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Soil Temperatures under Urban Trees and Asphalt

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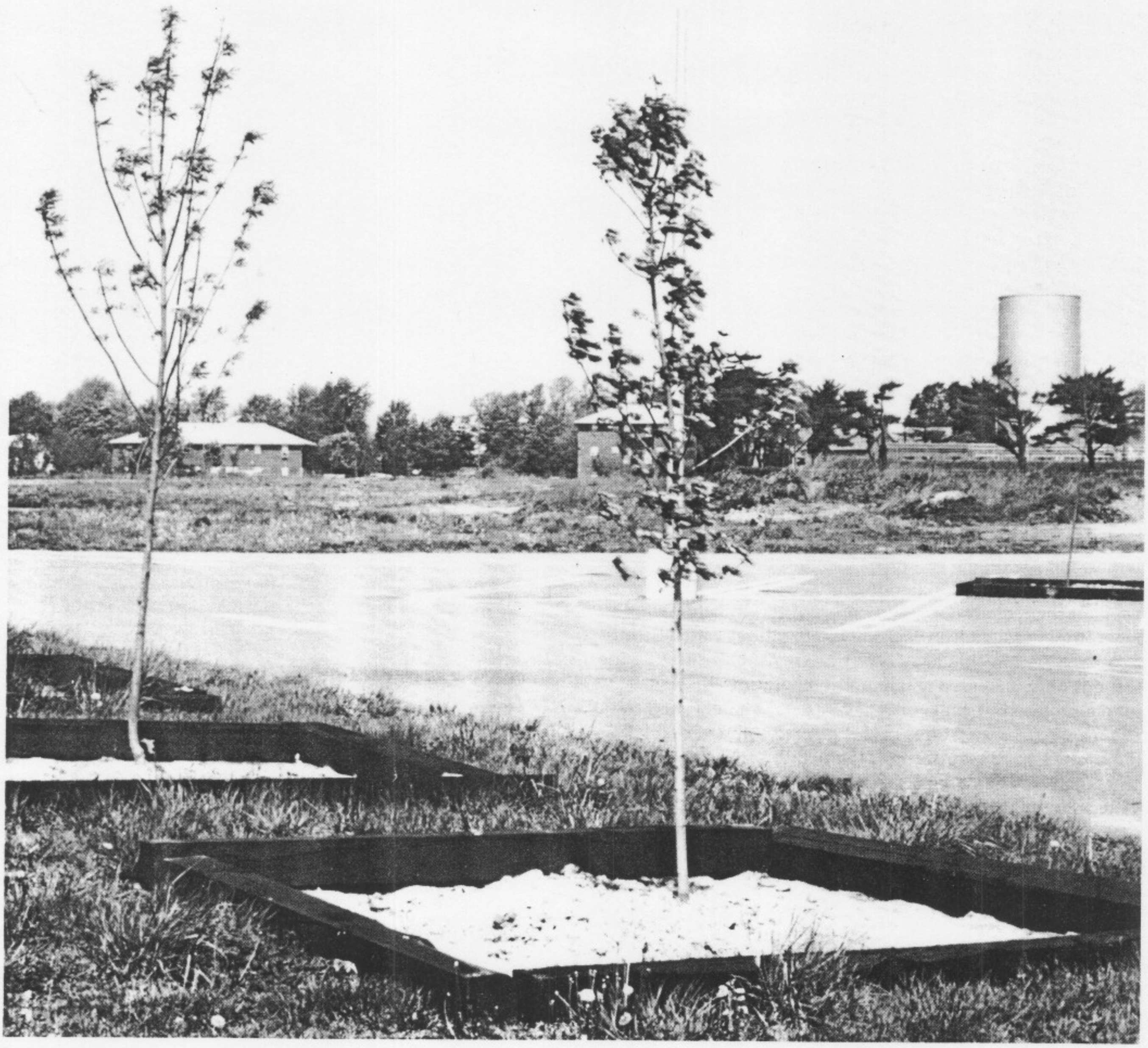

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Abstract

Summer temperatures under trees planted in holes cut through an asphalt cover in a parking lot and in soil beneath the surrounding asphalt were higher than soil temperatures under trees at a control site. Winter minimums were not different, but maximum summer temperature exceeded the control by 3°C beneath the parking lot trees and up to 10°C beneath the asphalt cover at a depth of 15 cm below the surface. Horizontal and vertical soil temperatures varied little at a given time within each type of site. Asphalt covering the soil not only increased maximum temperatures through a 60-cm profile, but apparently increased the rate of heat exchange since temperatures in the covered soil rose and fell more rapidly than control soil temperatures. The soil, even when covered, could be a sink or source of excess heat exchange in the urban energy balance.

Introduction

The soil temperature, as well as the rate and direction of heat transfer, is important to those managing urban forest vegetation or concerned with trends and modeling of urban climate. Heat and moisture are transferred simultaneously in the soil, especially near the soil surface. This can affect tree water stress by changing the distribution of soil water and the water demand of trees. Sap velocities in an urban honeylocust were shown to be 10 percent greater than sap velocities in a suburban tree (Christensen and Miller 1979), indicating greater water use by the urban tree. Evapotranspiration from urban grass was shown to exceed potential rates by about 30 percent (Oke 1979). These authors attributed excess water demand to advected sensible heat in the atmosphere over impervious surfaces. However, soil can be a major sink or source of energy during the different seasons and may also act to modify the urban climate. Extreme soil temperatures can be lethal to vegetation. Consequently, urban soil temperatures have significant impacts both on the urban environment and on urban forests.

Forest soil temperatures are responsive to many environmental factors. Soil temperatures are known to be changed by moisture conditions (Leonard et al. 1971, Willis et al. 1977). Bocock and his coworkers (1977) derived good predictive equations for forest soil temperatures from air temperature, wind, solar radiation, and precipitation data. However, the impact of an asphalt cover on forest soil temperatures has not been investigated.

Parking lots are a significant portion of urban areas. Shopping centers, for example, require three to four times as much parking space as retail space (Lull and Sopper 1969). The urban lots have little aesthetic appeal, and trees are often planted to improve their appearance and thermal comfort. However, urbanization may create a difficult environment for forest vegetation. Himelick (1976) lists insufficient soil moisture, nutrient deficiencies, and pollution, as well as insect and disease problems, as urban stress factors. Both soil moisture and soil temperature stresses could be increased by development.

The purpose of this study was to examine soil temperature at an urban forest site and determine whether soil temperatures were strongly influenced by one form of development, an asphalt cover. The temporal distribution of temperature is important, as well as the maximum and minimum temperatures and the rate of temperature change in the soil. In this study, we measured temperatures in the soil beneath 8 newly-established trees at a control site, beneath 32 similarly established trees in an adjacent parking lot, and at three points in the soil beneath the asphalt cover of the lot. The composite of trees on the lot could be considered to be an urban forest or a portion thereof.

Study Site and Procedures

The study site was on and near a university parking lot at New Brunswick, New Jersey (lat. 40°29′N, long. 74°26′W). The lot was 192 m by 50 m, only slightly less than a hectare. The lot slopes slightly eastward, across the narrow dimension, to promote drainage.

Three years after its construction, the lot underwent a major modification to improve its aesthetic value. In April of 1976, 32 gaps spaced about 18 m apart, each approximately 2.5 m square, were cut through the surface of the asphalt, and 32 trees were planted on the site. The aggregate of these 32 trees was our urban forest for soil temperature measurements. The control site consisted of 8 additional trees planted in an undisturbed area about 4 m from the lot. Planting material consisted of 5-year-old red maple (*Acer rubrum* L.) and green ash (*Fraxinus pennsylvanicum* L.) saplings, half bare root and half with a soil ball around the roots. Each parking lot and control planting location was curbed with railroad ties and backfilled to a level 10 to 15 cm above the surrounding surface. The fill gradually settled, and a thin layer of wood chips was added to control weeds.

The Soil

The soil exposed for planting beneath the lot cannot be described in the usual manner, because it had been disturbed by development activities. The parent soil is a somewhat poorly drained variant of the Nixon series in Middlesex County, NJ (U.S. Soil Conservation Service 1976). The topsoil in the series is usually about 30 cm deep and is classified as a silt loam. The subsoil, from about 30 to 84 cm deep, is higher in clay and is a silty clay loam. Depth to the water table was about 60 cm, so lower soil levels were frequently saturated.

During construction of the parking lot, roughly 50 cm of soil was removed from the site. There was some deeper disturbance to install utilities in parts of the area. The soil was not replaced; rather, a layer of coarse sand was spread over the remaining subsoil. The sand was capped with a 15-cm layer of asphalt.

The soil was completely changed during development of the lot. As shown in Table 1, the original horizons were destroyed, texture was changed, and pH was altered. The sand layer, although spread between 20 and 50 cm below the original surface, affected all layers in the soil, probably by mixing during construction activities. A new soil profile was created, almost a meter deep, that was unlike the parent profile.

The control trees were planted off the edge of the lot, sufficiently separated so that the Nixon soil was not disturbed by construction.

Table 1.—Physical properties of the undisturbed and disturbed soils

Property	Undisturbed soil adjacent to the lot depth, cm		Disturbed soil beneath lot approximate depth, cm		
	0-30	30-84	0-20	20-50	50-84
Percent sand	35	6	40	85	65
Percent silt	50	59	32	10	10
Percent clay	16	35	28	5	25
pH	6.8	5.0	5.4	5.9	5.4

Instrumentation

During and after tree planting in 1976, instruments were added to measure both soil moisture and soil temperature. The basic instrument chosen was the double-junction thermocouple psychrometer. One junction was used for soil water potential determinations and the second for soil temperature measurement.

The surface above the sensors was shaded by the tree crown, but the shadows were small and probably had little, if any, significant effect on soil temperatures at the depths of our measurements. Also, all temperatures we measured would have been influenced about equally by shade.

Eight of the openings that had been created in the lot surface were selected randomly for intensive instrumentation. At these points, a series of three psychrometers was installed at 15, 30, and 60 cm below the bottom of the railroad ties. We did not use the existing fill surface as a depth reference because settling caused changes in the surface elevation. These psychrometers were in the tree root zone but offset approximately 38 cm from the tree bole; in fill material around the trees that were planted as bare root stock and on a vertical line tangent to the soil ball on trees planted as balled stock. At three of the eight locations, psychrometers were also installed laterally beneath the asphalt, 30 cm behind the edge of the covering. At each of these locations, three psychrometers were installed at the same depths below the surface of the asphalt as the sensors in the root zone.

Four of the eight control locations were also instrumented with a series of three psychrometers extending through the root zone at 15, 30, and 60 cm below the bottom of the railroad ties, depths equivalent to those used on the experimental site.

Each of the other tree locations on the parking lot and in the control area was instrumented with a thermocouple psychrometer in the root zone 30 cm below the surface. During the summer, soil moisture tensiometers were installed at five parking lot tree locations when soil water potential was above the range where psychrometers are reliable (-1 bar). Three locations on the lot and one control location were also instrumented with ground water observation wells to follow changes in water table elevation.

Because of changes in the soil surface caused by fill added after planting and settling around the trees, the psychrometers in the root zone were not exactly the same distance below the surface as the psychrometers below the asphalt. The depth discrepancy was not considered a major shortcoming since the study objective was to determine the impact of the asphalt, rather than to document the vertical temperature profile.

Temporal Sampling

All of the instrumentation (except the tensiometers) was installed and had equilibrated by mid-November 1976. Sampling began in mid-November and continued until January 1, 1978. Temperature and moisture determinations were scheduled weekly, although adjustments had to be made on some occasions. Readings were taken during a one-hour period near midday.

Of the 73 psychrometers installed, one failed shortly after installation, and a second was vandalized in May 1977. The remaining sensors were operative during the entire 58-week period. Soil water potential and soil temperature values were read from the psychrometer junctions with a Wescor HR-33T microvoltmeter.[1] Accuracy of the equipment for temperature measurement was ±0.5°C.

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

Results

Soil Water Regime

The water table below the lot remained relatively stable, although there was some fluctuation with precipitation (Table 2). The five wells that were installed varied in absolute elevation by about a meter, owing to fluctuations in lot surface elevation. Only one well, the lowest, reached the water table during the entire growing season; it was monitored to determine the depth to the water table. The other wells, all slightly higher in elevation, reached the water table only intermittently and data from them were not included in Table 2. The water table fluctuated at a depth of about 50 cm below the surface at the lowest well. Depth to the water table before and after the 1977 growing season was about equal to the depths recorded during the growing season.

Table 2.—Depth to the water table, precipitation since the preceding measurement date, and average soil water potential beneath parking lot trees measured with tensiometers at five different locations and at 30 and 60 cm below the surface during 1977

Date	Depth to water table	Precipitation	Average soil water potential at: 30 cm	60 cm
	--------- *cm* ---------		-- *negative bars* ---	
6-27	50			
7-11	50	2.82	0.06	0.04
7-15	45	5.46	0.04	
7-18	51		0.12	0.07
7-25	58	0.36	0.05	0.09
7-26	37		0.04	
7-28	46	4.47	0.06	
8-1	46	0.15	0.08	0.06
8-3	43		0.07	0.05
8-5	43		0.06	0.05
8-8	49	0.33	0.13	0.06
8-12	58	1.47	0.10	0.07
8-15	44	5.46	0.05	0.05
8-16	46		0.06	0.14
8-19	52	0.03	0.10	0.14
8-23	54	0.33	0.09	0.14
8-29	52	4.47	0.06	0.10
9-19	50	2.67	0.07	
9-26	35	9.30		
10-3	42	0.66		
10-17	44	6.10		
10-31	78	3.20		
11-21	60	14.66		
11-28	45	3.76		

Soil water potential at the parking lot tree site also remained high. On only one date, 11 July 1977, and then at only one of 32 locations, was a water potential less than -1 bar recorded. Otherwise, soil water potential varied between -0.03 and -0.37 bars (Table 2). Soil water potentials at the control site and beneath the asphalt never indicated a water potential less than -1 bar. We therefore assumed that the soil moisture regime was the same at all sites, although there were small differences among the planting locations on the parking lot.

Soil Temperature

The mean soil temperatures for the soil below the parking lot trees and the asphalt were compared with those under the control trees by linear regression for each depth. Soil temperature was significantly higher under the parking lot trees than in the control site, as illustrated by the regression coefficients (Table 3). All slopes were different from unity. The comparisons for each depth showed a definite relationship among the temperatures at the site, with correlation coefficients greater than .99. Under the asphalt, temperatures rose more quickly and to higher maximums, as shown by the greater slopes. Correlations between control and asphalt-covered sites were between .94 and .98.

The correlation coefficients showed a temperature relationship between the control and the other sites, but an analysis of covariance showed that the individual regressions were not significantly different.

Table 3.—Linear regression statistics relating mean urban soil temperatures for a given depth to soil temperatures at a control site based on the model $y = a_o + b_1x$, where x is the mean soil temperature at the control site at the same depth.

Depth (cm)	Sample size	Intercept a	Slope b	Standard error	Correlation r
		PARKING LOT TREE SITE			
15	43	0.23(.09)[a]	1.09(.01)[a]	0.34	0.996
30	43	0.11(.13)	1.12(.01)	0.46	0.998
60	43	0.02(.12)	1.15(.01)	0.38	0.999
		ASPHALT-COVERED SITE			
15	42	0.83(1.05)	1.29(.07)	3.91	0.940
30	42	-0.13(.63)	1.25(.04)	2.13	0.976
60	42	-0.02(.50)	1.24(.04)	1.62	0.984

[a]standard error of coefficient in parenthesis

Although the regressions are not statistically different, some trends in the data are as might be expected: Temperatures beneath the asphalt rise faster, and to higher maximums, than soil temperatures at the control or parking lot sites. The parking lot tree site showed an intermediate response, with soil temperatures above those at the control site but below those under the asphalt cover.

There was little variation in temperature among locations within each type of site. As shown in Table 4, soil temperatures at the control points rarely differed by more than 1°C at a given depth, regardless of season. The differences between parking lot tree locations at a given time or depth were almost always less than 2°C during all seasons. Although soil temperatures beneath the asphalt were more variable, the different sites responded in the same fashion, with measured temperature at only one time and depth differing by more than 2°C from the temperatures measured at the other asphalt-covered sites. Among the asphalt-covered sample points, there was also no seasonal trend.

Vertical temperature profiles were also quite uniform, with the majority of mean temperature differences between the upper and lower measurement depth less than 2°C (Table 5). The temperature distribution beneath the asphalt was more variable than at the control and parking lot tree sites, with vertical gradients as high as 8°C.

The information about horizontal and vertical temperature gradients was not examined statistically, because most temperature gradients are within the ±0.5°C range of the thermocouple and reference junction accuracy. However, the results showed that an asphalt cover tends to make soil temperatures more erratic as well as higher during midday.

The impact of covering the soil with asphalt can be seen in data from a period of fluctuating temperatures (Table 6). In mid-April, the soils began to warm rapidly. Control site soil temperatures rose 3 to 4°C in one week and about an additional degree the following week. Vertical temperature differences never exceeded 1°C. The parking lot tree site showed the same pattern, but the increases were about a degree greater. Again, the vertical temperature differences never exceeded 1°C. The asphalt-covered soil showed a 5.5 to 8°C increase the first week, followed by decreases in temperature in the upper levels the second week. By the end of the second week, a uniform vertical temperature pattern had been established. The presence of an asphalt cover apparently accelerated heat exchange.

Although an asphalt cover affected the rate of heat exchange between the underlying soil and the atmosphere, it did not affect the timing of minimum and maximum temperature by

Table 4.—Number of occurrences of soil horizontal temperature differences between replicates at the control, parking-lot-tree, and asphalt-covered sites between 15 November 1976 and 9 January 1978

Depth (cm)	Number of measurement points	Temperature range, °C		
		<1	1-2	2-3
		CONTROL SITE		
15	4	41	2	0
30	8	43	0	0
60	4	43	0	0
		PARKING LOT TREE SITE		
15	8	34	9	0
30	32	21	20	2
60	8	35	7	1
		ASPHALT COVERED SITE		
15	3	30	12	0
30	3	37	5	0
60	3	38	3	1

Table 5.—Number of occurrences of mean soil temperature differences vertically through the soil profile from 15 to 60 cm at the control, parking-lot-tree, and asphalt-covered sites between 15 November 1976 and 9 January 1978.

Site	Temperature range, °C							
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
Control	22	14	6	1	0	0	0	0
Parking-lot tree site	20	10	8.	5	0	0	0	0
Asphalt-covered site	12	10	7	3	6	2	0	2

Table 6.—Average soil temperatures at three sites during a period of temperature fluctuation, in °C

Depth (cm)	Date		
	4-11-77	4-18-77	4-25-77
	CONTROL SITE		
15	6.2	10.2	11.1
30	6.1	9.9	11.1
60	6.5	9.5	10.8
	PARKING-LOT TREE SITE		
15	7.1	12.2	12.9
30	7.2	11.9	13.4
60	7.6	11.6	13.1
	ASPHALT-COVERED SITE		
15	12.2	20.0	14.2
30	9.7	16.5	14.5
60	9.2	14.7	15.3

Table 7.—Maximum and minimum mean soil temperatures and the date the temperature was recorded

Depth (cm)	Minimum temperature	Date	Maximum temperature	Date
	°C		°C	
		CONTROL SITE		
15	0.8	2-14-77	24.4	7-18-77
30	1.2	2-14-77	23.2	7-18-77
60	2.1	2-14-77	22.5	7-25-77
		PARKING-LOT TREE SITE		
15	0.8	2-14-77	27.1	7-18-77
30	1.2	2-14-77	26.4	7-18-77
60	2.1	2-14-77	25.9	8-15-77
		ASPHALT-COVERED SITE		
15	0.5	2-14-77	34.2	7-18-77
30	1.2	2-14-77	30.7	7-18-77
60	2.0	2-14-77	28.8	7-18-77

more than a week (Table 7). Minimum temperatures at all sites and all depths were recorded on the same day, 14 February. The temperatures at a given depth did not differ significantly among sites, although temperatures at the lowest measurement level were warmer than temperatures near the surface. Minimum temperatures had been less than 1°C above the tabular values for the preceding 4 weeks. Maximum temperatures increased from control to parking-lot-tree to asphalt-covered sites, but most maximums occurred in mid-July, regardless of site. At the parking-lot-tree and asphalt-covered sites, the maximum temperature at the lowest depth varied by less than 1°C between mid-July and mid-August, and that difference was within the resolution of the thermocouples. Increasing urbanization, as represented by increasing amounts of asphalt cover, increased the amplitude of the temperature wave in the soil but did not alter its timing within the 15 to 60 cm zone.

Conclusions

Construction activities changed the upper soil horizons in our study lot by mixing the soil and adding sand. These activities and the consequent changes in the soil limited the value of existing soil surveys for describing the soil. Structure, pH, texture, and soil horizons were all altered in the upper level of the soil, which is the most important for vegetation. In this lot, soil moisture remained high in the gaps cut for the trees, probably because of the high water table.

Soil temperatures were altered, both in the parking-lot tree site and under the surrounding asphalt cover. Temperature differences we observed can be categorized into changes in trend, horizontal and vertical distribution, timing of maximum and minimum temperatures, and magnitude of maximum and minimum temperatures. These temperature changes could affect vegetation directly through thermal effects or indirectly by modifying local energy balances in urban forests.

The trend of soil temperatures was clear. If we consider the series from soil beneath off-lot trees, to soil beneath on-lot trees, to soil beneath asphalt, as representing increasing degrees of urbanization, then urbanization results in higher soil temperatures. During winter, at the lowest temperatures, this effect was negligible, but it increased with increasing soil temperatures.

Increased soil temperatures at the parking-lot tree site and under asphalt were well distributed in the soils, both horizontally and vertically. The even temperature distribution is consistent with the conclusion of others that mean soil temperatures do not vary a great deal below 2 inches (Toy et al. 1978).

These results suggest the magnitude of the effect of an asphalt cover on the urban surface energy balance. The properties of asphalt are not well defined, because the composition of the material can vary. However, most thermal properties of asphalt are not greatly different from those of moist soil.

Since temperature fluctuations occur more rapidly under asphalt than in adjacent soil, we conclude that covered urban soil acts as a responsive sink or source of heat in urban environments. The contribution of soils to urban thermal extremes needs additional study.

The thermal responsiveness of the soil resulted in two other effects: Maximum temperatures occurred on all sites in the same week; so did minimum temperatures. Neither the highest nor the lowest temperatures at any site would preclude plant growth, since most plant limits are below freezing or in the 50 to 60°C range (Kramer and Kozlowski 1960). These extremes were never reached, even under the asphalt cover.

The study results and conclusions can be summarized as follows:

1. The urban energy balance is changed by an asphalt covering. Not only the paving, but the underlying soil contributes to increased storage and release of heat.

2. Direct thermal effects on trees were not severe.

3. Asphalt covering increased summer maximum soil temperatures but had no effect on winter minimums.

4. The timing of the annual soil temperature wave was not altered significantly by an asphalt cover, but the amplitude was increased.

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An asphalt cover increased summer soil temperatures throughout a 60 cm profile but did not affect winter soil temperatures. Horizontal and vertical temperatures were consistent within a site type. The rate of heat transfer between the atmosphere and the soil apparently was increased.

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