		0.20S	TS	0.05S		0.05S			0.35S	0.01S	0.45	0.01S	TS	T
6		0.25S	TS						0.11S	TS	0.32S	T	0.05S	0.67
7			TS	0.55S	TS				TS	TS	TS	0.05	0.01S	0.07
8		0.41S			0.44S				TS	TS	TS		0.02S	
9				0.30S		0.36				TS	0.11S		[illegible]	0.40
10	TS			1.0S						T	0.72S		TS	0.10
11		0.57S		TS		0.40		TS	0.58		0.05S		0.13	0.05
12	0.31S	0.47S	0.85S	TS				0.16S	0.02	1.36	0.02S			0.06
13	0.46S		0.10S					0.61S		0.25	TS	TS	T	0.02
14			TS		0.66S	0.50		0.24S		TS	TS	TS	0.30	
15	TS		0.8S		0.47S	0.10	No data			0.43S	TS		0.67	
16								TS		TS	TS	0.13S	T	0.05
17	TS	T	0.05S	0.36S	0.05S	0.18S		0.04S		TS	0.07S	0.09S	0.36	0.37
18		T	0.18S			0.05		TS		0.34S	T	0.01S	T	
19	TS	T			1.24S	0.54				0.05S	T	TS		
20								0.13S	TS	TS	T	TS		
21				0.07S					TS	0.01S	0.22S	0.05S	0.03	
22				0.50S				0.02S		0.03S	0.07S	0.06S	0.02	
23	0.34S	0.06S		0.25S		No data		T	0.05S	0.02S	TS	T		
24	0.43S	T		0.40S				0.01S	0.10S	0.01S		0.11S	0.02	
25	0.02S	T	0.10S					0.16S	0.01	0.03S	0.44S	0.01	0.80	
26		TS						0.02S	0.02	0.07S	0.09S	0.01S	0.07	
27		0.03S	0.10S	0.42S				T	0.16	0.15S	TS	TS		
28	0.04S			TS				0.04S	0.51		TS	T		
29		1.3		TS	0.30S			TS	0.12S	0.01S	0.03S	0.02	T	
30	0.22S	TS			0.30S			0.01S	0.02S			0.20	0.33	
31			0.25S									0.01		

Note: S - snow
T - < 0.01 inches of water.
* Kent County data from recording rain gage on herbaceous plot. Clinton County data from Capitol City Airport Weather Station, Lansing, Michigan.

Appendix Table A5. Mean moisture in three inches of soil

Date	Depth, in. 0 to 3	3 to 6	6 to 9	9 to 12	12 to 15
Kent County Bare					
1 Dec 59	1.09	0.92	0.96	0.73	--
10 Dec 59	0.92	0.98	0.90	0.98	0.90
16 Dec 59	1.00	0.95	0.94	0.76	0.72
21 Dec 59	1.00	0.88	1.01	0.78	0.89
30 Dec 59	1.28	0.99	1.04	0.83	0.85
2 Jan 60	1.07	0.97	0.85	0.84	0.90
7 Jan 60	0.96	0.95	0.87	0.89	0.90
11 Jan 60	1.01	1.03	0.87	0.82	0.81
14 Jan 60	1.00	1.04	0.86	0.89	0.84
19 Jan 60	2.07	1.08	1.01	0.92	0.84
21 Jan 60	1.11	1.04	0.91	0.93	0.71
26 Jan 60	1.34	0.98	1.03	0.77	0.77
30 Jan 60	1.07	1.08	0.96	0.97	0.84
3 Feb 60	0.98	0.92	0.86	0.83	0.87
6 Feb 60	1.03	0.97	1.10	0.95	0.90
12 Feb 60	1.15	1.02	0.83	0.89	0.98
16 Feb 60	1.01	0.96	0.89	0.85	0.89
20 Feb 60	1.10	0.97	0.89	0.81	0.91
25 Feb 60	1.27	1.00	1.00	0.79	1.08
5 Mar 60	0.86	0.92	0.88	0.86	0.87
10 Mar 60	1.28	0.98	0.92	0.84	0.85
14 Mar 60	1.09	0.90	0.87	0.85	0.85
17 Mar 60	0.88	0.77	0.80	0.78	0.75
23 Mar 60	1.36	0.93	0.86	0.85	0.82
28 Mar 60	1.03	0.98	0.95	0.99	0.82
30 Mar 60	0.76	0.76	0.76	1.10	0.85
1 Apr 60	1.13	1.00	0.96	0.89	0.94
8 Apr 60	0.92	0.98	0.93	1.30	0.95
12 Apr 60	0.97	0.95	0.87	0.83	0.90
16 Apr 60	0.92	0.95	0.83	0.86	0.84
20 Apr 60	0.51	0.53	0.57	0.54	0.50
22 Apr 60	0.86	0.83	0.76	0.80	0.84
28 Apr 60	0.94	0.86	0.81	0.80	0.98
13 May 60	0.97	0.90	0.85	0.86	0.84
Kent County Herbaceous					
1 Dec 59	0.72	0.72	0.80	0.73	--
10 Dec 59	0.82	0.81	0.79	0.80	0.91
16 Dec 59	0.76	0.73	0.78	0.68	0.79
21 Dec 59	0.99	0.74	1.02	0.85	0.63
30 Dec 59	0.94	0.82	0.83	0.85	0.83
2 Jan 60	0.95	0.81	0.78	0.82	0.83
7 Jan 60	1.00	1.08	0.73	0.66	0.73
11 Jan 60	1.20	0.65	0.75	0.73	0.79
14 Jan 60	1.06	0.81	0.79	0.78	0.83
19 Jan 60	--	--	--	--	--
21 Jan 60	0.91	0.77	0.94	0.78	0.91
26 Jan 60	1.11	0.82	0.80	0.84	0.87
30 Jan 60	1.01	0.79	0.81	0.52	0.77
3 Feb 60	0.87	0.76	0.77	0.69	0.74
6 Feb 60	0.97	0.86	0.78	0.94	0.92
12 Feb 60	0.98	0.88	0.92	0.92	0.90
16 Feb 60	0.98	0.79	0.81	0.83	0.83
20 Feb 60	1.20	0.76	0.79	0.81	0.83
25 Feb 60	0.95	1.07	0.88	0.80	0.84
5 Mar 60	1.13	0.78	0.79	0.82	0.82
10 Mar 60	1.09	0.74	0.77	0.82	1.09
14 Mar 60	1.02	0.72	0.72	1.17	0.71
17 Mar 60	1.06	0.90	0.66	0.62	0.68
23 Mar 60	1.21	0.69	0.76	0.74	0.74
28 Mar 60	1.07	0.87	0.85	0.71	0.83
30 Mar 60	0.96	0.80	0.86	0.82	0.85
1 Apr 60	0.98	0.86	0.88	0.85	0.87
8 Apr 60	0.84	0.71	0.79	0.75	0.77
12 Apr 60	0.89	0.83	0.81	0.82	0.79
16 Apr 60	0.96	0.80	0.75	0.75	0.73
20 Apr 60	0.56	0.57	0.61	0.55	0.71
22 Apr 60	0.71	0.73	0.83	0.77	0.76
27 Apr 60	--	--	--	--	--
28 Apr 60	0.79	0.72	0.78	0.87	0.83
13 May 60	0.80	0.87	0.78	0.85	0.82
Kent County Hardwood					
1 Dec 59	0.95	0.73	0.78	0.71	--
10 Dec 59	1.08	1.02	1.00	0.85	0.82
16 Dec 59	0.99	0.77	1.25	0.68	0.85
21 Dec 59	0.96	1.23	0.97	0.75	0.78
30 Dec 59	1.13	1.09	0.96	0.87	0.84
2 Jan 60	1.14	0.99	0.91	0.87	0.80
7 Jan 60	1.09	1.26	0.94	0.86	0.77
11 Jan 60	1.00	0.93	0.87	0.81	0.78
14 Jan 60	1.10	1.04	0.96	0.88	0.85
19 Jan 60	--	--	--	--	--
21 Jan 60	1.14	0.99	1.00	0.85	0.77
26 Jan 60	1.13	1.05	0.87	0.84	0.99
30 Jan 60	1.10	0.96	0.86	0.85	0.83
3 Feb 60	1.00	0.97	0.86	0.76	0.96
6 Feb 60	0.93	1.22	0.97	0.97	0.88
12 Feb 60	1.18	1.05	0.93	0.89	0.69
16 Feb 60	1.08	1.06	1.50	0.92	0.89
20 Feb 60	1.10	0.89	0.96	0.83	0.85
25 Feb 60	1.39	1.02	0.89	0.85	0.74
5 Mar 60	1.05	1.05	0.87	0.81	0.77
10 Mar 60	1.15	1.05	0.89	0.85	0.77
14 Mar 60	1.07	0.99	0.92	0.89	0.78
15 Mar 60	1.09	0.96	0.85	0.83	0.76
23 Mar 60	1.06	0.99	0.85	0.84	0.76
28 Mar 60	1.05	1.14	0.88	0.83	0.81
30 Mar 60	1.19	0.97	0.91	0.82	0.90
1 Apr 60	1.30	1.04	0.95	1.10	0.83
8 Apr 60	1.17	0.99	0.94	0.81	0.87
12 Apr 60	--	--	--	--	--
16 Apr 60	1.11	1.06	0.91	1.26	0.83
20 Apr 60	0.96	0.85	0.80	0.72	0.79
22 Apr 60	1.10	0.99	0.91	0.78	0.81
27 Apr 60	--	--	--	--	--
28 Apr 60	1.12	1.06	0.96	0.86	0.85
13 May 60	1.13	1.07	0.87	0.86	0.83
20 May 60	1.29	1.07	0.98	0.89	0.85
Clinton County Bare					
10 Nov 59	0.98	1.00	0.65	0.60	--
9 Dec 59	--	--	--	--	--
14 Dec 59	1.09	0.93	0.93	0.88	0.95
18 Dec 59	0.91	1.16	0.87	0.83	0.85
23 Dec 59	0.95	0.97	0.77	0.73	0.79
31 Dec 59	1.15	0.95	0.88	0.78	0.90
5 Jan 60	1.02	1.19	0.71	0.81	0.86
9 Jan 60	0.97	0.96	0.82	0.70	0.76
16 Jan 60	1.23	1.16	0.93	0.82	0.89
20 Jan 60	1.23	0.98	1.03	0.72	0.78
23 Jan 60	1.11	0.93	0.85	0.63	0.83
28 Jan 60	1.47	0.76	0.86	0.78	0.75
2 Feb 60	1.49	1.17	1.07	0.86	0.84
4 Feb 60	1.06	1.08	1.17	0.89	0.80
9 Feb 60	1.38	1.07	1.43	1.04	0.73
13 Feb 60	1.39	1.04	1.02	1.11	0.75
17 Feb 60	1.49	1.03	1.07	0.71	0.76
24 Feb 60	1.22	0.95	--	1.18	--
1 Mar 60	1.49	1.32	1.35	1.32	0.75
8 Mar 60	1.40	1.17	1.21	0.96	0.86
11 Mar 60	1.33	1.03	1.18	0.92	--
15 Mar 60	0.88	0.90	1.06	--	0.76
21 Mar 60	1.22	1.16	1.01	0.98	0.78
24 Mar 60	--	--	--	--	--
25 Mar 60	1.33	1.08	1.16	0.96	0.62
29 Mar 60	1.10	1.02	1.09	--	0.86
31 Mar 60	0.82	0.73	0.83	0.80	0.74
3 Apr 60	0.65	0.62	0.88	0.66	0.66
6 Apr 60	1.06	0.97	0.91	0.88	0.89
9 Apr 60	1.06	0.91	1.00	0.96	0.86
13 Apr 60	--	--	--	--	--
18 Apr 60	0.59	1.03	0.66	0.59	0.63
21 Apr 60	0.79	0.75	0.89	0.67	0.88
23 Apr 60	0.73	0.79	0.82	0.75	0.81
27 Apr 60	--	--	--	--	--
29 Apr 60	0.79	0.82	0.81	0.77	0.81
5 May 60	0.61	0.74	0.80	0.85	0.88
12 May 60	0.83	0.79	0.74	0.83	0.79
20 May 60	--	--	--	--	--
Clinton County Herbaceous					
11 Nov 59	0.81	0.87	0.84	0.77	--
9 Dec 59	--	--	--	--	--
14 Dec 59	0.97	0.94	0.95	0.91	0.81
18 Dec 59	0.91	0.92	0.87	0.84	0.86
23 Dec 59	0.93	0.72	0.81	0.77	0.86
31 Dec 59	1.00	0.94	0.83	0.82	0.85
5 Jan 60	0.88	0.84	0.95	0.91	0.74
9 Jan 60	0.97	0.59	0.82	0.86	0.82
16 Jan 60	1.08	0.96	1.08	0.84	0.81
20 Jan 60	1.40	0.88	0.89	0.72	0.74
23 Jan 60	1.34	0.93	1.10	1.00	0.83
28 Jan 60	1.08	0.93	0.85	0.81	0.84
2 Feb 60	1.77	0.99	0.84	0.80	0.77
4 Feb 60	1.17	0.96	0.85	0.84	0.74
9 Feb 60	1.41	0.90	1.03	0.79	0.95
13 Feb 60	1.42	0.95	1.16	0.89	0.90
17 Feb 60	1.40	1.05	0.86	0.82	0.88
24 Feb 60	1.53	1.05	0.83	0.73	1.03
1 Mar 60	1.69	1.04	0.86	0.89	0.85
8 Mar 60	1.81	1.28	0.76	0.86	0.81
11 Mar 60	1.88	0.92	0.75	0.80	0.79
15 Mar 60	1.07	0.98	0.91	0.88	0.99
21 Mar 60	1.61	1.12	0.78	0.75	0.76
24 Mar 60	--	--	--	--	--
25 Mar 60	2.29	0.97	0.86	0.77	0.77
29 Mar 60	0.98	1.09	0.98	0.86	1.02
31 Mar 60	0.95	0.83	1.02	0.65	0.72
3 Apr 60	0.87	0.74	0.57	0.56	0.57
6 Apr 60	--	--	--	--	--
9 Apr 60	1.00	0.94	0.85	0.78	0.80
13 Apr 60	0.83	1.07	0.84	0.84	0.79
18 Apr 60	0.72	0.84	0.68	0.72	0.67
21 Apr 60	0.97	0.89	0.85	0.80	0.86
23 Apr 60	0.87	0.80	0.83	0.80	0.79
27 Apr 60	--	--	--	--	--
29 Apr 60	0.87	0.83	0.77	0.78	0.80
5 May 60	0.75	0.76	0.77	0.71	0.80
12 May 60	0.93	0.84	0.83	0.80	0.77
20 May 60	--	--	--	--	--
Clinton County Hardwood					
19 Nov 59	1.17	1.08	1.02	0.91	--
9 Dec 59	--	--	--	--	--
14 Dec 59	1.39	0.96	0.90	1.07	0.95
18 Dec 59	1.21	1.20	0.99	0.97	1.05
23 Dec 59	0.91	1.15	1.06	1.09	0.96
31 Dec 59	1.25	1.09	1.11	0.79	0.85
5 Jan 60	1.25	1.12	0.94	0.93	0.94
9 Jan 60	1.18	1.45	0.98	1.00	1.00
16 Jan 60	1.35	1.69	0.99	1.00	0.99
20 Jan 60	1.37	1.13	1.06	0.94	1.03
23 Jan 60	1.26	1.03	0.91	0.96	0.95
28 Jan 60	1.25	1.09	1.25	0.89	0.92
2 Feb 60	1.41	1.29	1.15	1.19	1.03
4 Feb 60	1.32	1.21	1.05	0.99	1.01
9 Feb 60	1.40	1.32	1.24	1.06	1.08
13 Feb 60	1.42	1.19	1.10	1.00	1.20
17 Feb 60	1.34	1.09	1.01	1.06	1.02
24 Feb 60	1.29	1.26	0.97	1.04	1.05
1 Mar 60	1.34	1.32	1.04	1.04	1.16
8 Mar 60	1.35	0.89	1.06	1.12	--
11 Mar 60	1.23	1.38	0.95	1.05	1.06
15 Mar 60	1.37	1.04	0.93	0.99	0.95
21 Mar 60	1.31	1.05	0.94	0.99	1.05
24 Mar 60	--	--	--	--	--
25 Mar 60	1.34	1.30	0.96	1.04	1.41
29 Mar 60	1.54	1.20	1.01	1.03	1.08
31 Mar 60	1.34	1.02	0.88	0.90	0.99
3 Apr 60	1.26	1.05	0.95	1.00	1.05
6 Apr 60	--	--	--	--	--
9 Apr 60	1.42	1.10	0.90	0.91	0.92
13 Apr 60	1.20	1.03	1.00	1.04	1.12
18 Apr 60	1.68	1.16	0.94	1.18	1.04
21 Apr 60	1.31	1.06	1.01	0.97	1.02
23 Apr 60	1.46	1.25	1.08	0.97	0.99
27 Apr 60	--	--	--	--	--
29 Apr 60	1.08	1.15	1.15	1.00	1.06
5 May 60	1.53	1.40	1.00	1.00	0.93
12 May 60	1.58	1.21	1.07	0.92	0.90
20 May 60	1.68	1.34	1.13	1.02	1.18

Appendix Table A6. Mean bulk density

Date	Depth, in. 0 to 3	3 to 6	6 to 9	9 to 12	12 to 15
Kent County Bare					
1 Dec 59	1.58	1.74	1.80	1.91	--
4 Dec 59	1.53	1.49	1.63	1.64	1.67
10 Dec 59	1.39	1.66	1.73	1.70	1.63
16 Dec 59	1.56	1.52	1.55	1.47	1.71
21 Dec 59	1.39	1.50	1.67	1.67	1.65
30 Dec 59	1.39	1.51	1.83	1.79	1.80
2 Jan 60	1.35	1.60	1.60	1.59	1.71
7 Jan 60	1.17	1.58	1.63	1.69	1.65
11 Jan 60	1.19	1.59	1.61	1.66	1.71
14 Jan 60	1.19	1.45	1.65	1.60	1.75
19 Jan 60	1.07	1.53	1.58	1.52	1.83
21 Jan 60	1.44	1.49	1.54	1.75	1.75
26 Jan 60	1.07	1.61	1.55	1.66	1.55
30 Jan 60	1.29	1.55	1.60	1.82	1.72
3 Feb 60	1.42	1.71	1.68	1.74	1.70
6 Feb 60	1.20	1.57	1.66	1.74	1.75
12 Feb 60	1.43	1.75	1.78	1.74	1.71
16 Feb 60	1.24	1.67	1.74	1.83	1.74
20 Feb 60	1.23	1.65	1.72	1.80	1.81
25 Feb 60	1.20	1.60	1.89	1.68	1.77
5 Mar 60	1.52	1.71	1.70	1.86	1.87
8 Mar 60	--	--	--	--	--
10 Mar 60	1.19	1.62	1.83	1.82	1.79
14 Mar 60	1.20	1.58	1.59	1.83	1.74
17 Mar 60	1.14	1.61	1.64	1.75	1.69
23 Mar 60	1.10	1.50	1.66	1.76	1.78
28 Mar 60	1.44	1.45	1.67	1.68	1.76
30 Mar 60	1.39	1.49	1.87	1.64	1.82
1 Apr 60	1.46	1.49	1.68	1.74	1.77
4 Apr 60	1.68	1.61	1.81	1.80	1.72
8 Apr 60	1.58	1.62	1.72	1.58	1.76
12 Apr 60	1.56	1.59	1.72	1.82	1.81
16 Apr 60	1.58	1.62	1.69	1.80	1.80
20 Apr 60	1.77	1.73	1.87	1.84	1.87
22 Apr 60	1.60	1.64	1.79	1.79	1.81
27 Apr 60	--	--	--	--	--
28 Apr 60	1.55	1.60	1.66	1.75	1.69
13 May 60	1.62	1.56	1.73	1.77	1.82
Kent County Herbaceous					
1 Dec 59	1.48	1.67	1.36	1.71	--
10 Dec 59	1.58	1.77	1.82	1.80	1.84
16 Dec 59	1.25	1.57	1.65	1.51	1.78
21 Dec 59	1.34	1.65	1.58	1.81	1.80
30 Dec 59	1.44	1.71	1.81	1.85	1.84
2 Jan 60	1.45	1.74	1.88	1.88	1.85
7 Jan 60	1.13	1.73	1.60	1.43	1.73
11 Jan 60	0.97	1.59	1.65	1.73	1.77
14 Jan 60	1.23	1.61	1.69	1.71	1.80
19 Jan 60	--	--	--	--	--
21 Jan 60	1.41	1.57	1.70	1.59	1.83
26 Jan 60	1.35	1.71	1.70	1.79	1.73
30 Jan 60	1.36	1.68	1.68	1.75	1.79
3 Feb 60	1.42	1.67	1.68	1.57	1.72
6 Feb 60	1.49	1.77	1.62	1.86	1.79
12 Feb 60	1.39	1.80	1.83	1.81	1.71
16 Feb 60	1.46	1.78	1.78	1.87	1.80
20 Feb 60	1.34	1.70	1.81	1.82	1.75
25 Feb 60	1.22	1.55	1.66	1.74	1.86
5 Mar 60	1.39	1.71	1.82	1.89	1.86
10 Mar 60	1.22	1.59	1.91	2.01	1.80
14 Mar 60	1.19	1.69	1.75	1.87	1.88
17 Mar 60	1.36	1.52	1.71	1.57	1.79
23 Mar 60	1.16	1.79	1.91	1.82	1.87
28 Mar 60	1.02	1.53	1.63	1.81	1.84
30 Mar 60	1.43	1.64	1.71	1.78	1.83
1 Apr 60	1.67	1.72	1.83	1.80	1.89
8 Apr 60	1.50	1.60	1.72	1.80	1.78
12 Apr 60	1.55	1.72	1.82	1.88	1.84
16 Apr 60	1.67	1.72	1.79	1.84	1.83
20 Apr 60	1.56	1.66	1.81	1.88	1.89
22 Apr 60	1.57	1.70	1.75	1.75	1.74
27 Apr 60	--	--	--	--	--
28 Apr 60	1.57	1.63	1.71	1.74	1.85
13 May 60	1.59	1.66	1.81	1.79	1.82
Kent County Hardwood					
1 Dec 59	0.84	1.17	1.35	1.40	--
10 Dec 59	0.98	1.28	1.68	1.88	1.82
16 Dec 59	1.05	1.10	1.46	1.28	1.61
21 Dec 59	0.78	1.16	1.49	1.51	1.84
30 Dec 59	1.10	1.43	1.66	1.73	1.77
2 Jan 60	1.04	1.34	1.62	1.78	1.65
7 Jan 60	0.95	1.25	1.43	1.58	1.60
11 Jan 60	1.04	1.40	1.56	1.62	1.74
14 Jan 60	0.86	1.40	1.51	1.59	1.69
19 Jan 60	--	--	--	--	--
21 Jan 60	0.95	1.27	1.67	1.69	1.80
26 Jan 60	1.04	1.35	1.42	1.60	1.86
30 Jan 60	1.09	1.44	1.72	1.89	1.76
3 Feb 60	0.99	1.31	1.51	1.46	2.10
6 Feb 60	0.98	1.36	1.55	1.65	1.73
12 Feb 60	0.89	1.33	1.46	1.59	1.46
16 Feb 60	0.87	1.32	1.58	1.73	1.77
20 Feb 60	1.07	1.37	1.64	1.78	1.94
25 Feb 60	0.98	1.40	1.57	1.72	1.66
5 Mar 60	0.89	1.43	1.60	1.82	1.74
10 Mar 60	0.78	1.45	1.63	1.83	1.80
14 Mar 60	0.81	1.40	1.54	1.77	1.74
18 Mar 60	0.91	1.23	1.51	1.70	1.68
23 Mar 60	0.84	1.57	1.57	1.68	1.77
28 Mar 60	1.01	1.38	1.65	1.67	1.81
30 Mar 60	1.06	1.53	1.62	1.72	1.74
1 Apr 60	0.94	1.38	1.50	1.81	1.87
8 Apr 60	1.10	1.53	1.62	1.73	1.78
12 Apr 60	--	--	--	--	--
15 Apr 60	1.09	1.59	1.55	1.62	1.79
20 Apr 60	1.07	1.52	1.67	1.75	1.83
22 Apr 60	1.11	1.49	1.63	1.69	1.74
27 Apr 60	--	--	--	--	--
28 Apr 60	0.97	1.48	1.57	1.64	1.78
13 May 60	1.08	1.51	1.65	1.71	1.81
20 May 60	0.98	1.47	1.52	1.70	1.70
Clinton County Bare					
10 Nov 59	1.74	1.51	1.85	1.51	--
9 Dec 59	--	--	--	--	--
14 Dec 59	1.28	1.72	1.82	1.78	1.75
18 Dec 59	1.48	1.63	1.81	1.82	1.76
23 Dec 59	1.30	1.55	1.49	1.75	1.86
31 Dec 59	1.44	1.63	1.77	1.70	1.71
5 Jan 60	1.18	1.49	1.62	1.88	1.81
9 Jan 60	1.38	1.39	1.46	1.73	1.81
16 Jan 60	1.31	1.42	1.54	1.65	1.66
20 Jan 60	1.22	1.34	1.39	1.75	1.77
23 Jan 60	1.31	1.58	1.42	1.49	1.79
28 Jan 60	1.16	1.29	1.38	1.78	1.74
2 Feb 60	1.26	1.24	1.28	1.61	1.69
4 Feb 60	1.17	1.26	1.24	1.54	1.74
9 Feb 60	0.93	1.41	1.22	1.42	1.62
13 Feb 60	1.01	1.33	1.39	1.44	1.76
17 Feb 60	1.20	1.25	1.34	1.36	1.77
24 Feb 60	0.92	1.40	--	1.29	--
1 Mar 60	1.26	1.35	1.36	1.28	1.62
8 Mar 60	0.81	1.16	1.30	1.65	1.64
11 Mar 60	1.01	1.25	1.06	1.56	--
15 Mar 60	0.92	1.11	0.92	--	1.84
21 Mar 60	1.01	1.42	1.08	1.02	1.22
24 Mar 60	--	--	--	--	--
25 Mar 60	0.87	1.21	1.35	1.37	1.78
29 Mar 60	1.23	1.16	1.16	--	1.69
31 Mar 60	1.54	1.68	1.58	1.71	1.85
3 Apr 60	1.64	1.66	1.52	1.81	1.86
6 Apr 60	1.34	1.55	1.76	1.79	1.74
9 Apr 60	1.35	1.56	1.70	1.74	1.80
13 Apr 60	--	--	--	--	--
18 Apr 60	1.69	1.62	1.86	1.83	1.86
21 Apr 60	1.61	1.64	1.90	1.63	1.85
23 Apr 60	1.55	1.55	1.72	1.74	1.77
27 Apr 60	--	--	--	--	--
29 Apr 60	1.58	1.50	1.74	1.80	1.82
5 May 60	1.54	1.54	1.69	1.81	1.82
12 May 60	1.64	1.57	1.75	1.84	1.77
20 May 60	--	--	--	--	--
Clinton County Herbaceous					
11 Nov 59	1.50	1.62	1.69	1.73	--
9 Dec 59	--	--	--	--	--
14 Dec 59	1.63	1.68	1.65	1.35	1.65
18 Dec 59	1.51	1.54	1.74	1.76	1.83
23 Dec 59	1.23	1.54	1.81	1.78	1.84
31 Dec 59	1.58	1.59	1.82	1.76	1.70
5 Jan 60	1.08	1.61	1.74	1.86	1.75
9 Jan 60	1.03	1.41	1.54	1.73	1.75
16 Jan 60	1.12	1.57	1.77	1.80	1.73
20 Jan 60	1.02	1.51	1.55	1.58	1.56
23 Jan 60	1.05	1.62	1.80	1.99	1.70
28 Jan 60	0.95	1.74	1.73	1.77	1.90
2 Feb 60	0.88	1.35	1.57	1.76	1.71
4 Feb 60	1.02	1.44	1.86	1.82	1.69
9 Feb 60	0.97	1.56	1.59	1.65	1.73
13 Feb 60	1.12	1.61	1.72	1.81	1.80
17 Feb 60	1.20	1.57	1.66	1.71	1.47
24 Feb 60	1.09	1.51	1.59	1.59	1.74
1 Mar 60	0.90	1.43	1.62	1.74	1.73
8 Mar 60	0.76	1.39	1.42	1.94	1.67
11 Mar 60	1.09	1.09	1.43	1.68	1.70
15 Mar 60	0.82	1.28	1.58	1.83	1.79
21 Mar 60	0.77	1.45	1.47	1.82	1.83
24 Mar 60	--	--	--	--	--
25 Mar 60	0.91	1.13	1.68	1.68	1.82
29 Mar 60	0.84	1.56	1.73	1.59	1.79
31 Mar 60	1.54	1.50	1.65	1.79	1.83
3 Apr 60	1.68	1.72	1.77	1.89	1.88
6 Apr 60	--	--	--	--	--
9 Apr 60	1.48	1.57	1.73	1.79	1.85
13 Apr 60	1.59	2.03	1.65	1.79	1.80
18 Apr 60	1.65	1.63	1.82	1.84	1.82
21 Apr 60	1.55	1.56	1.72	1.77	1.79
23 Apr 60	1.48	1.54	1.70	1.69	1.69
27 Apr 60	--	--	--	--	--
29 Apr 60	1.55	1.59	1.78	1.80	1.82
5 May 60	1.52	1.53	1.76	1.87	1.73
12 May 60	1.51	1.57	1.72	1.77	1.77
20 May 60	--	--	--	--	--
Clinton County Hardwood					
19 Nov 59	0.95	1.19	1.47	1.63	--
9 Dec 59	--	--	--	--	--
14 Dec 59	1.23	1.20	1.48	1.33	1.65
18 Dec 59	1.08	1.39	1.66	1.66	1.63
23 Dec 59	0.78	0.90	1.35	1.35	1.73
31 Dec 59	1.04	1.25	1.88	1.54	1.65
5 Jan 60	1.09	1.41	1.68	1.75	1.74
9 Jan 60	1.02	1.49	1.70	1.67	1.63
16 Jan 60	1.14	1.53	1.66	1.68	1.71
20 Jan 60	1.13	1.37	1.61	1.65	1.59
23 Jan 60	1.14	1.41	1.73	1.75	1.73
28 Jan 60	1.15	1.36	1.56	1.69	1.68
2 Feb 60	1.11	1.38	1.46	1.53	1.68
9 Feb 60	1.10	1.36	1.59	1.70	1.59
13 Feb 60	1.02	1.34	1.64	1.73	1.63
17 Feb 60	0.99	1.32	1.59	1.68	1.65
24 Feb 60	0.94	1.28	1.55	1.62	1.63
1 Mar 60	0.97	1.48	1.57	1.65	1.59
8 Mar 60	1.25	1.55	1.64	1.73	--
11 Mar 60	0.84	1.39	1.40	1.76	1.69
15 Mar 60	1.28	1.68	1.72	1.76	1.72
21 Mar 60	1.03	1.44	1.72	1.65	1.61
24 Mar 60	--	--	--	--	--
25 Mar 60	0.84	1.36	1.61	1.76	1.55
29 Mar 60	1.03	1.35	1.68	1.71	1.73
31 Mar 60	1.19	1.58	1.72	1.71	1.73
3 Apr 60	1.13	1.42	1.61	1.62	1.69
6 Apr 60	--	--	--	--	--
9 Apr 60	1.15	1.48	1.66	1.76	1.24
13 Apr 60	1.16	1.36	1.62	1.72	1.64
18 Apr 60	1.02	1.44	1.62	1.58	1.75
21 Apr 60	1.01	1.47	1.67	1.80	1.70
23 Apr 60	1.04	1.32	1.51	1.59	1.63
27 Apr 60	--	--	--	--	--
29 Apr 60	1.13	1.49	1.64	1.69	1.65
5 May 60	1.10	1.34	1.66	1.67	1.68
12 May 60	1.09	1.39	1.62	1.48	1.64
20 May 60	0.98	1.31	1.55	1.51	1.43

Appendix Table A7. Mean daily shear strength readings, frozen depths from surface

Date	Depth, in. 0	3	6	9	12	Frozen Depths from Surface, in. A	B	C	D
Kent County Bare									
2 Dec 59	41.2	136.2	197.5	217.5	198.7				
16 Dec 59	98.3	116.7	173.3	156.7	181.7				
21 Dec 59	300.0	242.5	256.7	293.3	290.0	4-13/16	2	19	19
30 Dec 59	163.7	60.0	110.0	233.7	185.0		1	1	
14 Jan 60	165.0	112.5	101.2	176.7	133.7	3		3	
21 Jan 60	58.7	95.0	206.2	175.0	188.7		3	2	
30 Jan 60	167.5	71.2	101.2	153.7	138.7	2	3		2
6 Feb 60	238.7	100.0	180.0	207.5	175.0				
16 Feb 60	237.5	153.7	153.7	225.0	210.0	4	2	2	
20 Feb 60	242.5	163.7	171.2	232.5	216.2	2	4	2	
5 Mar 60	192.7	116.2	187.5	262.5	216.2				
10 Mar 60	300.0	107.5	202.5	237.5	217.5	3	2	2	1
14 Mar 60	235.0	252.5	275.0	285.0	297.5	19	19		19
17 Mar 60	212.5	187.5	230.0	270.0	275.0	3			19
23 Mar 60	250.0	220.0	261.2	272.5	275.0	3		19	19
28 Mar 60	47.5	71.2	130.0	136.2	166.2				
30 Mar 60	93.7	143.7	86.2	160.0	141.2		5		
1 Apr 60	13.7	51.2	160.0	175.0	175.0				
4 Apr 60	18.7	60.0	126.2	190.0	153.7				
8 Apr 60	26.2	88.7	162.5	160.0	141.2				
12 Apr 60	26.2	68.7	137.5	158.7	162.5				
16 Apr 60	25.0	87.5	175.0	195.0	148.7				
20 Apr 60	51.2	133.7	152.5	176.2	151.2				
22 Apr 60	41.2	111.2	201.2	200.0	157.5				
28 Apr 60	50.0	81.2	186.2	203.7	153.7				
13 May 60	53.7	92.5	180.0	202.5	192.5				
Clinton County Bare									
10 Nov 59	33.7	45.0	62.5	207.5	243.7				
18 Dec 59	300.0	111.2	93.5	186.2	245.0	1	1	1	
31 Dec 59	88.7	72.5	85.0	170.0	223.7				
29 Mar 60	2.0	227.5	300.0	300.0	300.0	5d*	2d	2d	3d
31 Mar 60	5.0	17.5	190.0	195.0	300.0	12d	8d	5d	12d
3 Apr 60	8.7	21.2	31.2	237.5	280.0	9d	10-1/2d	10d	15d
6 Apr 60	300.0	151.2	65.0	146.2	162.5	3	4; 16d	2	3
9 Apr 60	136.2	68.7	75.0	167.5	172.5		1	1	
13 Apr 60	32.5	73.7	67.5	120.0	155.0				
18 Apr 60	31.2	52.5	46.2	135.0	187.5				
21 Apr 60	48.7	95.0	81.2	163.7	210.0				
23 Apr 60	82.5	118.7	141.2	280.0	271.2				
29 Apr 60	76.2	85.0	117.5	152.5	188.7				
5 May 60	138.7	180.0	172.5	256.2	233.7				
12 May 60	35.0	85.0	87.5	137.5	212.5				

Date	Depth, in. 0	3	6	9	12	Frozen Depths from Surface, in. A	B	C	D
Kent County Herbaceous									
12 Nov 59	102.5	225.0	257.5	240.0	126.7				
16 Dec 59	107.5	227.5	285.0	200.0	192.5				
21 Dec 59	300.0	217.5	245.0	268.7	300.0	2	2	5	19
30 Dec 59	43.7	180.0	202.5	232.5	226.2				
14 Jan 60	300.0	118.7	195.0	192.5	210.0		2	3	3
21 Jan 60	161.2	188.7	236.2	183.7	128.7			1	
30 Jan 60	127.5	185.0	237.5	262.5	258.7	2			
6 Feb 60	40.0	141.2	206.2	230.0	150.0				
16 Feb 60	242.5	270.0	210.0	215.0	233.7		5	1	1
20 Feb 60	222.5	215.0	235.0	206.7	200.0		1		2
5 Mar 60	242.5	270.0	262.5	283.7	277.5		3	1	1
10 Mar 60	236.2	228.7	270.0	255.0	272.5	4	3	3	
14 Mar 60	250.0	275.0	276.2	281.2	300.0	4	6	19	
17 Mar 60	231.2	272.5	280.0	285.0	275.0	19	19	4	
23 Mar 60	250.0	238.7	263.3	266.7	273.3	3	4	4	
28 Mar 60	300.0	238.7	120.0	100.0	110.0	4	4	1	4
30 Mar 60	110.0	240.0	196.2	211.2	242.5	3-5	2-3	19	
1 Apr 60	32.5	163.7	233.7	156.2	176.2				
4 Apr 60	35.0	223.7	262.5	245.0	190.0				
8 Apr 60	42.5	147.5	206.2	250.0	222.5				
12 Apr 60	33.7	130.0	170.0	210.0	231.2				
16 Apr 60	36.2	162.5	232.5	203.7	197.5				
20 Apr 60	48.7	192.5	232.5	245.0	225.0				
22 Apr 60	52.5	216.2	231.2	243.7	233.7				
28 Apr 60	55.0	126.2	262.5	177.5	255.0				
13 May 60	62.5	227.5	265.0	247.5	248.7				
Clinton County Herbaceous									
11 Nov 59	87.5	108.7	110.0	187.5	190.0				
18 Dec 59	37.5	61.2	52.5	162.5	230.0				
31 Dec 59	31.2	80.0	60.0	168.7	180.0				
16 Jan 60	300.0	90.0	50.0	127.5	185.0	3	3	2	3
23 Jan 60	300.0	118.7	105.0	145.0	185.0	2	3	3	2
29 Mar 60	207.5	33.7	42.5	75.0	126.2			2	2
31 Mar 60	10.0	36.2	40.0	150.0	201.2			2-3	
3 Apr 60	17.5	45.0	78.7	215.0	248.7				
6 Apr 60	27.5	56.2	50.0	152.5	167.5				
9 Apr 60	23.7	68.7	66.2	187.5	211.2				
13 Apr 60	28.7	80.0	80.0	137.5	192.5				
18 Apr 60	20.0	42.5	53.7	148.7	206.2				
21 Apr 60	33.7	83.7	81.2	143.7	161.2				
23 Apr 60	38.7	121.2	121.2	188.7	257.5				
29 Apr 60	50.0	81.2	87.5	187.5	213.7				
5 May 60	82.5	160.0	118.7	256.2	185.0				
12 May 60	33.7	42.5	42.5	113.7	150.0				

Date	Depth, in. 0	3	6	9	12	Frozen Depths from Surface, in. A	B	C	D
Kent County Hardwood									
17 Nov 59	21.2	98.7	103.7	110.0	135.0				
30 Nov 59	16.2	43.7	53.7	70.0	110.0				
16 Dec 59	17.5	45.0	47.5	65.0	55.0				
21 Dec 59	153.7	52.5	71.2	107.5	117.5				
30 Dec 59	23.7	53.7	51.2	60.0	75.0				
14 Jan 60	162.5	57.5	92.5	111.2	70.0	1	1		
21 Jan 60	37.5	83.7	82.5	130.0	162.5				
30 Jan 60	36.2	78.7	95.0	120.0	92.5				
6 Feb 60	25.0	45.0	70.0	57.5	90.0				
16 Feb 60	16.2	60.0	71.2	90.0	107.5				
20 Feb 60	26.2	68.7	66.2	147.5	18.2				
5 Mar 60	27.5	66.2	80.0	110.0	142.5				
10 Mar 60	171.2	102.5	156.2	142.5	172.5			1	1
14 Mar 60	50.0	25.0	81.2	77.5	125.0				
18 Mar 60	22.5	84.7	72.5	86.2	95.0				
23 Mar 60	233.7	65.0	100.0	137.5	221.2	1		3	2
28 Mar 60	88.7	51.2	78.7	70.0	140.0		3		
30 Mar 60	83.7	150.0	88.7	65.0	95.0				6
1 Apr 60	15.0	55.0	42.5	60.0	98.7				
8 Apr 60	27.5	76.2	90.0	83.7	137.5				
12 Apr 60	22.5	78.7	52.5	66.2	146.2				
16 Apr 60	13.7	60.0	95.0	67.5	105.0				
20 Apr 60	16.2	53.7	78.7	78.7	83.7				
22 Apr 60	20.0	62.5	78.7	60.0	140.0				
28 Apr 60	16.2	66.2	50.0	30.0	72.5				
13 May 60	21.2	57.5	70.0	87.5	127.5				
20 May 60	12.5	58.7	86.2	14.0	167.5				
Clinton County Hardwood									
12 Nov 59	43.7	108.7	125.0	158.7	228.7				
18 Dec 59	31.2	82.5	103.7	145.0	188.7				
31 Dec 59	27.5	62.5	196.2	140.0	201.2				
5 Jan 60	60.0	93.7	158.7	235.0	240.0	1			
16 Jan 60	42.5	87.5	98.7	135.0	210.0				
23 Jan 60	42.5	106.2	107.5	152.5	160.0				
4 Feb 60	37.5	91.2	127.5	188.7	191.2				
13 Feb 60	43.7	67.5	152.5	237.5	260.0				
11 Mar 60	56.2	72.5	146.2	183.7	188.7				
15 Mar 60	45.0	88.7	143.7	225.0	188.7				
21 Mar 60	107.5	77.5	183.7	212.5	212.5	1			
25 Mar 60	168.7	70.0	110.0	211.2	243.7	2			2
29 Mar 60	18.7	55.0	62.5	122.5	175.0				
31 Mar 60	17.5	42.5	93.7	145.0	170.0				
3 Apr 60	16.2	36.2	83.7	158.7	178.7				
6 Apr 60	17.5	61.2	92.5	117.5	171.2				
9 Apr 60	15.0	47.5	93.7	121.2	126.2				
13 Apr 60	16.2	48.7	101.2	122.5	167.5				
18 Apr 60	18.7	53.7	88.7	86.2	112.5				
21 Apr 60	23.7	47.5	91.2	186.2	203.7				
23 Apr 60	20.0	48.7	88.7	101.2	137.5				
29 Apr 60	13.7	33.7	80.0	96.2	123.7				
5 May 60	27.5	55.0	85.0	117.5	161.2				
12 May 60	18.7	27.5	63.7	141.2	187.5				
20 May 60	25.0	47.5	91.2	126.2	188.7				

* "d" following frozen depth means frozen from that depth down.

APPENDIX B: DESCRIPTION AND USE OF THE CONE PENETROMETER

The cone penetrometer is an instrument used in evaluating soil trafficability. It consists of a 30-degree cone of 1/2-sq-in. base area, two 18-in. extension rods to provide an 18- or 36-in. shaft, a proving ring, dial gage, and handle (see Figure B1). When the cone is forced in the ground, the proving ring is deformed in proportion to the force applied. The amount of force required to move the cone slowly through a given plane is indicated by the dial gage. This force is considered to be an index of the shearing resistance of the soil. The range of pressure measured is 0 to 300 lb/sq in.

Use of the penetrometer

Inspection. Inspect the instrument before using to make sure all nuts, bolts, and joints are tight and that the dial-gage stem contacts the proving-ring bearing block (Figure B2).

Zeroing. Allow the penetrometer to hang vertically from the handle and rotate the dial face until "0" is under the needle.

Operation. Place the hands over each other on the handle, palms down and approximately at right angles as shown in Figure B1. This minimizes eccentric loading of the proving ring, and helps to keep the rod vertical.

Next, apply force by pressing the chest against the hands until slow, steady downward movement occurs.

The first dial reading is taken just as the base of the cone is flush with the ground surface. Continue the slow, steady downward movement and take successive dial readings at 3-in. intervals to the lowest desired depth (12 in. in this study).

The operator can quickly learn to shift his vision from the rod at ground level to read the dial at the proper moment, maintaining a proper penetration rate. Readings are recorded by an assistant.

Cautions.

(1) The instrument should be kept vertical while in use.

(2) Readings higher than the capacity of the dial should not be attempted. Excess pressure may stress the proving ring.

(3) The instrument should never be withdrawn by the proving ring, but always by the rod or the handle.

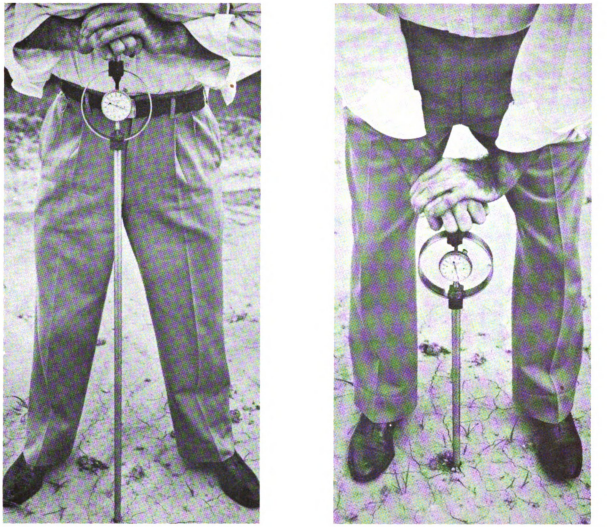

Figure B1. Cone penetrometer in use

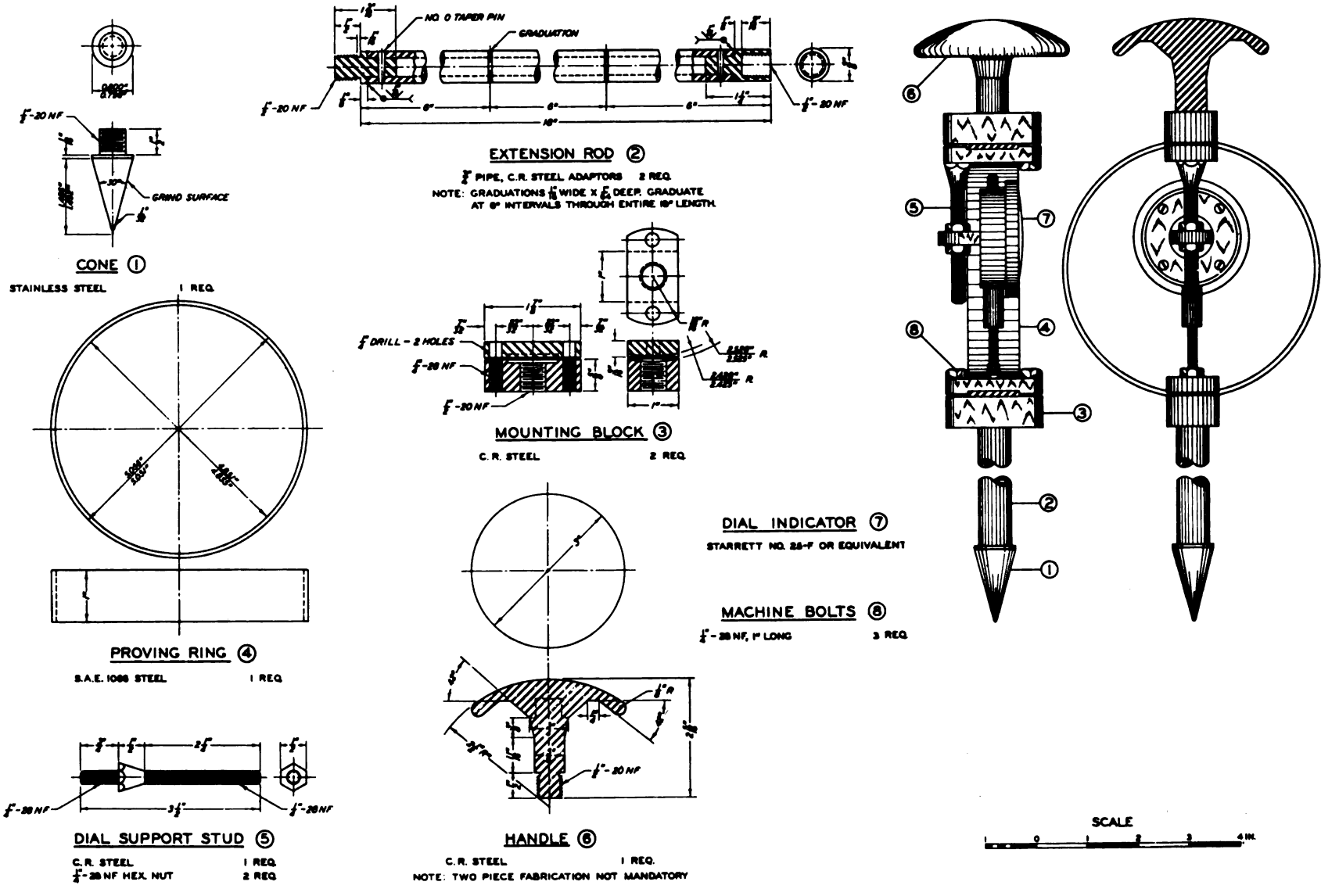

Figure B2. Detailed drawing of cone penetrometer

VITA

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