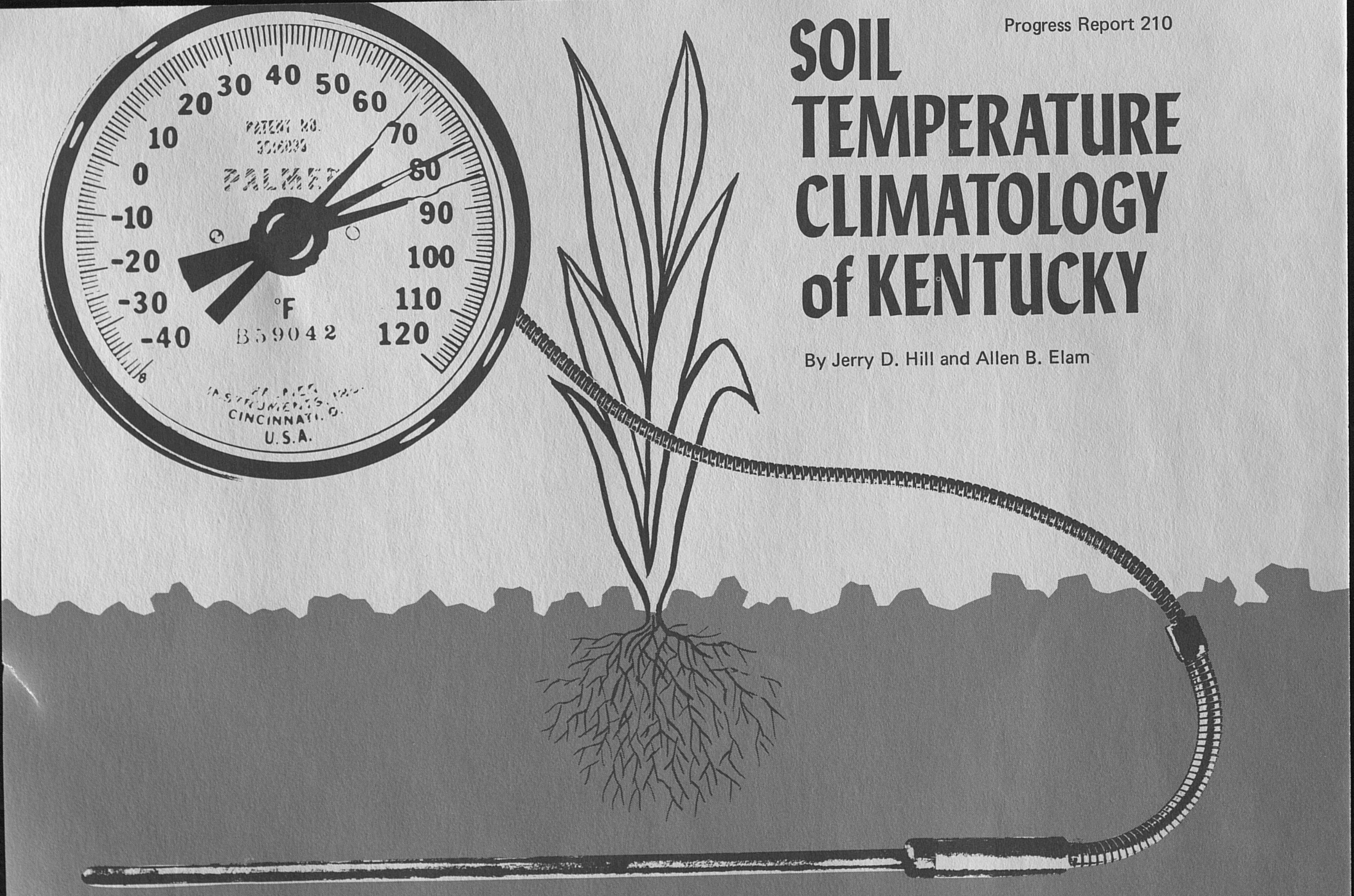
Progress Report 210

SOIL TEMPERATURE CLIMATOLOGY of KENTUCKY

By Jerry D. Hill and Allen B. Elam



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*by JERRY D. HILL and ALLEN B. ELAM, JR.**

Soils have several physical characteristics which make them suited or, in some cases, unsuited for man's use. In addition to a soil's structure, texture, and profile, there are certain thermal characteristics which determine the temperatures to be experienced at various depths under given conditions of moisture and exposure. These conditions vary over a reasonably wide range, but there are fairly narrow limits in which they will frequently fall. The purpose of this publication is to discuss the effect of soil temperatures on several plant species, to present the temperatures normally measured in the soil at a variety of locations, and to give a reasonable estimate of what might be expected at any particular time of year.

SOIL FACTORS INFLUENCING TEMPERATURE

Except for a very small amount produced by biological processes, the source of all heat reaching the soil is solar radiation. The nature of the soil surface determines the amount of this radiation which will be absorbed and the amount reflected back into the atmosphere. The term "albedo" is normally used to characterize the ratio of radiation reflected to the total initially falling on the surface. Color plays an important role in determining the albedo, with dark soils absorbing about 80% of the radiation falling on them and light-colored soils absorbing only about 50%. In mid-latitude locations, such as Kentucky, the direct rays of the sun always strike level soil at an angle and never from directly overhead, even in midsummer. Those soils on a south-facing slope face the sun and, thus, receive somewhat more concentrated radiation and have more heat available per unit area of surface than those on a level or north-facing slope.

The sun's energy absorbed by the soil is used initially to raise the temperature of the surface layer, then it penetrates downward to heat progressively deeper layers. The amount of heat required to change the temperature of a given volume of soil by 1 degree is called its heat capacity, while the rate at which it transfers heat downward is called the thermal conductivity. Both properties vary somewhat in a given soil, owing to its moisture content and the amount of air in the pore spaces.

As for heat capacity, a typical soil requires about 0.3 calorie of heat energy to raise the temperature of a cubic centimeter of soil by 1 degree centigrade. For the water and air components of the soil, these values are:

water—1 calorie per cubic centimeter per degree Centigrade and

air—0.00026 calorie per cubic centimeter per degree Centigrade, thus indicating that water requires a much greater amount of heat to raise its temperature by 1 degree than would an equal volume of air.

As the soil surface warms, there is a transfer of heat downward, and the rate at which it proceeds varies with the thermal conductivity as noted before. Again, the values vary considerably, but some approximate magnitudes for thermal conductivity are:

Silt loam soil	- 0.002 calorie per square centimeter per second per degree C.,
Water	- 0.001,
Air	- 0.00006.

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The low thermal conductivity of the air makes it a much less efficient transporter of heat than is soil, while water is of the same order of magnitude as the soil particles themselves.

By comparing the values given for both the heat capacity and thermal conductivity, we see that soil with a high percentage of water in it requires more heat to change its temperature than does a dry soil; however, a wet soil conducts heat downward to the lower depths much better. A very dry soil with a large proportion of air in the upper layers would tend to have very high daytime temperatures near the surface but much less of a temperature change below 6 to 8 inches.

The soil surface in contact with the atmosphere is the point of greatest heat exchange. During the day it receives heat from the sun, and at night the heat is radiated away. Since the heat capacity of the soil requires that it lose much more heat than the air before its temperature changes by 1 degree, the soil temperatures tend to remain much more stable than air temperatures. Under a sod cover, the soil temperature will have less than 1 degree variation during the day below a depth of about 20 inches. This means that at night and, usually, during the winter the deeper depths are warmer than the surface and heat flows upward, while on sunny days the surface is warmest and heat flows downward.

PLANT RESPONSE TO SOIL TEMPERATURES

Most biological responses take place at a rate determined directly by the temperature sensed by the organism. For the plant, photosynthesis proceeds at a rate determined by the leaf temperature. This is a complex interaction of air temperature, moisture availability, and the amount of solar radiation falling on the leaf. Many of the other plant processes such as germination, nutrient uptake, and translocation, which take place below the soil surface, depend on the soil temperature at that depth. Since the soil temperature undergoes a daily cycle at most planting depths, we normally speak of a single figure, the daily average, which is the average of the daily high and low temperatures at that point.

Many researchers have studied plant response, particularly germination, in relation to soil temperatures, and it would seem appropriate to list some of their findings here for the principal crops grown in Kentucky. These studies have taken two main approaches, the first being a determination of emergence time required at various temperatures. The basic reasoning here is that a long period under the soil surface exposes seed to a variety of pathogens and insects, thus reducing the chance of emergence and the probability of a satisfactory plant stand. The second approach is to determine the threshold temperatures below which and above which germination does not occur. Then an optimum range can be established where germination will be most rapid and likely. Since seed is an expensive production item and sometimes in short supply, soil temperatures are a key to obtaining maximum production from available resources.

Corn

The minimum temperature for germination of corn has been determined to be about 50° F, although the rate here is slow and the optimum would be somewhere above 60°. It would seem that corn planted in a seedbed at temperatures below 50° has very little chance for germination. The upper lethal temperature for the seed is about 107° which is not an unusual temperature for a bare soil surface in mid-summer. Farmers who might be considering mid-summer planting of short-season hybrids for silage should consider that temperatures at shallow depths in dry soil could very likely exceed the lethal level on a sunny day and result in very poor stands.

Results of emergence studies of corn made at various depths and temperatures (1) are shown in Table 1.

TABLE 1.—CORN: DAYS TO 80% EMERGENCE.

Soil Temperature (°F)	Planting Depth (inches) 1	 3	 5
44		No emergence in 24 days	
56	16 days	21 days	24 days*
68	8	7	8
80	4	4	4

*60% emergence at the end of 24-day test period.

There was very little variation in the emergence time at various depths, but temperatures had a much greater effect in determining the time the seed remained below the soil.

Soybeans

Emergence studies made on two varieties of soybeans grown in Kentucky (2) indicated about the same response to temperature in both. The seedlings exhibited essentially no growth at 50° and 104° F, with a maximum growth rate at about 86° F. Figure 1 indicates the time required to achieve 50% emergence using a planting depth of 1 inch.

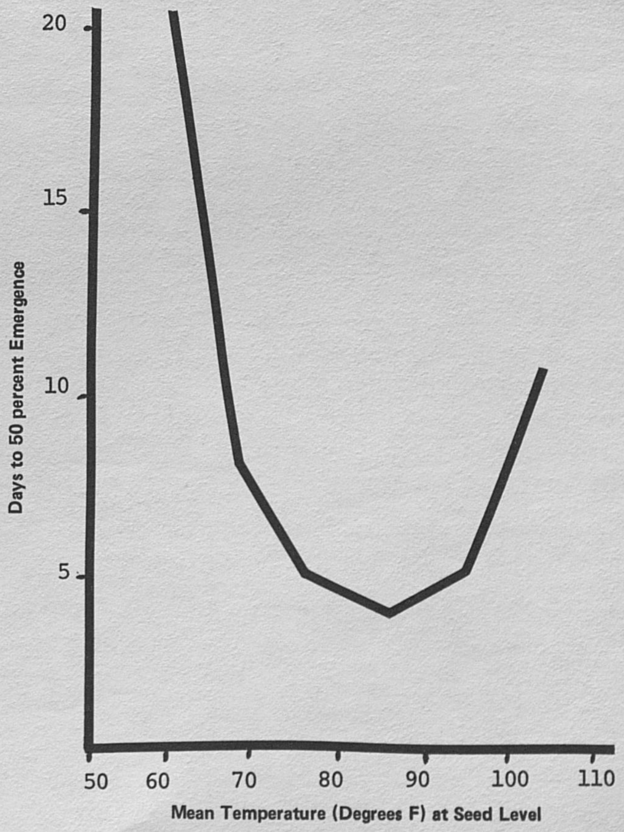

Fig. 1.—Days to 50 percent emergence at various soil temperatures.

Sorghum

The sorghums have tropical origins and, as a result, seem to grow best at high temperatures. Studies of emergence (6) show that they are less sensitive to depth than to temperature. There appears to be little effect of planting depth on days to emergence except at the cooler temperatures where the deeper planting has a pronounced retarding effect (Table 2). The germination percentage also shows a similar response (Table 3).

TABLE 2.–SORGHUM: DAYS TO EMERGE.

Temperature (°F)	Planting Depth (inches) 0.5	1.5	2.5
59	6	9	11
68	7	8	8
77	5	4	5
86	4	4	4
95	4	4	5

TABLE 3.–SORGHUM: PERCENT GERMINATION.

Temperature (°F)	Planting Depth (inches) 0.5	1.5	2.5
59	71	58	56.5
68	80.5	75	72.5
77	79	80	78.5
86	77	83.5	82
95	82	82.5	74

Cotton

Because of its long growing season, it would seem advantageous to plant cotton as early as possible. However, cotton does not emerge as rapidly as some other plant species, so early planting at cool soil temperatures is conducive to seed rot and poor stands. To reduce emergence time to about 7 days, average soil temperatures should be 68° F or higher. Each 2 degrees added to the soil temperature can reduce emergence time by about 1 day, as indicated by Fig. 2(5).

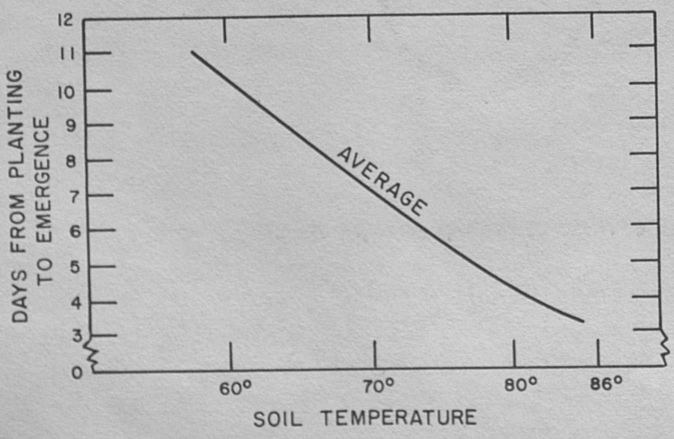

Fig. 2.–Emergence time required by cotton (5).

Tobacco

The use of cloth netting over tobacco beds allows the grower a certain amount of management of soil temperature for his seedlings. When he transplants to the field, however, there is no control and the young plants may make a very slow start if the soil is too cool. In an experiment to determine the most favorable temperature for tobacco growth (6), burley was grown under various temperatures; then the roots were weighed 40 days after transplanting. The results are shown in Table 4. This indicates that soil temperatures in the mid 70s are most favorable for transplanting, and higher temperatures are likely to cause a slowing of the rate at which plants begin growing in the field. This would reduce their resistance to attack by insects and certain plant diseases.

TABLE 4.—BURLEY TOBACCO: AVERAGE WEIGHT 40 DAYS AFTER TRANSPLANTING

Soil Temperature (°F)	Average dry weight of roots (gram)
63	0.32
69	0.66
74	0.86
76	0.79
83	0.70
89	0.25

Vegetable Crops

Research with lima beans (7) points very vividly to the inhospitable environment prevailing in cold soil. Seeds were placed in both unsterilized and a sterilized soil and then maintained at various temperatures. The results are shown in Table 5.

TABLE 5.—LIMA BEANS: GERMINATION PERCENTAGE IN 21 DAYS.

Soil Temperatures 59° F		68° F		86° F	
Sterile	Unsterile	Sterile	Unsterile	Sterile	Unsterile
91%	35%	95%	81%	95%	94%

The pathogens present in the unsterilized soil significantly reduced the resulting stands. However, the seeds planted in warm soil apparently emerged before the pathogen could damage them, thereby resulting in a higher germination percentage. If a grower does not sterilize his soil, the only alternative is to wait for warmer soil temperatures in order to achieve satisfactory stands.

Tomatoes are grown in Kentucky mostly from transplants, and very little research has been done to determine optimum soil temperatures to place plants in the field. Experiments with tomato plants grown from seed (4) do show considerable dependence between growth and soil temperature as presented in Table 6. The plants made their best growth at 85 degrees and showed a distinct stunting at temperatures over 100 degrees. Although growth was slow at 55° F there would be very little disadvantage from planting when temperatures were in the 60° F. range. In fact, market considerations may make it desirable to plant some time before the temperatures reach the optimum level.

TABLE 6.–TOMATOES: HEIGHT 34 DAYS AFTER SEEDING.

Soil Temperatures (°F)	Height (inches)
55	2.6
65	4.5
75	6.1
85	7.9
95	6.3
105	4.1

The lower limit of soil temperature favorable for germination of other vegetable crops (8) is shown in Table 7.

TABLE 7.–MINIMUM TEMPERATURES FOR GERMINATION OF OTHER VEGETABLES.

	(°F)
Asparagus	50
Beets	40
Cabbage	40
Carrots	40
Cucumbers	60
Lettuce	35
Onions	35
Peas	40
Radishes	40
Squash	60
Watermelon	60

SOURCE OF SOIL TEMPERATURE DATA

In 1966 the National Weather Service inaugurated special weather forecasts for agriculture in Kentucky. As part of this service, volunteer weather observers across the state were recruited to take daily observations of those meteorological factors having a direct effect on agricultural production. These observers, many of whom are also active farmers, are provided with a complete set of weather instruments including a soil thermometer. Its sensor is placed at a depth of 4 inches, and an indicator dial is mounted in a box a few feet away where it will not shade or otherwise affect the area where the temperature is being measured.

The temperature dial has an indicator pointer with a "slave" hand on either side. As the temperature rises, one "slave" hand is pushed up to the maximum where it stops and, likewise, the "slave" hand on the other side of the pointer is pushed down to the minimum temperature where it stops. When the observer makes his readings he need only read the position of the "slave" hands to determine the high and low temperature for the day; he then resets them against the pointer to be ready for the next day's readings.

At every location, the temperature is measured under a full sod cover which is kept mowed to the height of an average lawn. The standard depth is 4 inches (10 cm) which is a reference depth at which soil temperatures are taken throughout the world. At this depth, the soil temperature has a cycle which varies through about 5-10 degrees each day. At greater depths the temperature is more constant with less variation, while nearer the surface the variation can be as much as 20 degrees in a day. Examples of soil temperatures at four different depths under sod on a typical day are shown in Figure 3.

Temperatures in a field with bare soil may show a somewhat different cycle than those under sod. Without the insulating effect of the sod, the sun's heat penetrates faster and deeper to give temperatures which are warmer earlier in the day, but the absence of a cover allows more heat to be lost at night and temperatures to be colder near the surface then. An example of the temperatures at the same depths on the same day as the previous ones are shown in Fig. 4, only this time they were measured under a bare silt loam soil near-by.

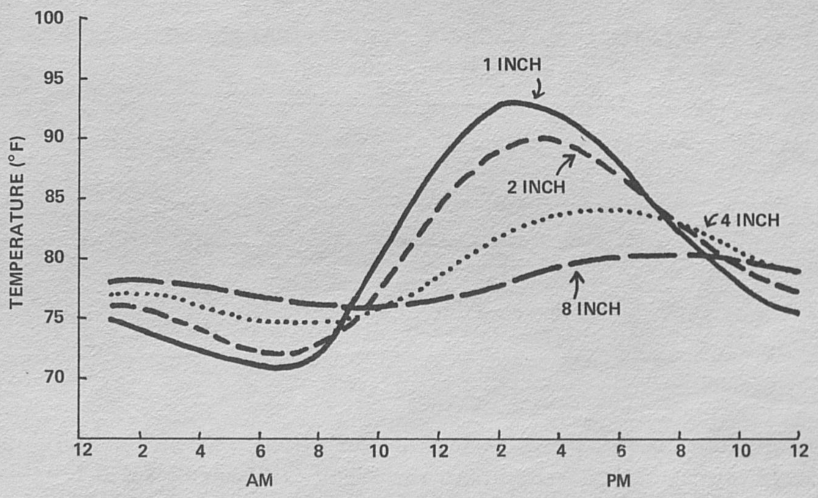

Fig. 3.–Lexington, Ky., soil temperature under sod, Aug. 18, 1973.

We can see that the temperatures are warmer during the day under the bare ground and there is a much greater range in the temperature there. During the growing season the average temperature for the day is normally several degrees warmer under bare ground than under sod. The daily maximum temperature there is much warmer than the maximum under the sod while the night-time minimum temperatures may not be greatly different. The daily average temperature is computed by this equation:

$$\frac{\text{maximum temperature} + \text{minimum temperature}}{2}$$

For the data plotted in the figures, the average temperatures for that day are shown in Table 8.

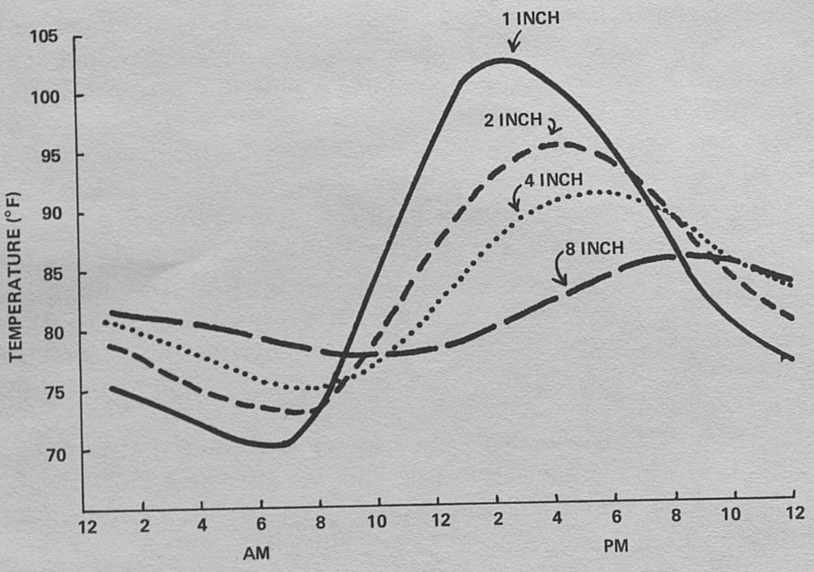

Fig. 4.–Lexington, Ky., soil temperature under bare ground, Aug. 18, 1973.

TABLE 8.–AVERAGE SOIL TEMPERATURES, LEXINGTON, KY., AUG. 18, 1973.

Depth (inches)	Sod (°F)	Bare (°F)
1	82	86
2	81	84
4	79.5	83
8	78.5	81.5

Every evening during the growing season the observers report their high and low soil temperature readings at the 4-inch depth to the Weather Service's State Forecast Office. These reports are then distributed statewide twice each day as part of the agricultural weather forecasts. This enables Kentucky's farmers to keep track of day-by-day changes in the soil temperature, but the long-term record of these observations can also be valuable. Many farmers making plans for crop rotations several years ahead may ask the question, "When is the soil in my area usually warm enough to plant corn?" Also, for example, tobacco growers may wonder when the soil temperature in plant beds in the fall drops below the level for them to get good weed control with methyl bromide.

To help answer these questions, five years of Kentucky soil temperature observations from 1967 to 1972 were processed by the National Climatic Center in Asheville, N. C., to determine the average weekly soil temperature for each of the weeks of the year at several locations scattered across the state (Fig. 5). At each location the temperature averages were then fitted to a smooth curve showing the annual cycle for the full 12 months. Soil types and slope at the observing sites are shown in Table 9.

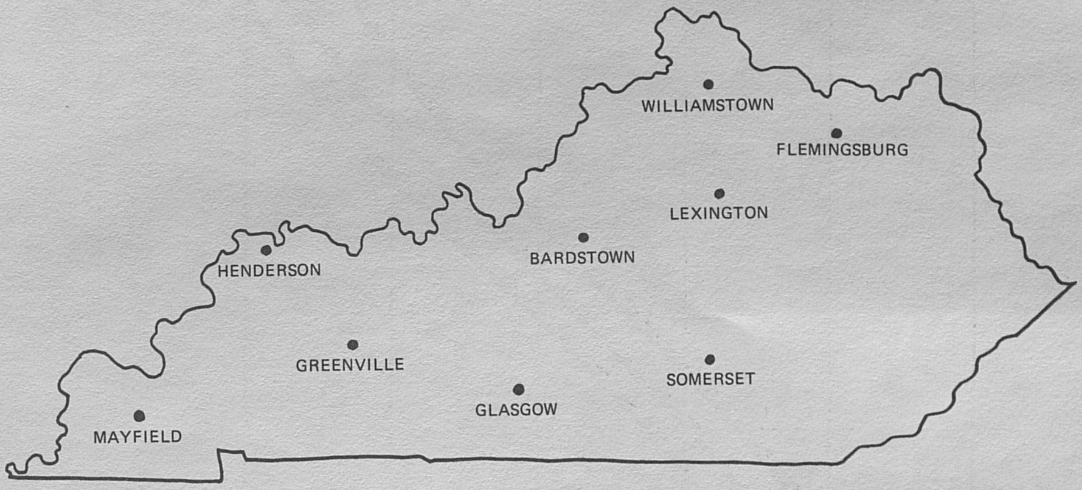

Fig. 5.–Locations in Kentucky with soil temperatures used in this study.

TABLE 9.–SOIL CHARACTERISTICS AT OBSERVING LOCATIONS.

Location	Soil Type	Degree of Slope
Henderson	Memphis Silt Loam	10 percent to the south
Mayfield	Collins Silt Loam	Zero
Greenville	Tilsit Silt Loam	Zero
Glasgow	Silt Loam Fill	6 percent to the west
Bardstown	Pembroke Silt Loam	Zero
Somerset	Captina Silt Loam	3 percent to the east
Williamstown	Nicholson Silt Loam	9 percent to the southeast
Flemingsburg	Lowell Eroded	5 percent to the south
Lexington	Maury Silt Loam	Zero

Most years depart from average though, and there is a range of soil temperatures which can be expected for any week of the year. To determine the range of these temperatures, the weekly temperatures were checked for the 5-year period, then the highest daily average and lowest daily average were selected. The complete set of data for each week then consisted of the average daily temperature for the 5 years, the warmest average observed during the period and the coldest average observed during the period.

Data for eight locations are shown in Figs. 6 through 13 and include the annual cycle of the 4-inch average, while the top curve is the warmest ever observed and the bottom curve is the coldest. Using the location nearest him, a farmer can select a particular temperature along the left margin, then move across to the middle line and down to determine the average date when it occurs. The first curve he reaches will give him the earliest date the given temperature has occurred, and the third curve will tell him the latest. For instance, if a farmer at Mayfield (Fig. 7) decided to seed his corn when the soil temperature reached 50° F he would find that this temperature normally occurs about March 20, but it has occurred as early as the first week in March and as late as the first week in April.

COMPARISON OF SOIL TEMPERATURES AT VARIOUS DEPTHS

Many farmers would make the objection that they do not plant their crops at 4 inches under sod but 1 or 2 inches below bare soil. Unfortunately, it would be too expensive to provide

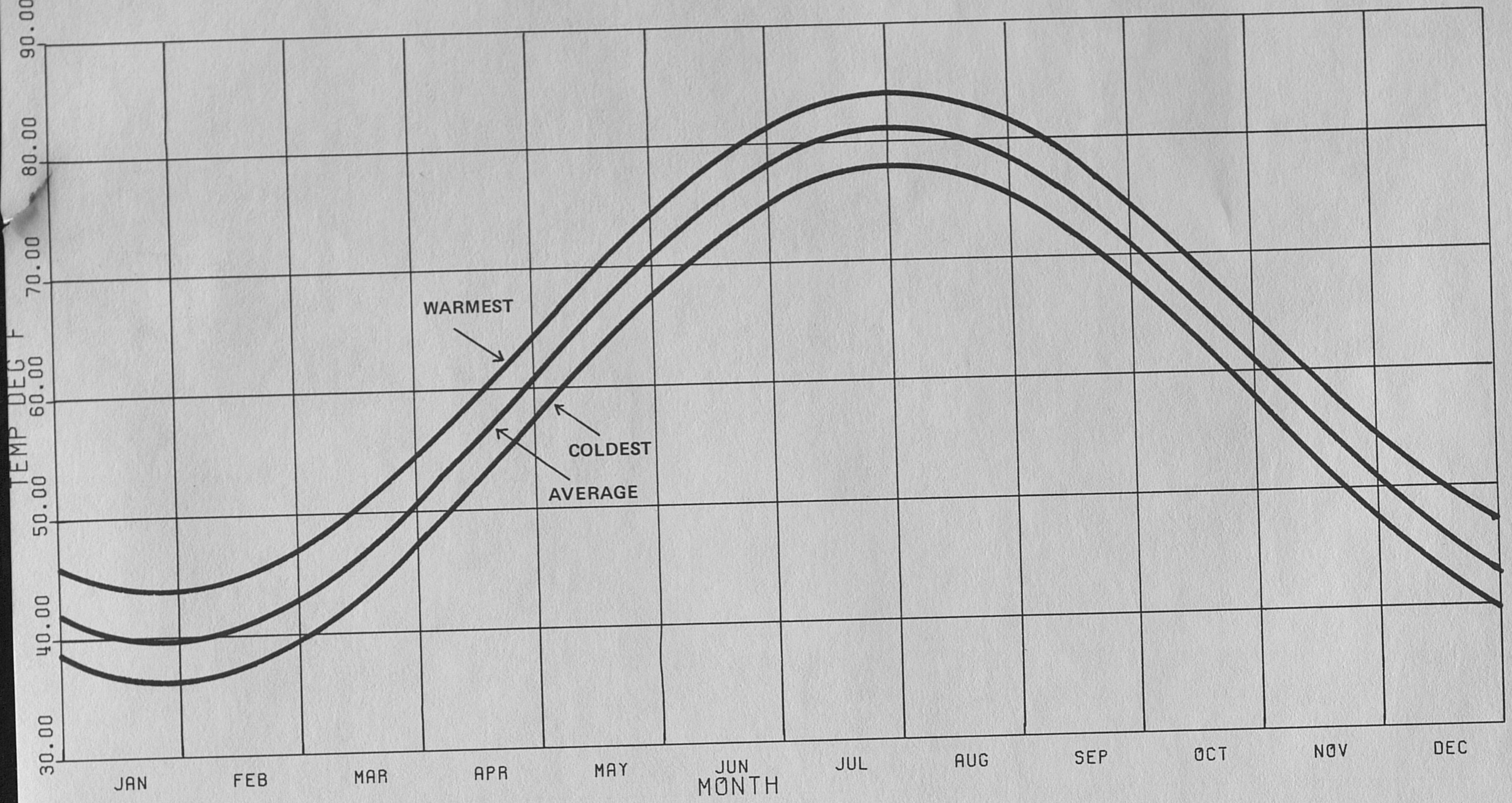

Fig. 6.–Soil temperature data for Henderson, Ky.

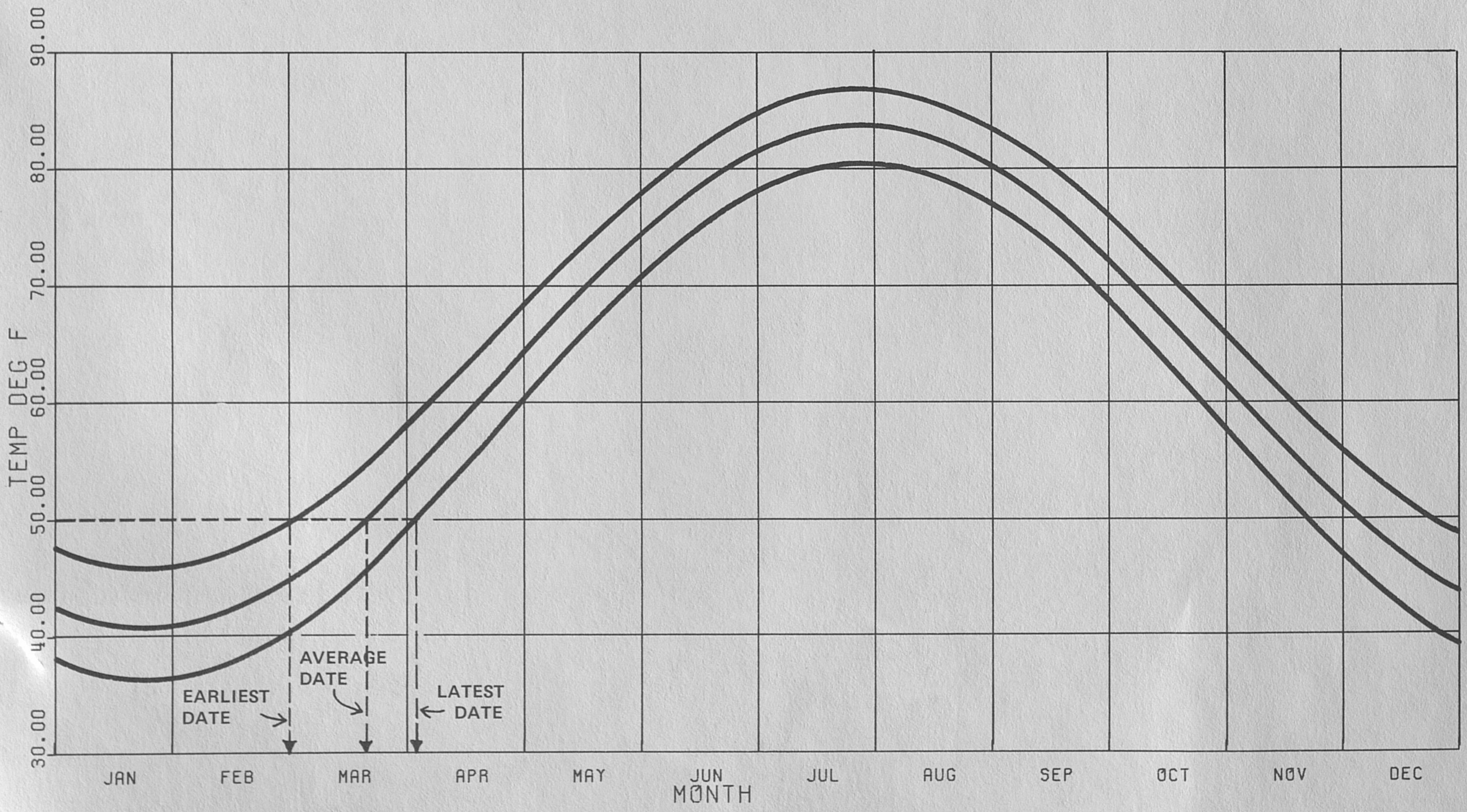

Fig. 7.–Soil temperature data for Mayfield, Ky.

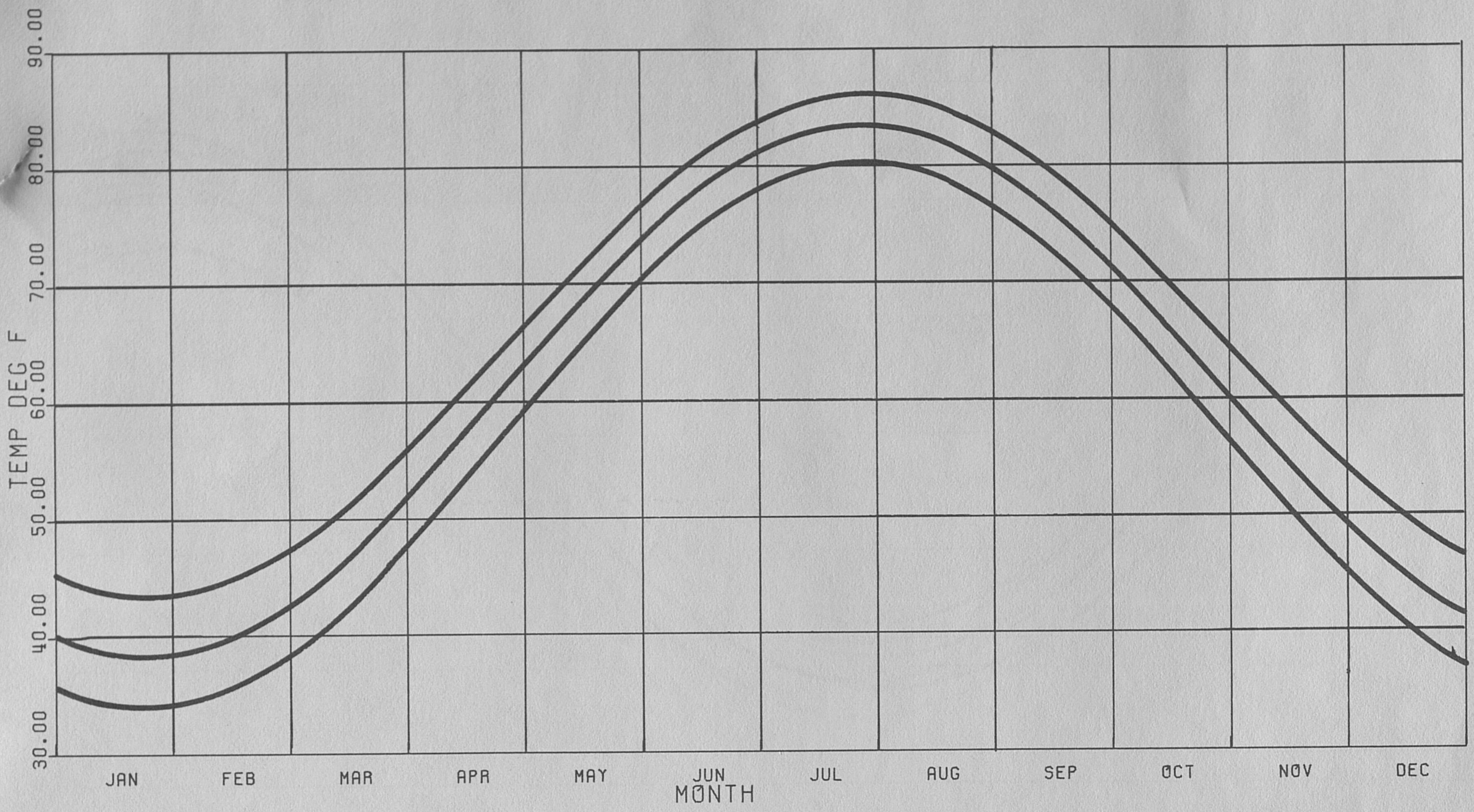

Fig. 8.—Soil temperature data for Greenville, Ky.

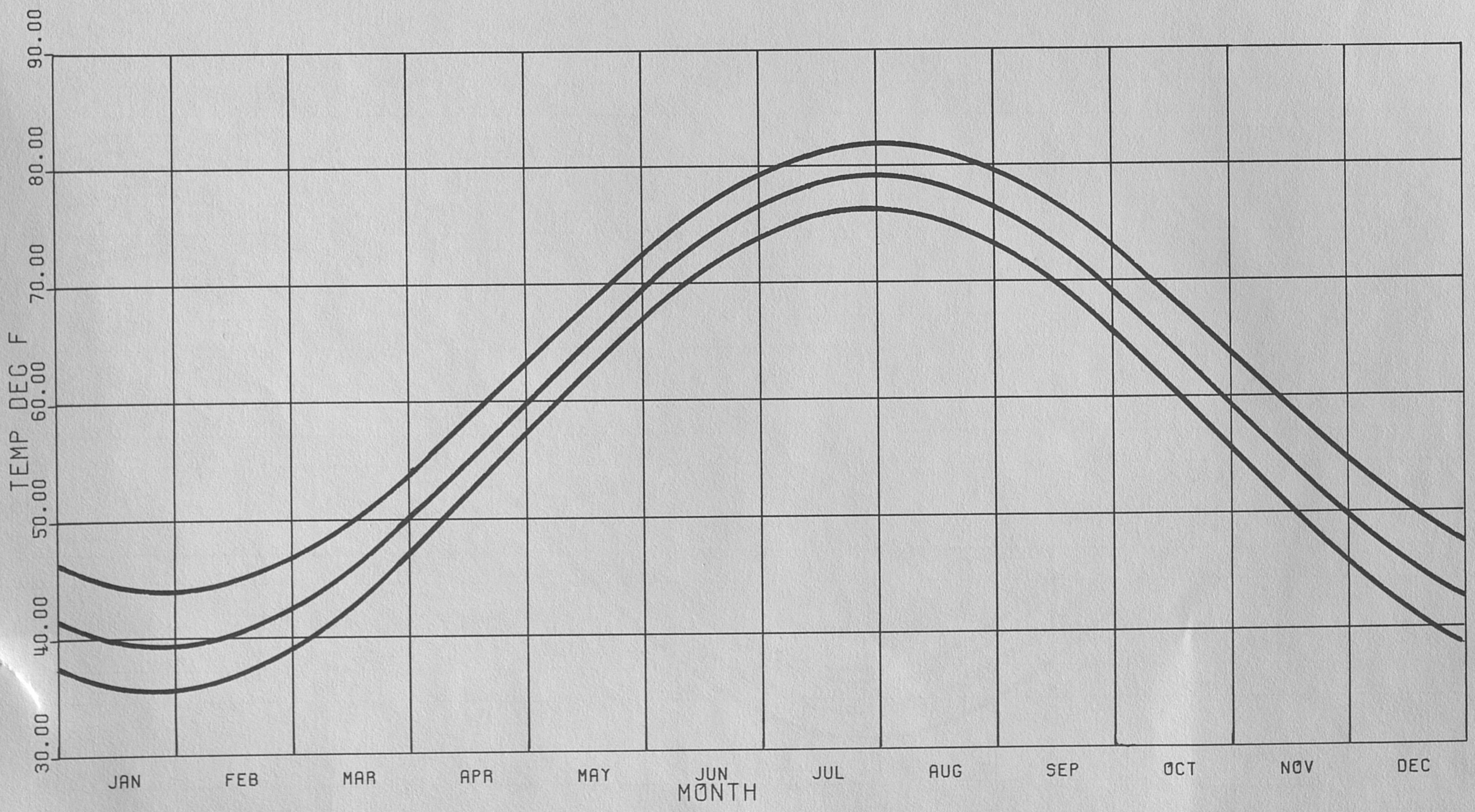

Fig. 9.—Soil temperature data for Glasgow, Ky.

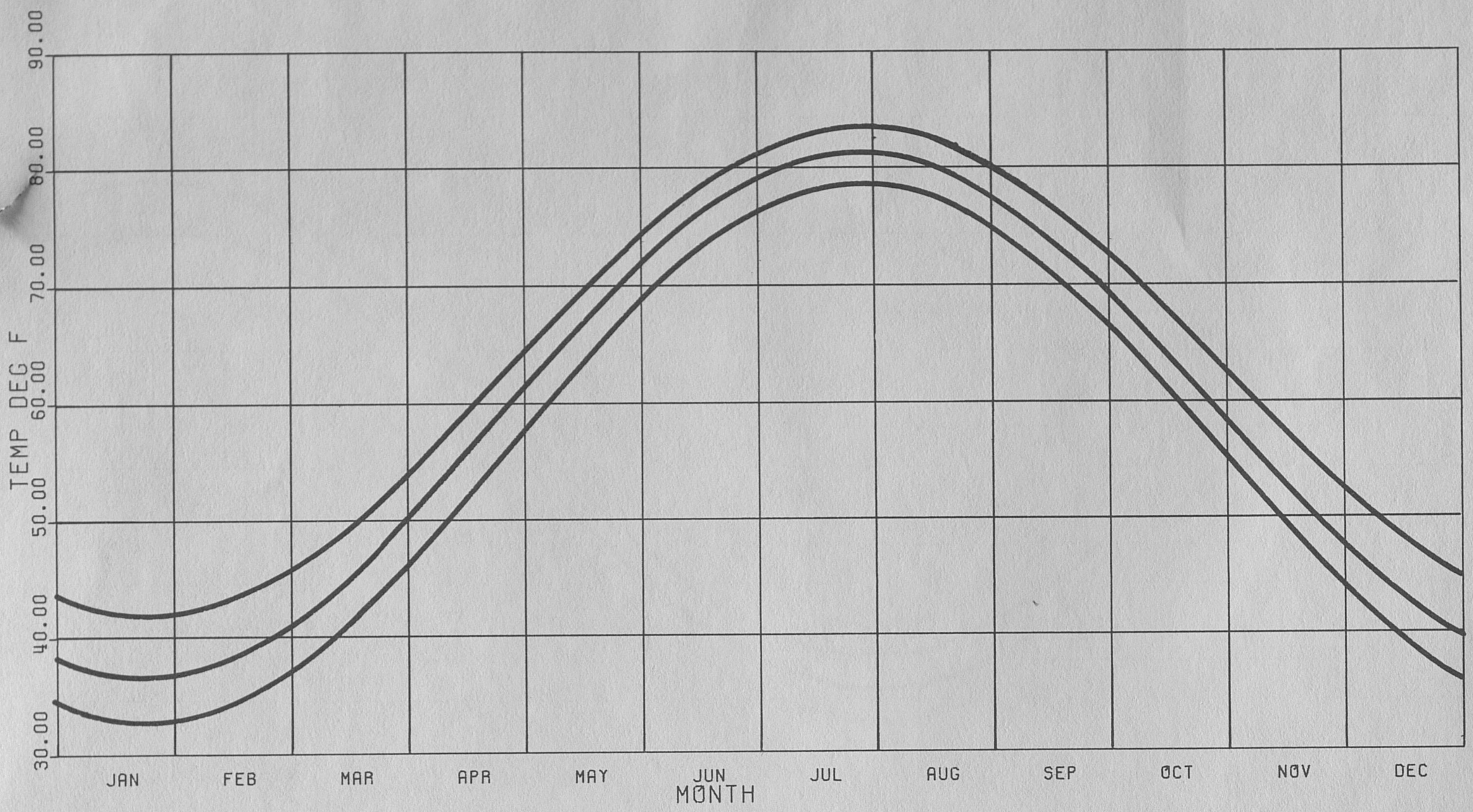

Fig. 10.–Soil temperature data for Bardstown, Ky.

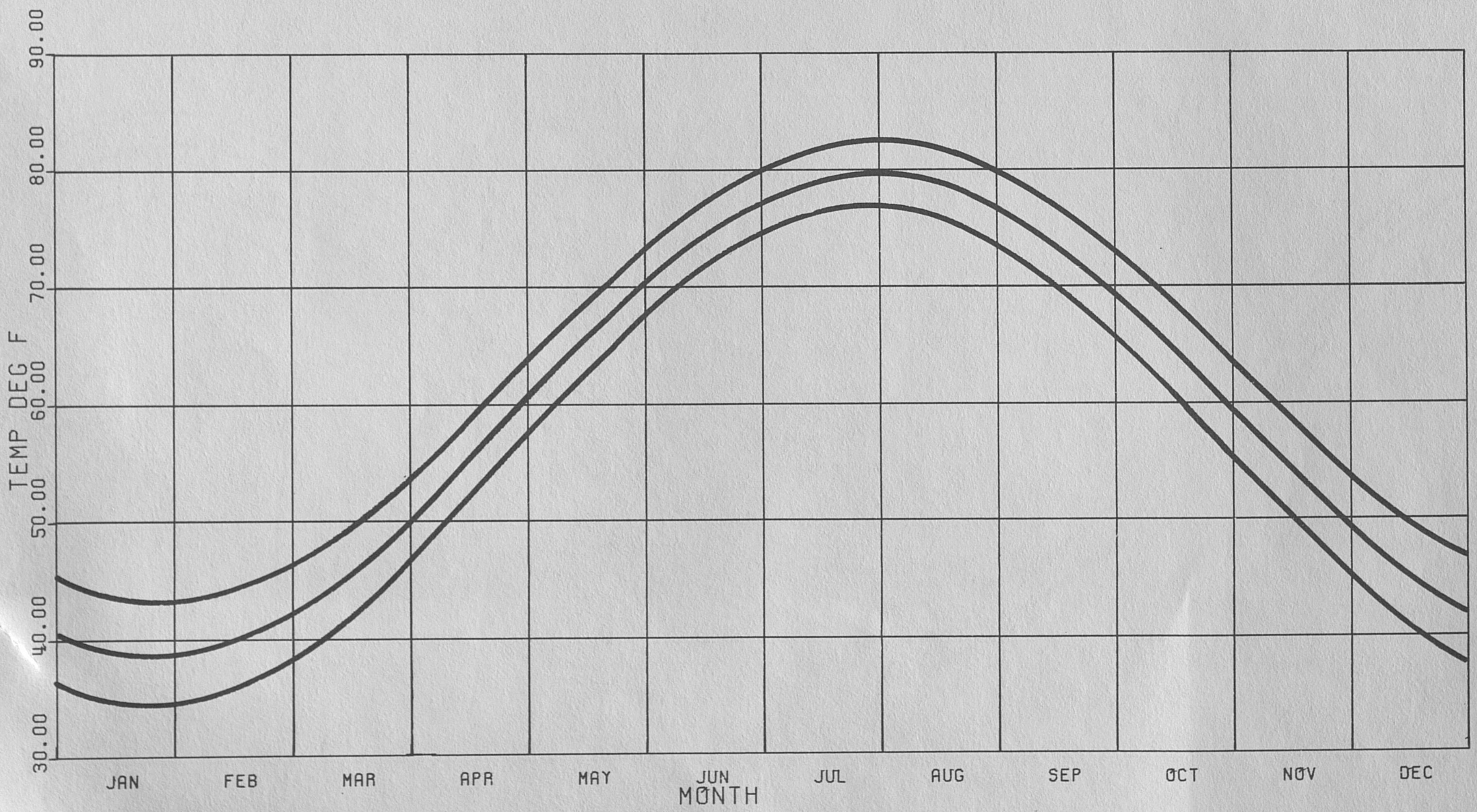

Fig. 11.–Soil temperature data for Somerset, Ky.

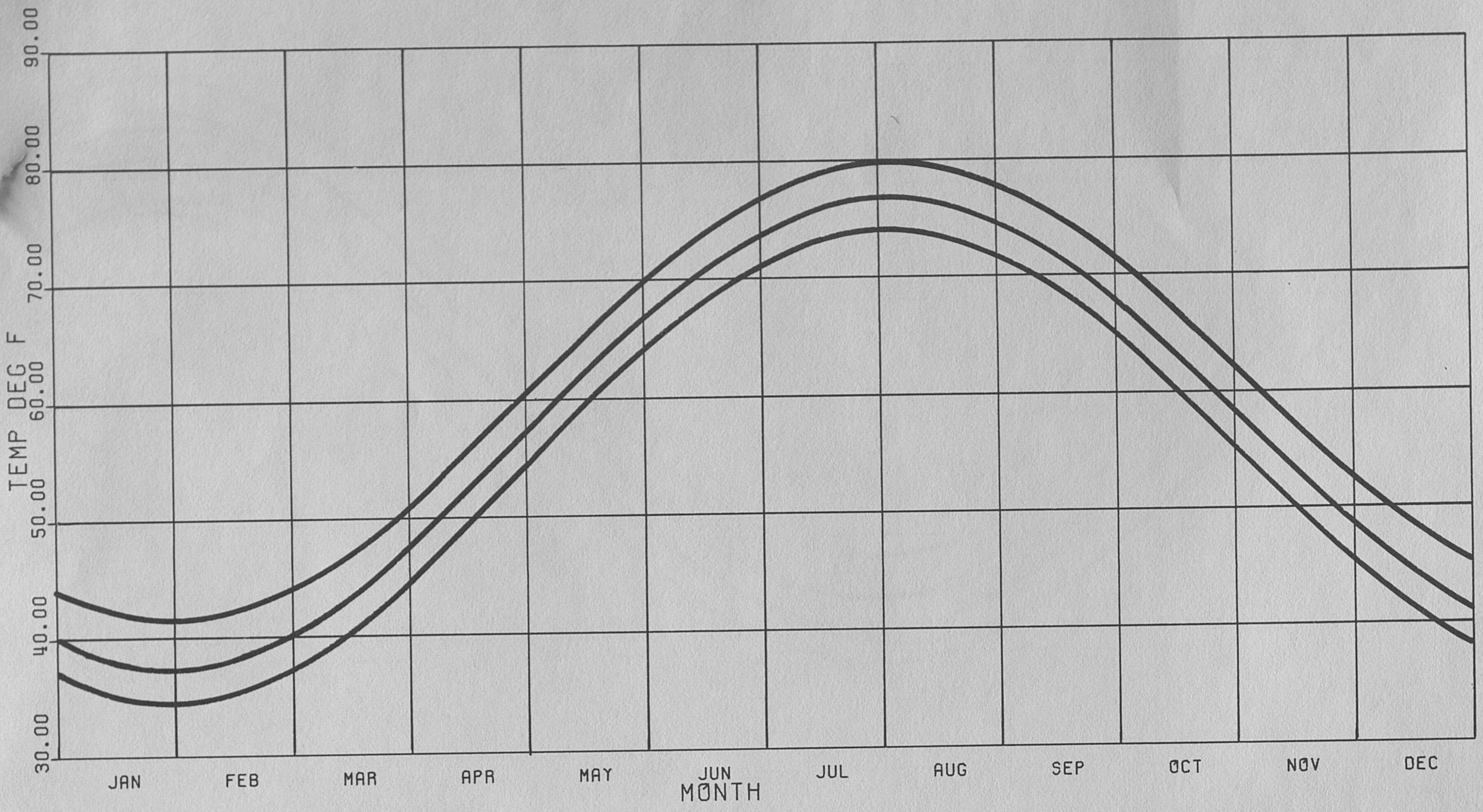

Fig. 12.—Soil temperature data for Williamstown, Ky.

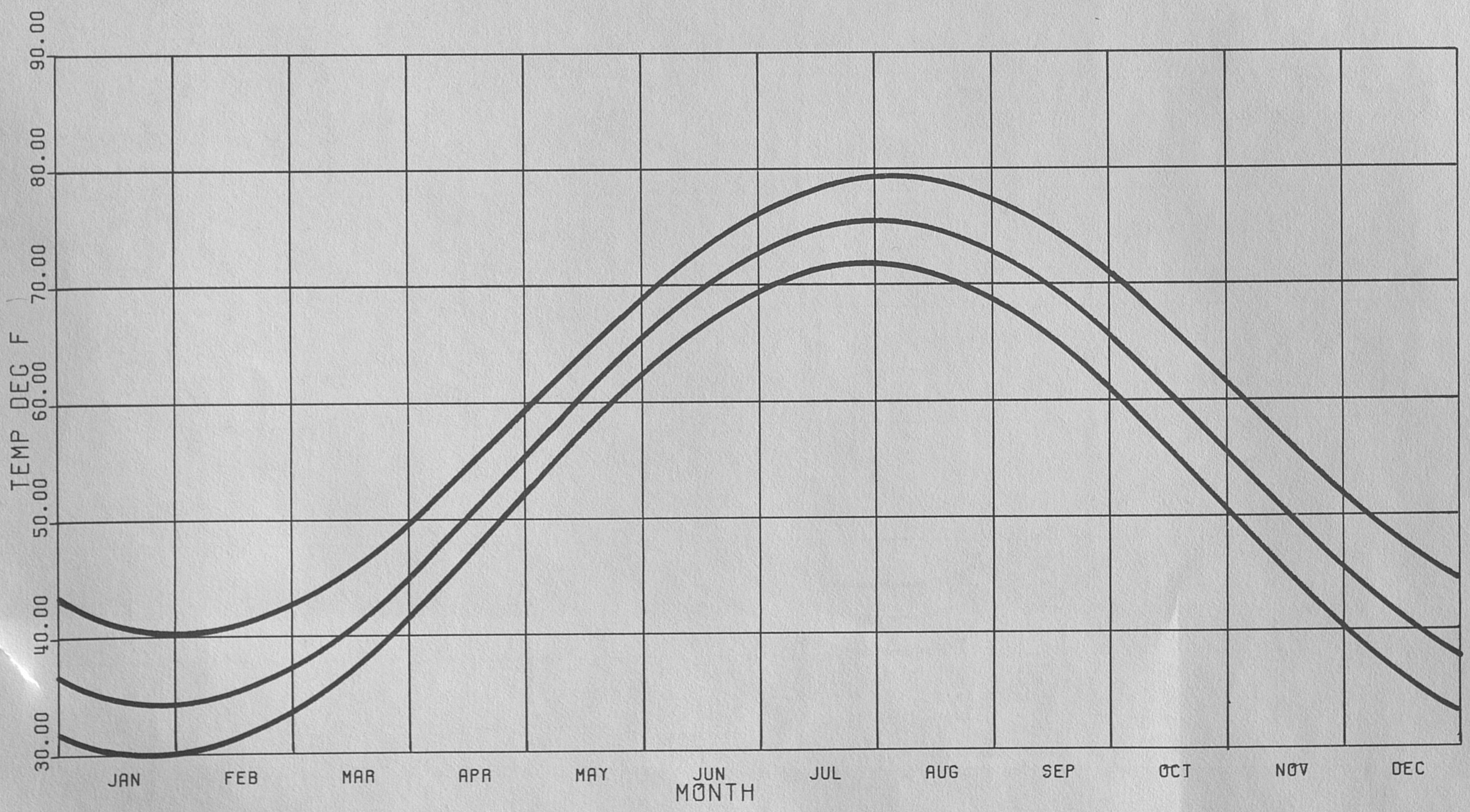

Fig. 13.—Soil temperature data for Flemingsburg, Ky.

equipment for collecting temperatures in every observing location to obtain the needed information. However, in the National Weather Service Office for Agriculture at the University of Kentucky, Agricultural Experiment Station Building, in Lexington, a complete record of soil temperature observations at various depths is available from which comparisons can be made. Figure 14 shows the average weekly 4-inch soil temperature measured under sod and also the 1- and 2-inch soil temperatures measured under bare ground. From this it can be seen that the bare soil temperatures warm up faster in the spring, and the difference could be applied to any of the charts for other locations in the state. For instance, the 60° F temperature is normally reached in late April at the 1-inch depth under bare soil but not until early May at 4 inches under sod. This difference of about 12 days could be universally applied for the spring warm-up at any other location in the state.

Table 10 has been prepared for certain temperatures and planting depths to convert from average date of 4-inch temperature under sod to the average date of that temperature under bare soil. For example, the farmer at Mayfield who found that the temperature at 4 inches below the sod normally reached 50° F on March 20 would subtract 7 days and find that the temperature at 1 inch under bare soil normally reached 50° F on March 13. The 2-inch temperature under bare soil normally reaches that point on March 14.

TABLE 10.–CORRECTIONS* TO BE MADE TO 4-INCH SOD TEMPERATURE DATES.

	Spring (days)		Fall (days)	
Temp. (°F)	1″ bare	2″ bare	1″ bare	2″ bare
45	- 5	- 4	+ 9	+ 9
50	- 7	- 6	+ 8	+ 8
55	- 9	- 8	+ 5	+ 6
60	- 12	- 10	+ 4	+ 5
65	- 14	- 11	+ 1	+ 2

*Days earlier (-) or later (+) than those associated with the temperature 4 inches under sod.

FREEZING OF SOILS DURING THE WINTER SEASON

Until recently, soil temperature data for Kentucky locations were limited to that obtained for special studies for one or two locations, and published data were sparse. Figure 15, "Average Depth of Frost Penetration," was prepared from "information collected from unofficial sources" (3). The regular reports from 15 National Weather Service stations have provided us with considerably more information. Figure 16 shows for a 5-year period (1967-71) the "Number of Days In An Average Year with Minimum Temperatures Less Than 32° F Inches Below the Surface Under Sod." It will be noted that over much of Kentucky there are few or no days with temperatures below 32° F at the 4-inch depth under sod. At Lexington, the average for the 5-year period was 5 days.

Table 11 demonstrates the effectiveness of a sod cover as a blanket to retain heat. At Lexington there were 5 days with temperatures below 32° F at the 4-inch depth under sod, but 13 days under bare soil. This same insulative effect is apparent at a number of depths below the surface. This table also lists for Lexington the number of days below 30° F and 28° F and the lowest temperature recorded at each depth below the surface in the 5-year period 1967-71.

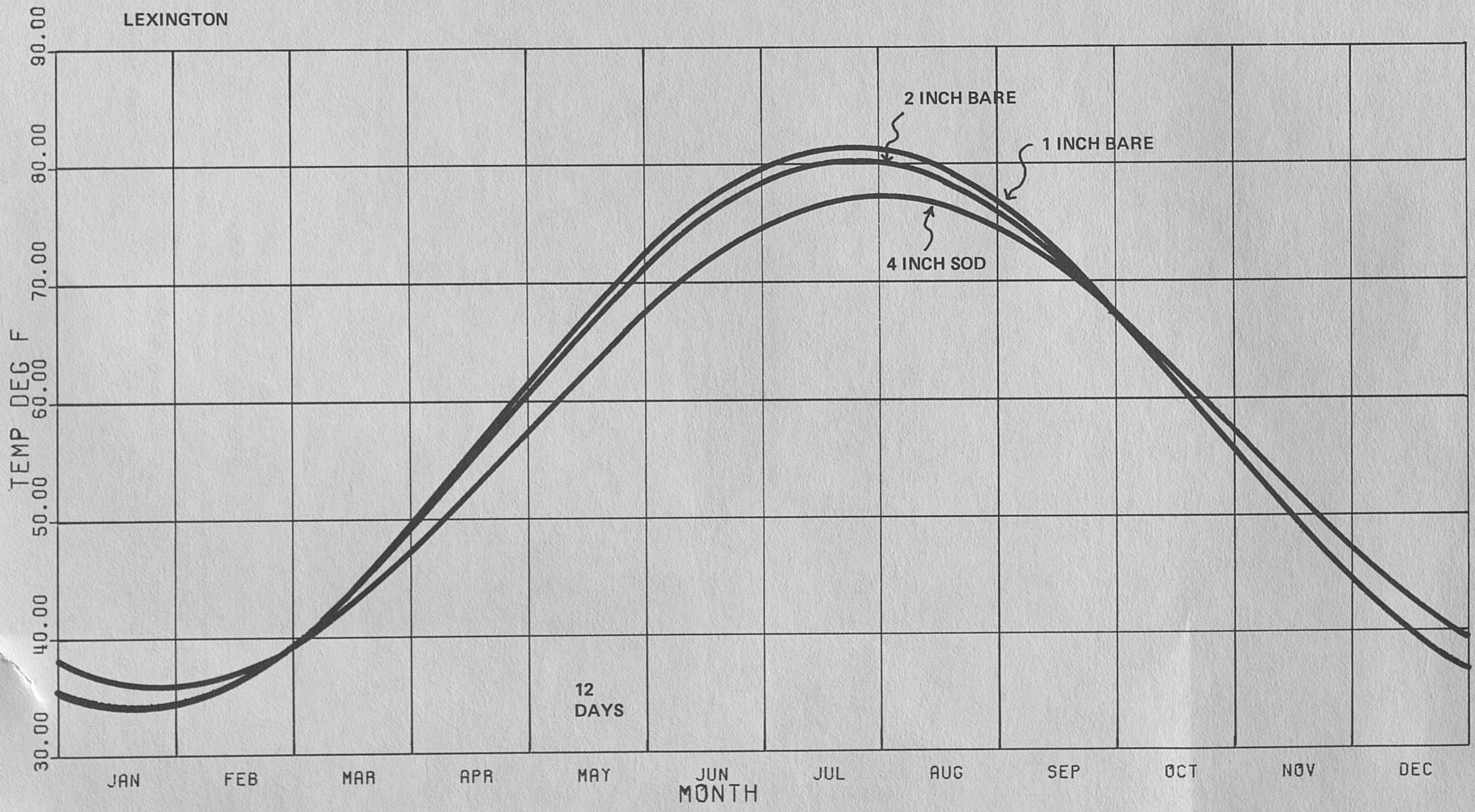

Fig. 14.—Soil temperature data for Lexington, Ky., at depths of 1, 2 and 4 inches.

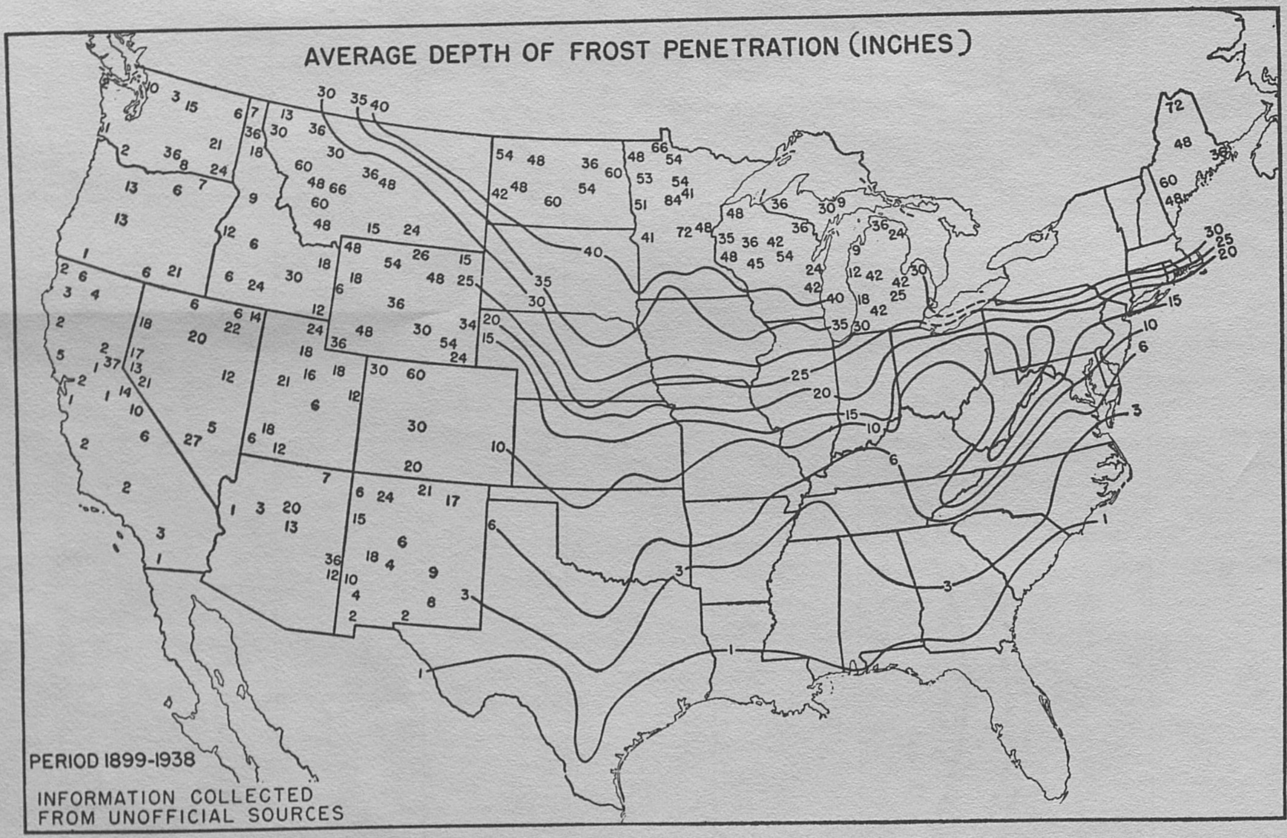

Fig. 15.—Average depth of frost penetration (inches), U.S.

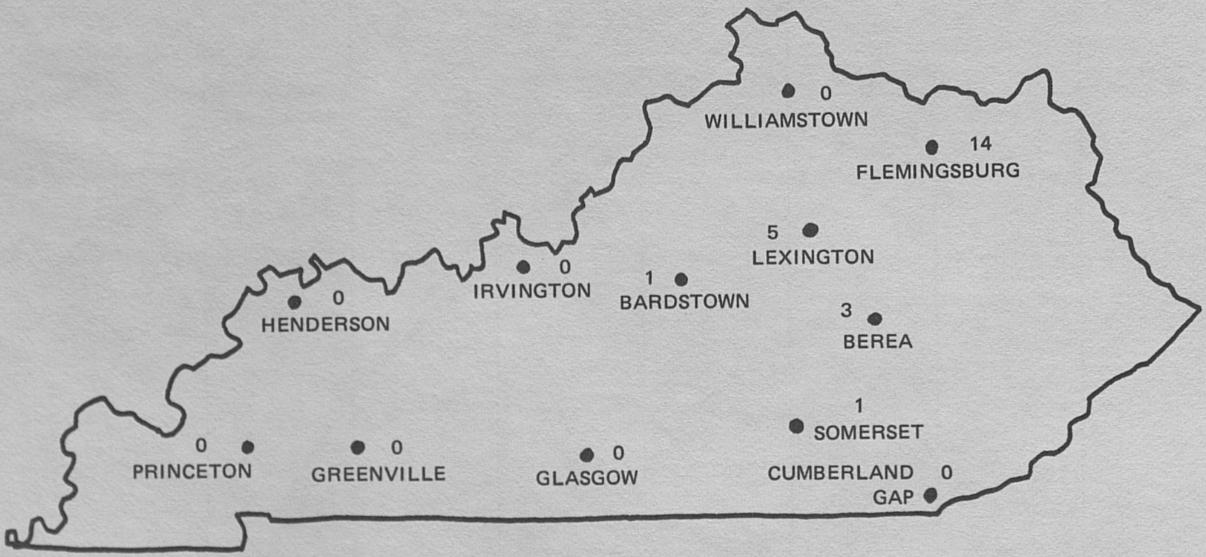

Fig. 16.—Number of days in average year in Kentucky with minimum temperatures less than 32°F at 4 inches below sod surface. Data period: 1967-71.

TABLE 11.–LOW SOIL TEMPERATURES, LEXINGTON, KY., 1967-1971.

Number of days in Average Year the Soil Temperature Fell Below
32°, 30°, 28° F. and Lowest Temperature Recorded (°F)

Inches Below Surface	Days Below 32° Under Bare Soil	(Sod)	Days Below 30° Under Bare Soil	(Sod)	Days Below 28° Under Bare Soil	(Sod)	Lowest Temperature Under Bare Soil	(Sod)
1	33	12	19	1	12	*	15°	14°
2	26	8	13	0	8	0	17°	30°
4	13	5	7	0	4	0	18°	30°
8	8	*	0	0	0	0	30°	31°

*Less than 0.5 day. Other data rounded.

Figure 16 and Table 11 do not indicate the actual depth of penetration of freezing temperatures since observations were made only at certain points in the profile. However, they should be of value in supplying some indications of frequency and extent of penetration of freezing temperatures. Penetration of freezing temperatures at a given site is dependent on a number of factors–including moisture content of the soil, soil type, soil cover, and topography. Therefore, it is suggested that for specific locations the data in the attached figures and table be supplemented by actual reports. For example, utility companies and cemetery custodians often can supply such information.

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