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SOIL TEMPERATURE IN A DECIDUOUS WOODLAND IN NORTH-WEST ENGLAND

by

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SUMMARY

Temperature was recorded hourly at six soil depths from 0-50 cm over three years and variation with soil depth, season and year was analysed. A sine surve accounted for over 90% of the variability in mean temperature for individual weeks. Mean temperature for the year ranged from 8.3° to 9.2° and varied < 0.23°C with soil depth in any year and < 0.85°C between years at any soil depth. Phase angle and amplitude of the annual curve varied markedly between years and decreased significantly with soil depth. Temperature lags (0-50 cm depth) were 14.5, 14.0 and 15.0 days in the three years. Damping depths (daily basis) were 10.7, 10.5 and 10.1 cm. Thermal diffusivities (0-50 cm) ranged from 3.72 to 4.25 cm^2 sec^{-1} x 10^{-3}.

Of several climatic variables, air temperature had a dominating influence on soil temperature under the tree canopy. Solar radiation had little direct effect and soil moisture an approximately constant effect. The number of days with a mean greater than 5.6°C was lower and the accumulated temperature above 5.6°C higher at 0 cm than at 50 cm depth.

INTRODUCTION

Soil temperature regimes of many woodland sites in Britain have been outlined but few detailed accounts exist (Coutts, 1955; Smith, 1970). Regimes in some temperate woodlands outside Britain have been detailed (Geiger, 1965). This paper describes the soil temperature of a main International Biological Programme (IBP) site in Meathop Wood, south Cumbria (Nat. Grid ref. SD 435796), its variation with time and soil depth, relations with climatic variables, and implications for biological activity. It also discusses heat transfer through the soil.

Soil temperatures were required in the IBP study to allow

a. the setting up of laboratory experiments at field temperatures,

b. correction of soil organism metabolic rates for differences in temperature between laboratory and field, and,

c. comparison of temperature and metabolic data within the site spatially and temporally and with data from other sites.

DATA COLLECTION AND ANALYSIS

Soil temperature was recorded hourly using thermistor probes linked to a Grant strip-chart recorder (Bocock 1973). Data were extracted from the charts manually or semi-automatically and processed by computer. All values were corrected for a recorder error which varied systematically with the temperature being recorded (Bocock 1973). After this correction, individual hourly temperatures had a maximum error of about ± 2.5°C if all the errors were additive (Bocock 1973).

Mean air temperatures under the tree canopy 80 m from the soil temperature recording area were measured using 2 Grant probes exposed to freely circulating air but screened from direct insolation 43 cm above the soil (Howard & Howard 1974). Other meteorological variables, including screen air temperature (Table 2),were measured in 2 clearings 25 m and 250 m from the soil temperature site. They therefore provided only an index of conditions under the canopy (Bocock *et al.* 1977b). Day length was extracted from Nautical Almanacs (Royal Greenwich Observatory, 1966-69).

Soil temperature variation in the particular hectare studied in the IBP was measured at the base of the 01 horizon at 23 points selected by stratified random sampling from a grid of 30 standard sampling points (Bocock 1973). Recording began in April 1966, when the trees were leaflesss, and continued until June 1966, when the canopy was in full leaf. Means and ranges of hourly temperatures were calculated for the 2 or 3 days in each month on which the range was greatest.

Although measurements were made near the soil surface, variation in mean temperature was small (Table 1). Temperature range varied considerably, especially immediately before the trees came into leaf, presumably because of variation in characteristics of the litter layer, herb layers and tree canopy. Temperature trends across the site were not apparent.

To avoid disturbance of the hectare, a small adjacent area was investigated as a routine recording site using 6 probes placed at the base of the 01 horizon. The remaining 17 probes gave an adequate estimate of soil temperature on the hectare (Table 1). Mean soil temperatures on the small area and on the hectare in July 1966 were not significantly different but those on the small area were less variable (Table 1). Probes were installed horizontally in 4 stacks on the small area in late July 1966 and left in position until late November 1970. Stacks were located at the corners of a rectangular plot approximatley 2 m by 3 m (Bocock 1973), with probes at 0, 5, 10, 20, 30 and 50 cm (2 stacks) or 0 and 5 cm depth (2 stacks), 0 cm being the base of the 01 horizon. Data for only 3 complete years, 1 August 1966 - 31 July 1969, were extracted to give means and maximum and minimum temperatures per probe and per soil depth for individual days, weeks, months and years (Bocock 1973).

Temperature variation with soil depth, with time, and with other climatic variables, and estimation of soil temperature from other variables was examined using harmonic analysis and synthesis (Bocock *et al.* 1977b). The model used was

$$T\ (z,t) = \bar{T} + \sum_{n=1}^{N/2} a_n \sin \left(\frac{360}{P} \right) nt + A_n$$

where $T(z, t)$ is temperature at depth z and time t, $\bar{T}$ is the mean of N observed temperatures, a_n is the amplitude or half-range of the nth sine curve, P denotes the length of the fundamental period in chosen time units, eg 52 where 52 consecutive weeks are being examined, $t = 0, 1, 2 \ldots\ldots (n-1)$ and A_n is the phase angle which indicates lag of a sine curve in angular degrees compared with a curve which rises from an origin of 0°.

VARIATION IN SOIL TEMPERATURE RANGE WITH SOIL DEPTH, SEASON AND YEAR

Diurnal temperature range at 0 cm varied from virtually zero during cloudy stable weather to about 9° when very sunny daylight hours were followed by clear night skies (Fig. 1). Maximum and minimum ranges for individual days in each month changed markedly with season. The smallest ranges occurred in December-February when incident radiation was low and a thick insulating layer of litter was present above the probes, the largest in March-May just before the tree canopy came into leaf and when incident radiation was high and the litter layer had thinned considerably as a result of soil faunal activity and wind action. This seasonal pattern contrasts with that for mean temperature which peaks in July-August (Fig. 2 and below).

At 50 cm depth, as in most other soils examined (Carson 1961; Van Wijk & De Vries 1963; Meteorological Office 1968; Mochlinski 1969), diurnal temperature range approached zero (Fig. 1) and seasonal variation was much reduced. At both depths, variation between years was unremarkable except perhaps in April-July 1968 when the range was rather high at 50 cm although it was not extreme at 0 cm. This may have been an effect of warm rain (Rose 1966).

VARIATION IN MEAN TEMPERATURE WITH SOIL DEPTH, SEASON AND YEAR

As on many other sites, for example, see Carson, 1961), the main seasonal soil temperature trend was described well by a sine curve (Fig. 2). Percentage of variance accounted for decreased from 96.2, 95.8 and 95.1% at 50 cm depth to 92.2, 91.3 and 91.8% at the 0 cm in the 3 years. Comparable values for screen air temperature were only 74.9, 72.4 and 84.0%.

Change in mean temperature with soil depth was described using regressions of the mean, phase angle or natural logarithm of the amplitude of the fundamental sine term for each of the 3 years on soil depth (Figs. 3-5). Linearity of each relationship was examined by testing whether inclusion of a quadratic term significantly reduced the sum of squares of deviation from the regression. Since curvature was only just significant ($0.01 < P < 0.05$) and present in only one regression line in three for phase angle (Fig. 4) and natural logarithm of amplitude (Fig. 5), other analyses which assume linearity were undertaken.

The significance of the slope of each curve was tested by examining the t value, calculated by dividing the regression coefficient b by the sample standard deviation of the regression coefficient. Since the residual mean squares for each dependent variable showed no indication of heterogeneity using Bartlett's test,parallelism and difference in elevation of the regression lines was tested using covariance analysis.

Mean temperature for the year (Fig. 3) increased slightly with soil depth in 1967-68 ($0.01 < P < 0.02$) but did not change significantly in the other 2 years ($P > 0.20$). Change in the mean with soil depth was not significantly different in the three years ($0.05 < P < 0.10$). Elevation of the 2 closest lines, those for 1967-68 and 1968-69, differed marginally ($0.01 < P < 0.05$). Both differed highly significantly from the elevation of the 1966-67 line ($P < 0.001$).

The phase angle (Fig. 4) decreased highly significantly with soil depth ($P < 0.001$) but the slopes of the 3 regression lines were not significantly different ($P > 0.20$). Elevations of the lines for 1966-67 and 1967-68 did not differ significantly ($0.05 < P < 0.20$) but both differed from the elevation of the 1968-69 line ($P < 0.001$).

The logarithm of the amplitude of the fitted sine curve (Fig. 5) decreased significantly with soil depth ($P < 0.001$ for 1966-67 and 1967-68; $0.001 < P < 0.01$ for 1968-69) but the slopes of the lines did not differ significantly ($P > 0.20$). Elevations of the 1967-68 and 1968-69 lines did not differ significantly ($0.05 < P < 0.20$) but both were very highly significantly different from the elevation for 1966-67 ($P < 0.001$).

To summarise, the 3 harmonic parameters varied little with soil depth between years except in their elevations (Figs. 3-5), 1966-67 was significantly warmer and had a more even temperature than 1967-68 and 1968-69 (Figs. 3 & 5) and 1968-69 had the most variable temperature (Fig. 5) and a significantly later temperature fall and rise than the other two years (Fig. 4). This pattern was the effect of one or more factors which varied considerably between years and which affected temperature at all soil depths in a similar way. These requirements rule out soil factors except moisture. The latter varied little from November 1966 to September 1968, 45.6 ± S.E. 2.2%, $n = 21$ (Gray *et al.* 1974). Moreover, precipitation at Meathop in August-July, 1966-67, 1967-68 and 1968-69, respectively 126.4, 146.7 and 106.0 cm, was distributed fairly evenly over each year and was retained strongly by the silt-clay loam soil. Soil moisture therefore appeared to exert an approximately constant effect on soil temperature. In contrast, the pattern of air temperature parameters over the 3 years agreed well with the comparable pattern for soil temperature (Figs. 3-5) suggesting a functional relationship.

DAMPING DEPTH AND TEMPERATURE LAG

Damping depth (D), the soil depth at which the amplitude of the sinusoidal temperature wave is equal to the reciprocal of the base of natural logarithms, e, times the amplitude of the corresponding wave at the soil surface, increases with increasing mineral particle size, with increasing moisture content and with decreasing organic matter content (Van Wijk & De Vries 1963). For Meathop, D was estimated from the slope ($= 1/D$) of the regression of ln amplitude of the fundamental sine wave on soil depth (Fig. 5). Annual values for 1966-1969 were 204.0, 199.8 and 183.0 cm and equivalent daily values (annual value $\sqrt{365}$) 10.7, 10.5 and 10.1 cm. These depths are consistent with the observed silt-clay loam texture, the low to moderate organic matter content and the moderate moisture content of the Meathop soi, and published values for various soils, 3.3-18.5 cm (Van Wijk & De Vries 1963; Ballard 1972; Jager 1972).

Temperature lags for 0-50 cm soil depth estimated from the phase angles for the 3 years (Bocock *et al.* 1974), were 14.5, 14.0 and 15.0 days. These compare well with 12.6 days for 10-50 cm depth for a loess in Germany (Siegenthaler 1933) and 8 days per 30 cm for British soils in general (Meteorological Office 1968). The low between-year variability in the lags confirms that soil moisture varied little. The fitted fundamental sine curves (Fig. 2) peaked on 24 and 23 July and 1 August (0 cm) and 7, 6 and 16 August (50 cm) in the 3 years. These dates are close to the average dates of the last week in July (30 cm depth) and the first week in August (60 cm) for British soils (Mochlinski 1969). The late maxima in 1968-69 is consistent with the late maximum air temperature 3 August compared with 22 July in 1966-67 and 21 July in 1967-68.

HEAT TRANSFER

In a homogeneous soil, lag in maximum or minimum temperature and phase angle of the fundamental temperature wave should respectively increase and decrease linearly, and logarithm of the temperature amplitude should decrease linearly with soil depth (Carson, 1961). Moreover, annual mean temperature should be the same at all soil depths (Gloyne 1971). On these criteria, the Meathop soil appears almost homogeneous thermally. This is surprising because, although apparent homogeneity has been found in other soils Carson 1961; Ballard 1972), organic matter, and root, stone, and moisture contents vary with soil depth at Meathop. This anomaly may be due to insufficient temperature data in the regressions and/or the overriding influence of the fairly constant soil water content (see above). Alternatively, appreciable heat may be transferred down the soil profile in rainwater as suggested by Rose (1966). Thermal diffusivity was examined to help to resolve this anomaly, an average value, a, for the top 50 cm of soil, being calculated in 2 ways;

a) From the relation $a = D^2 w/2$ where D is the damping depth and w is 2π the frequency of temperature variation, that is $2\pi/365 \times 86400$ for annual variation (Van Wijk & De Vries 1963).

b) From the relation

$$a = \frac{P\ (z_2 - z_1)^2}{4\ \pi\ (\Delta\ t)^2}$$

where P is the period of the fundamental wave in seconds, z_2 and z_1 are the 2 soil depths in cm, and Δt is the lag in seconds between the waves at the 2 depths (Carson 1961).

Approach a) gave 4.16, 3.99 and 3.72 x 10^{-3} cm^2 s^{-1} whereas b) gave 4.12, 4.10 and 4.25 cm x 10^{-3} cm^2 s^{-1} for the 3 years. Results from the 2 approaches therefore agree well and are similar to published values for British soils, 2 - 10 x 10^{-3} cm^2 s^{-1} (Meteorological Office 1968) and an average of 8 x 10^{-3} cm^2 s^{-1} (Mochlinski 1969).

Diffusivities for individual soil strata varied greatly with soil depth within a year and between years at one soil depth (Fig. 6). No one year gave consistently higher or lower diffusivities in all strata but values tended to increase with soil depth. Those for the more organic and porous top 5 cm were significantly lower ($0.01 < P < 0.025$) than those for the 30-50 cm stratum in a one-tailed t test. This parallels results for a sandy loam soil under conifers with diffusivities of $0.1\text{-}0.5 \times 10^{-3}$ $cm^2 s^{-1}$ for the 01 and $2.7\text{-}5.7 \times 10^{-3}$ $cm^2 s^{-1}$ for the A horizon (Coutts 1955). Clearly, the Meathop soil is not thermally homogeneous.

INTERRELATIONS OF SOIL TEMPERATURE AND OTHER VARIABLES

Many workers have examined the mathematical interrelations of soil and air temperatures but few have investigated their causal relationships. Mathematical studies of soil temperature and variables other than air temperature are few and restricted to non-woodland situations eg Carson (1961), Rahn *et al.* (1967), Ouellet (1973). Bocock *et al.* (1977b) analysed interrelations of soil temperature and other variables at Meathop in detail. Many variables were intercorrelated (Table 2) so orthogonalized regression analysis was used to obtain standardized regression coefficients which were independent of intercorrelations and therefore indicated the relative importance of each variable as an estimator of soil temperature (Table 3). Significance in estimation was tested by examining the ability of each to reduce the residual sum of squares in a step-wise series of multiple regressions.

Heat enters the soil from the sun, from warm vegetation, from the air and in precipitation. Many inputs vary markedly with season. At Meathop, seasonality was reflected in the high correlations between soil temperature and day length, screen air temperature and solar radiation (Table 2). When intercorrelations were allowed for,day length was still significant as an estimator of temperature at 0 cm (Table 3). One or more seasonally changing factors, which were not correlated with air temperature and solar radiation,were therefore operative. The condition of the tree canopy could be one of these.

As in other studies cited by Bocock *et al.* (1977b), soil temperature was correlated very highly with air temperature, particularly when intercorrelations of air temperature and other variables were excluded (Table 3). Curvilinearity of the relationship was not significant for any of the 6 soil depths ($P > 0.20$). As expected, correlation and regression coefficients were highest and intercepts lowest near the soil surface.

Air temperatures measured in a clearing and under the canopy differed but mean screen and sub-canopy air temperatures for 94 individual weeks during November 1968 - September 1970 were very highly correlated ($r = 0.992$, $P < 0.001$). Moreover, both air temperatures were very highly correlated with 0-5 cm soil temperatures under the canopy in the same period ($r > 0.90$, $P < 0.001$). Soil temperature lagged behind air temperature but was not correlated significantly with recent changes in air temperature (Table 2).

Correlations between soil temperature under the canopy and total solar radiation (0.3 - 3μ wavelength) in a clearing (Table 2) were as high as, or higher than, most similar correlations published for non-woodland areas (eg Siegenthaler 1933; Carson 1961; Rahn *et al.* 1967). However, solar radiation was not an effective estimator of soil temperature (Table 3), because of its high correlation with air temperature. The results suggest that soil temperature under the canopy was influenced much more by air temperature or some variable highly correlated with it, eg long-wave radiation emitted by vegetation, than by predominantly short-wave solar radiation (Bednarek 1966). This is supported by the similarity in pattern of the harmonic parameters for soil and air temperature in the 3 years (Figs. 3-5) and is consistent with the observation that only a small proportion of incident radiation reaches the forest floor (Hutchinson & Matt 1977).

Soil moisture influences soil temperature regimes through its effect on thermal capacity and conductivity (Jackson & Kirkham 1958). Soil moisture data were unavailable for our regression analyses but precipitation, which is correlated with soil moisture content and soil moisture tension, was included. Surprisingly, none of the moisture variables was an effective estimator of mean soil temperature (Table 2) and correlations between them and soil temperature were, with one exception, zero or weakly positive. This contrasts with the strong positive correlations between soil temperature and precipitation found by Rahn *et al.* (1967) and Ouellet (1973) for non-woodland sites. The most likely explanation is the low variability in soil moisture at Meathop mentioned above. The soil temperature/precipitation relationships must include the effects of reduced insolation and soil cooling during summer rain and of soil warming and reduced radiation from the soil during winter rain. Cooling by summer rain was never sufficient to swing the relationship from positive to negative and solar radiation and precipitation were uncorrelated.

The low correlation between soil temperature and days of low relative humidity (Table 2) and the unimportance of the latter as an estimator (Table 3) suggest that latent heat effects were relatively unimportant. This perhaps reflects the protective influence of the woodland, particularly during most of the warmer months when the tree canopy was best developed and evaporation from the soil was potentially high.

The negative coefficients for run of wind reflect its direct cooling effect and possible indirect cooling by soil water evaporation. Carson (1961) found average wind speed negatively correlated with, and a significant estimator of soil temperature change. The significance of the wind as an estimator of soil temperature at 50 cm but not at 0 cm (Table 3) may reflect a greater uptake of moisture from the deeper soil by the trees during windy weather.

ACCUMULATED SOIL TEMPERATURE

Accumulated temperature (day degrees) and the number of days on which particular mean temperatures were exceeded (days-in-excess) were calculated for 1C° intervals over the observed range of daily means and for each of the 6 soil depths (Figs. 7-9). At each depth, day degrees and days-in-excess varied between years, particularly at the lower temperatures (Fig. 7). These differences appear to be responsible for the higher mean temperature in 1966-67 than in 1967-69 (Fig. 3). For both variables, the 3 curves were virtually identical in the upper half of the temperature range, where the effect on chemical or biological processes is greatest. Temperature differences between years may therefore have less effect on soil processes than annual means suggest.

The days-in-excess tended to be lower for 0 cm than for 50 cm at the lower temperatures and vice versa for the higher temperatures. Day degrees also tended to be slightly greater for 0 cm than for 50 cm at the higher temperatures. Regressions of days-in-excess or accumulated temperature on soil depth may therefore be difficult to interpret in relation to soil organism activity. Fig. 8, for example, indicates that the 'growing season' (Gloyne 1958) was significantly longer ($0.01 < P < 0.05$) at 50 cm than at 0 cm. However, accumulated temperature was significantly higher ($0.01 < P < 0.05$) near the soil surface than at 50 cm (Fig. 9).

Days-in-excess or accumulated temperature tend to be the same or slightly higher for soil than for air (French 1974) hence the accumulated temperatures above 6°C at 0 cm at Meathop, 1200-1300 day degrees (Fig. 7), are consistent with the location of the site in the 1111-1389 day-degree zone on the basis or air temperatures (Gregory 1954). French (1974) found accumulated temperatures of 3454, 3460 and 3460 day degrees above 0°at the soil surface for 3 frost-free sites at 30 m altitude in wester Mayo, Ireland. The values for Meathop at 45 m (Fig. 7) agree closely with these data. Smith (1970) found 178 and 182 days had means in excess of 6°C at 10 cm soil depth inside and outside a pine plantation in County Durham. These values are considerably lower than those for Meathop (Fig. 7), probably because of the difference of 400 m in altitude between the sites (Ministry of Agriculture, Fisheries and Food, 1966).

COMPARISON OF SOIL TEMPERATURE MEANS AND RANGES AT MEATHOP AND ON OTHER SITES

Discussion above of temperature lag with soil depth, damping depth, thermal diffusivity and accumulated temperature suggests that the soil temperature regimes at Meathop and at other sites are compatible. For comparisons of temperature means and ranges, Meteorological Office (MO) sites under short turf provide the majority of available data.

Rankings of the years 1966-69 on the basis of mean temperatures at 30 cm depth were similar for Meathop and for the 5 MO sites closest and most similar to Meathop in altitude and exposure (Table 4). Means at 30 cm for individual years at Meathop were not significantly different ($P > 0.05$, 1966-67 and 1968-69) or were marginally lower ($0.01 < P < 0.05$, 1967-68) than the average for the 5 MO sites. When 0.35°C was added to each of the MO means to correct bias associated with time of recording (Mochlinski 1969), the Meathop means were all lower than the corresponding MO means, significantly so for 1967-68 and 1968-69 ($0.01 < P < 0.05$). Temperature range, as indicated by range of monthly means, was less at Meathop than on the other sites (Table 4).

Meathop falls in the 9.0°C-9.5°C zone on Mochlinski's (1969) soil temperature map for Britain based on annual means for 1921-50. Since the latter are 0-0.2°C less than the 1941-70 means (Meteorological Office 1975). Meathop means for 1966-67, 1967-68 and 1968-69 were lower than the 1941-70 mean.

In a separate study, temperature was measured at 5 cm soil depth in 48 Lake District woodland, including Meathop, using the sucrose inversion technique (Bocock, Bailey & Adamson 1977a). Exponential mean temperature for May 1971-May 1972 at Meathop was 9.4°C. With a temperature range of about 10°C, this mean was about 0.5-1.0°C higher than the corresponding arithmetic means. The Meathop arithmetic mean for 1971-72 thus agrees well with arithmetic means for the site in 1966-69 (Fig. 3).

The above discussion suggests that the Meathop 1966-69 soil temperatures were typical of temperatures in north-west England and probably of a longer run of data if differences between temperature regimes under grassland (MO sites) and woodland (Meathop) are allowed for. Soil temperatures appeared to be lower and less variable within the wood than outside. This is consistent with the variable influence of woodland conditions on soil temperature depending on the balance between shelter, which raises the winter minimum, and shading, which reduces the summer maximum (Kittredge 1948; Smith 1970). Usually the latter exceeds the former so the mean for woodland is lower than that for adjacent non-woodland areas (Cooper 1973).

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Table 1. Variation in mean temperature at the base of the 01 horizon

A. Variation across the IBP hectare

Day	Mean of mean temperatures for individual probes ± S.E. (°C)		Mean of hourly temperature ranges ± S.E. (C°)
	n=17	n=23	n=23
8.4.66	6.5 ± 0.05	6.5 ± 0.04	3.5 ± 0.12
9.4.66	6.6 ± 0.03	6.6 ± 0.03	1.3 ± 0.06
10.4.66	7.1 ± 0.04	7.1 ± 0.04	4.1 ± 0.27
7.5.66	8.8 ± 0.07	8.7 ± 0.08	7.0 ± 0.49
8.5.66	8.4 ± 0.03	8.3 ± 0.03	3.1 ± 0.17
9.5.66	9.3 ± 0.09	9.3 ± 0.11	7.7 ± 0.69
12.6.66	14.8 ± 0.06	14.8 ± 0.05	2.0 ± 0.12
13.6.66	14.5 ± 0.06	14.5 ± 0.05	2.6 ± 0.16

B. Variation between the hectare and a small adjacent area

	Hectare n=17	Adjacent area n=6	Hectare n=17	Adjacent area n=6
8-9.7.66	15.1 ± 0.11	15.2 ± 0.11	4.3 ± 0.34	3.3 ± 0.21

In both A. and B., the 2 means given for each day were not significantly different (P > 0.20). In B, the ranges were significantly different (0.001 < P < 0.01)

	Mean soil temperature (°C)													
	0cm	5cm	1	2	3	4	5	6	7	8	9	10	11	12
1. Mean air temperature, °C, week (N)	0.918***	0.839***	1											
2. Mean air temperature, °C, week (N)-week (N-1)	-0.030	-0.177	0.260*	1										
3. Mean air temperature, °C, week (N)-week (N-2)	-0.060	-0.073	0.305*	0.442***	1									
4. Mean air temperature, °C, week (N)-week (N-3)	0.099	-0.045	0.385***	0.543***	0.610***	1								
5. Total solar radiation (J cm^{-2})	0.668***	0.553***	0.665***	0.161	0.228	0.274*	1							
6. Total solar radiation (J cm^{-2}), week (N-1)	0.741***	0.652***	0.702***	0.016	0.104	0.191	0.871***	1						
7. Mean day length (min), week (N)	0.747***	0.630***	0.698***	0.082	0.142	0.160	0.936***	0.922***	1					
8. Total run of wind (km) week (N)	-0.233	-0.287*	-0.166	0.133	0.113	0.160	-0.311*	-0.304*	-0.238	1				
9. Total run of wind (km) week (N-1)	-0.261*	-0.320**	-0.174	-0.155	0.073	0.099	-0.164	-0.278*	-0.167	0.576***	1			
10. Duration (d) of low relative humidity (<80%), week (N)	0.019	-0.086	0.035	0.108	0.174	0.102	0.580***	0.387**	0.507***	-0.045	0.191	1		
11. Total precipitation (mm), week (N)	0.198	0.256*	0.110	-0.199	-0.165	-0.280*	-0.162	-0.024	-0.039	0.260*	-0.024	-0.400	1	
12. Total precipitation (mm), week (N-1)	0.146	0.121	0.141	0.155	-0.041	0.010	-0.066	-0.135	-0.036	0.165	-0.371**	-0.152	0.155	1

N = 67 for all analyses week N = current week *0.01 < P < 0.05 **0.001 < P < 0.01 ***P < 0.001

Table 3. Results of multiple and orthogonalized regression analysis of climatic data

		Standardized regression coefficients		Significance of reduction of residual sum of squares by inclusion of variables	
		0 cm	50 cm	0 cm	50 cm
1.	Mean air temperature ($^\circ$C), week (N)	0.898	1.000	**	***
2.	Mean air temperature ($^\circ$C), week (N) - week (N-1)	-0.174	-0.266	**	***
3.	Mean air temperature ($^\circ$C), week (N) - week (N-2)	-0.070	-0.132	*	***
4.	Mean air temperature ($^\circ$C), week (N) - week (N-3)	-0.135	-0.174	***	***
5.	Total solar radiation (J cm^{-2}), week (N)	0.076	0.032		
6.	Total solar radiation (J cm^{-2}), week (N-1)	0.016	-0.062		
7.	Mean day length (min), week (N)	0.087	0.020	**	
8.	Total run of wind (km), week (N)	-0.026	-0.090		*
9.	Total run of wind (km), week (N-1)	-0.028	-0.039		
10.	Duration (d) of low relative humidity (< 80%), week (N)	-0.043	-0.033		
11.	Total precipitation (mm), week (N)	0.010	0.033		
12.	Total precipitation (mm), week (N-1)	0.062	0.032		

Only complete sets of data, 67 in all, covering the period January 1967-July 1969, and including mean soil temperature ($^\circ$C) in week (N) as the dependent variable, were used in these analyses.

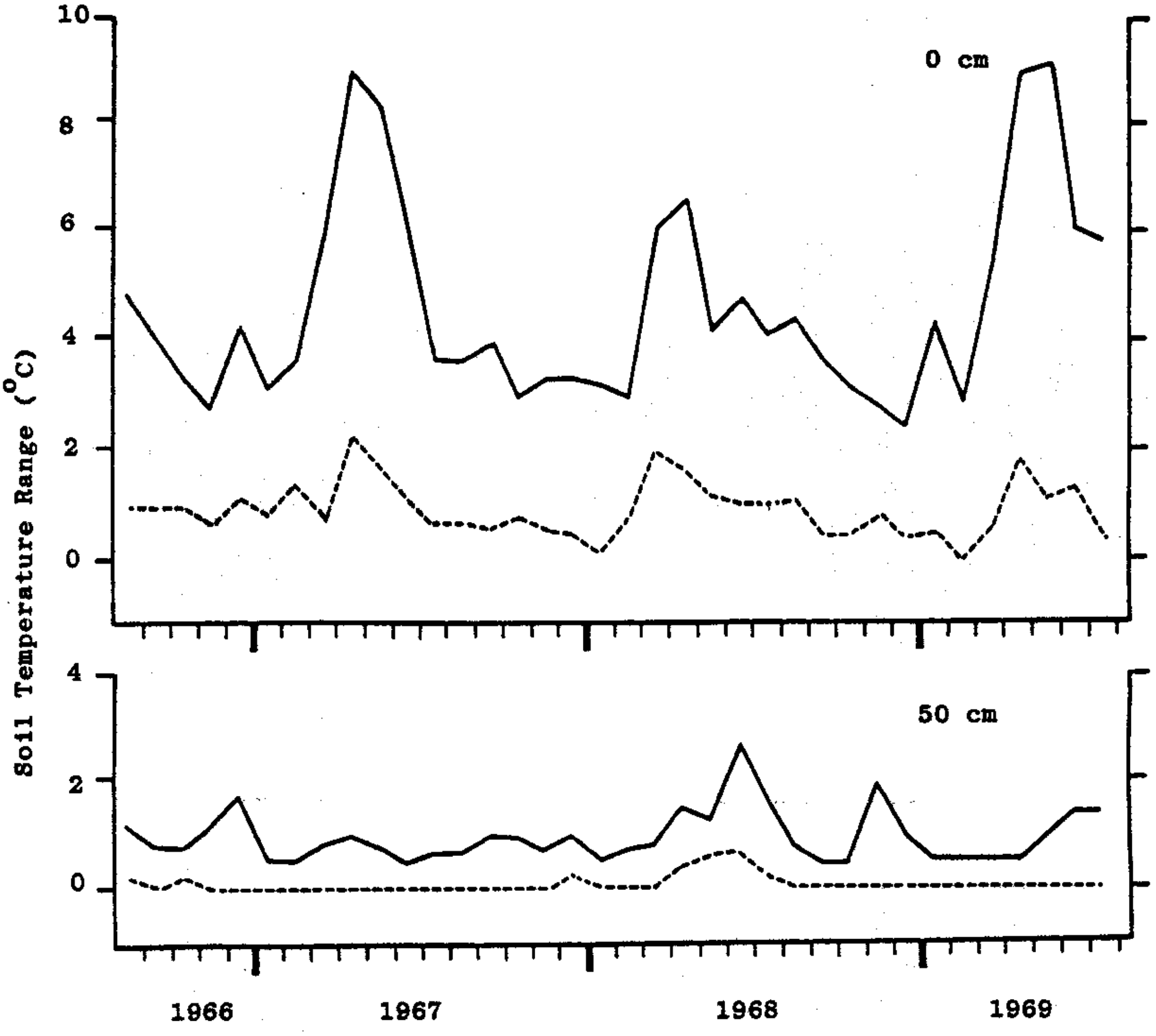
*$0.01 < P < 0.05$ **$0.001 < P < 0.01$ ***$P < 0.001$

Table 4. Mean temperature for a year and range of mean temperature for individual months at 30 cm soil depth for Meathop Wood and Meteorological Office sites in north-west England.

Site	Height above mean sea level (m)	Distance (km) and direction from Meathop	Period	Mean for the year (°C)	Range of means for individual months (°C)
Meathop	45	0	1966-67	9.2	5.3-13.0
Meathop			1967-68	8.3	3.6-13.3
Meathop			1968-69	8.5	3.2-13.0
1. Grizedale	91	17 NW	1966-67	9.4	3.6-15.8
Grizedale			1968-69	8.8	2.1-15.6
2. Newton Rigg	171	51 N	1966-67	8.8	2.8-15.4
Newton Rigg			1967-68	8.6	1.9-15.4
Newton Rigg			1968-69	8.6	1.3-15.9
3. Nelson	165	61 SE	1966-67	8.9	2.9-15.9
Nelson			1967-68	8.8	2.3-15.7
Nelson			1968-69	8.8	1.8-15.4
4. Burnley	140	63 SE	1966-67	8.6	3.8-13.9
Burnley			1967-68	8.4	2.9-13.9
Burnley			1968-69	8.5	2.4-14.2
5. Helmshore	260	69 SE	1966-67	8.7	3.4-14.9
Helmshore			1967-68	8.5	2.4-14.4
Helmshore			1968-69	8.5	2.0-14.5

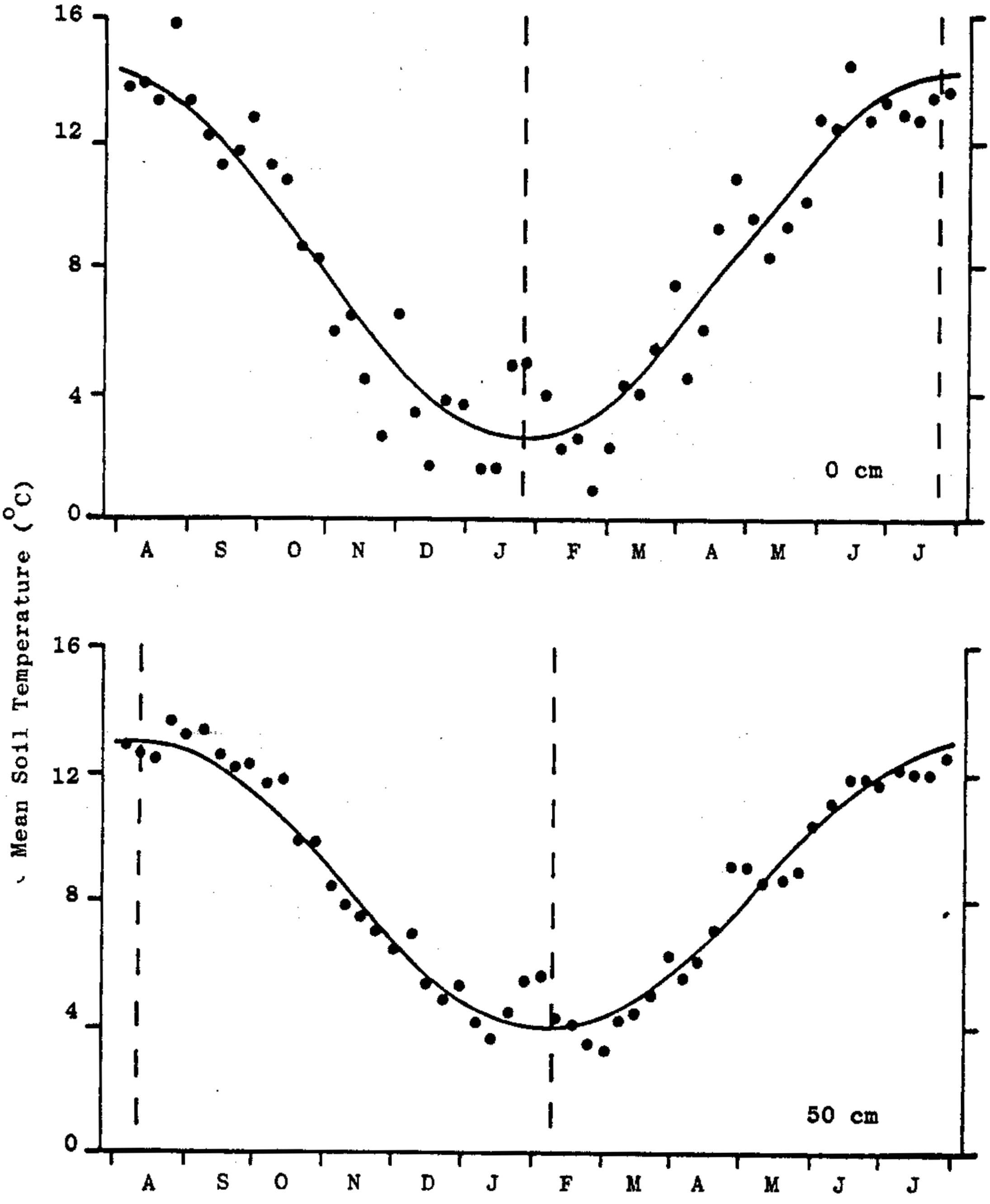
Data for sites other than Meathop were taken from Monthly Weather Reports (Meteorological Office , 1966-70).

Figure 1.



Maximum (———) and minimum (------) ranges of temperature for individual days in each calendar month at 0 cm and 50 cm soil depth.

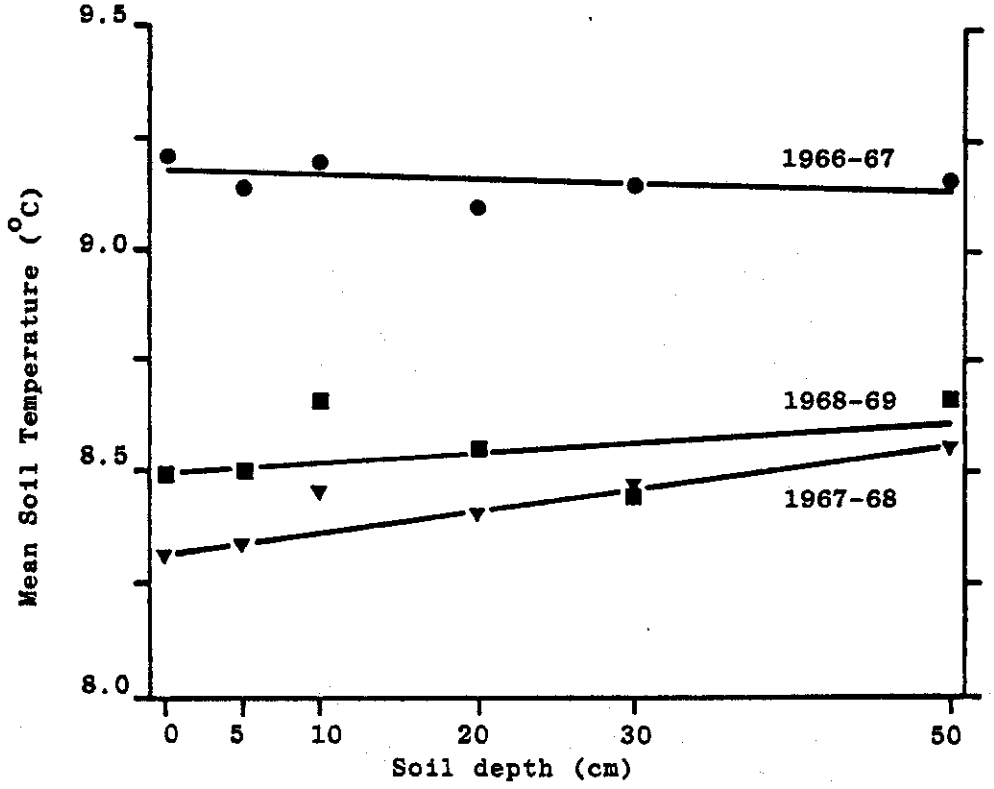
Figure 2.



Months

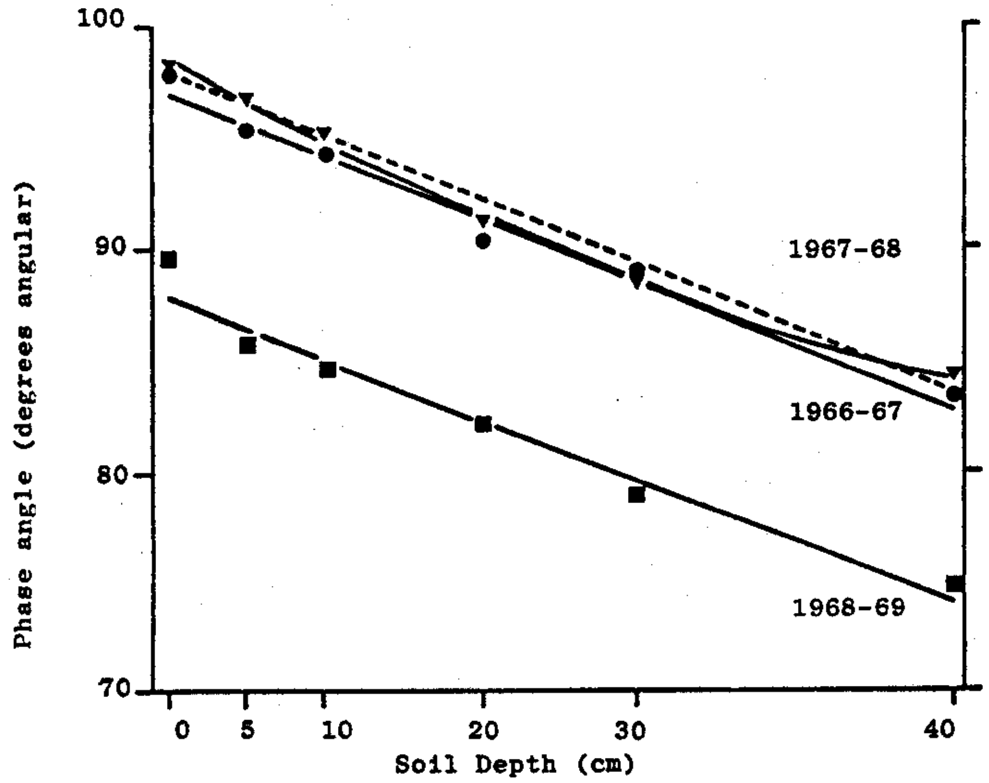
Mean soil temperature at 0 and at 50 cm soil depth for individual weeks from August 1967 to July 1968. Vertical dashed lines indicate maximum and minimum values on sine curves representing the fundamental term from harmonic analysis of the means.

Figure 3.



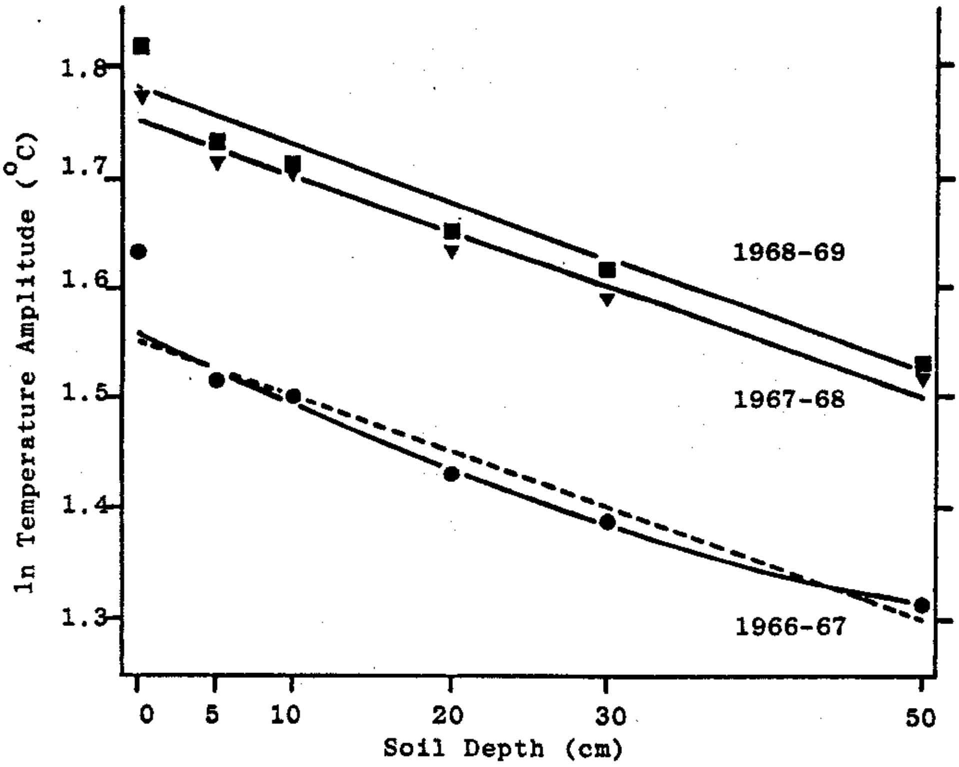
Mean soil temperature for years August - July and soil depth. Comparable means for screen air temperature were 7.98, 7.59 and 7.30°C.

Figure 4.



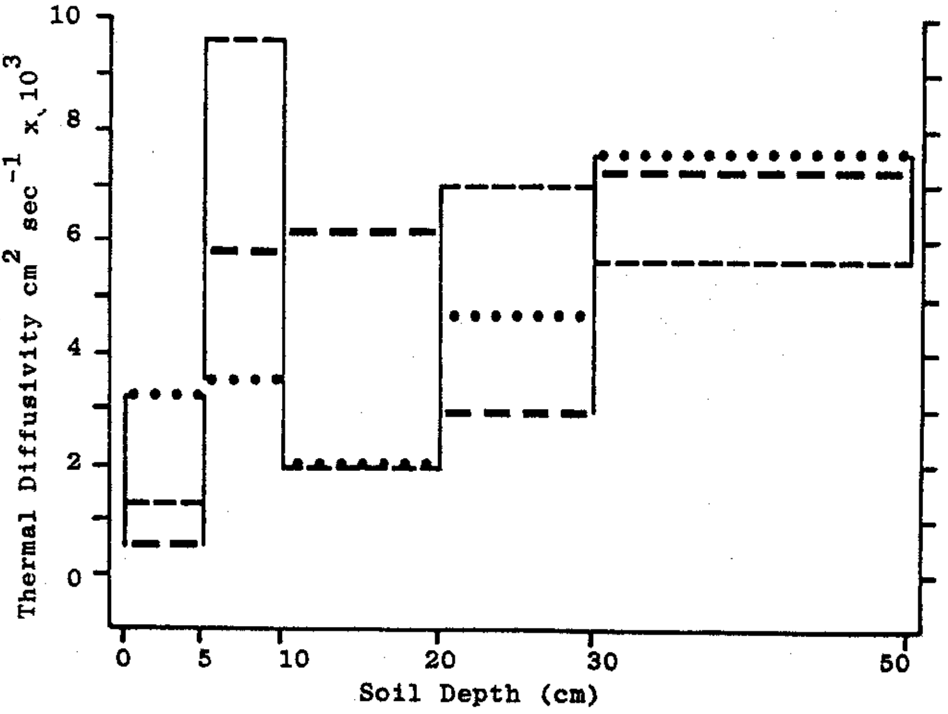
Phase angle of the fundamental sine curve of soil temperature for years August - July and soil depth. ——Line of best fit, ------linear regression where line of best fit is curvilinear. Comparable angles for screen air temperature were 99.9°, 100.7° and 87.3°.

Figure 5.



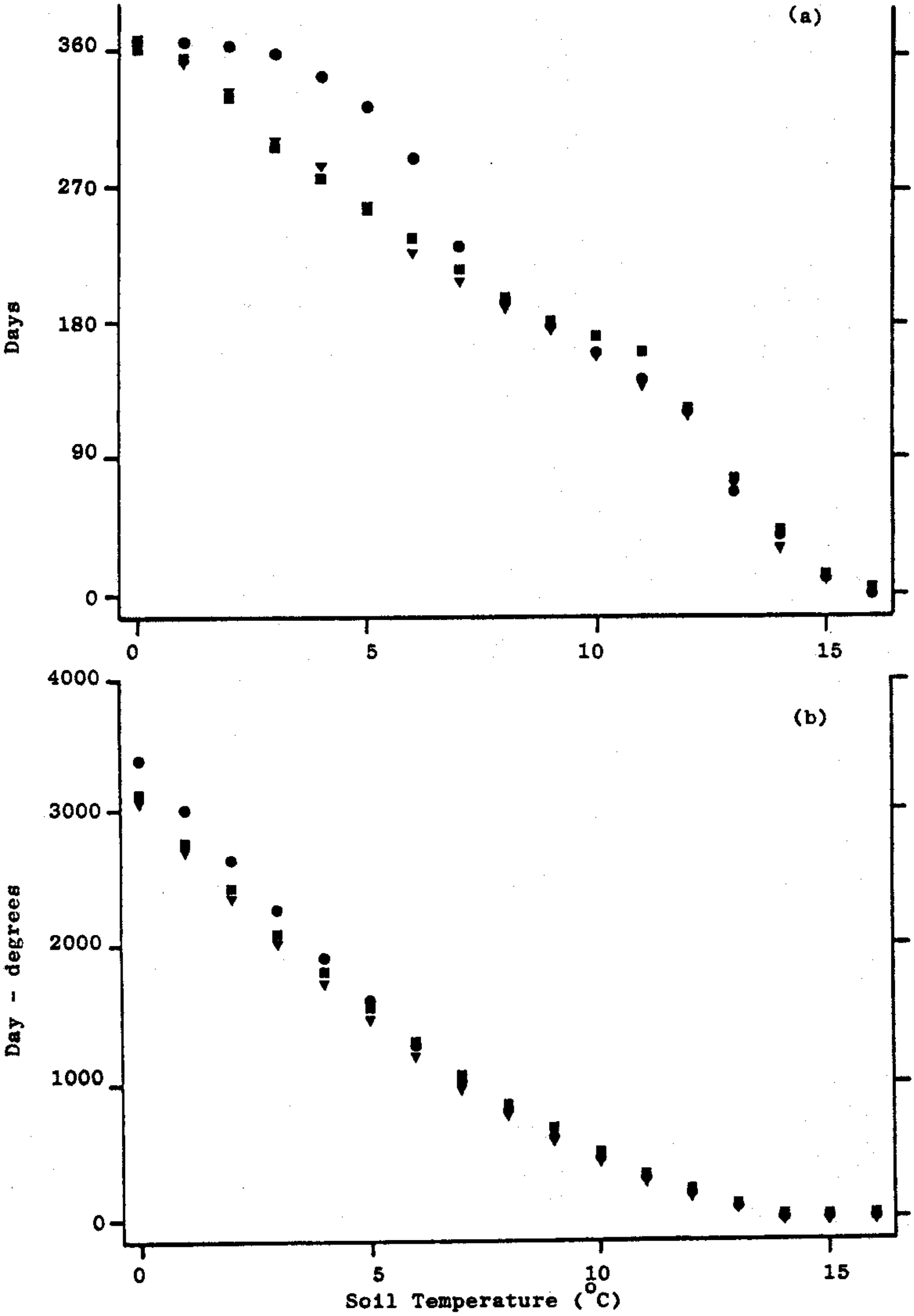
Natural logarithm of the amplitude of the fundamental sine curve of soil temperature for years August - July and soil depth. ——— Line of best fit, ------ linear regression where line of best fit is curvilinear. Comparable data for screen air temperature were 1.52, 1.65 and 1.72

Figure 6.



Mean thermal diffusivity calculated from phase angles of the fundamental sine waves for the top and bottom of each soil stratum. ——— 1966-67, ······ 1967-68, ------ 1968-69.

Figure 7.

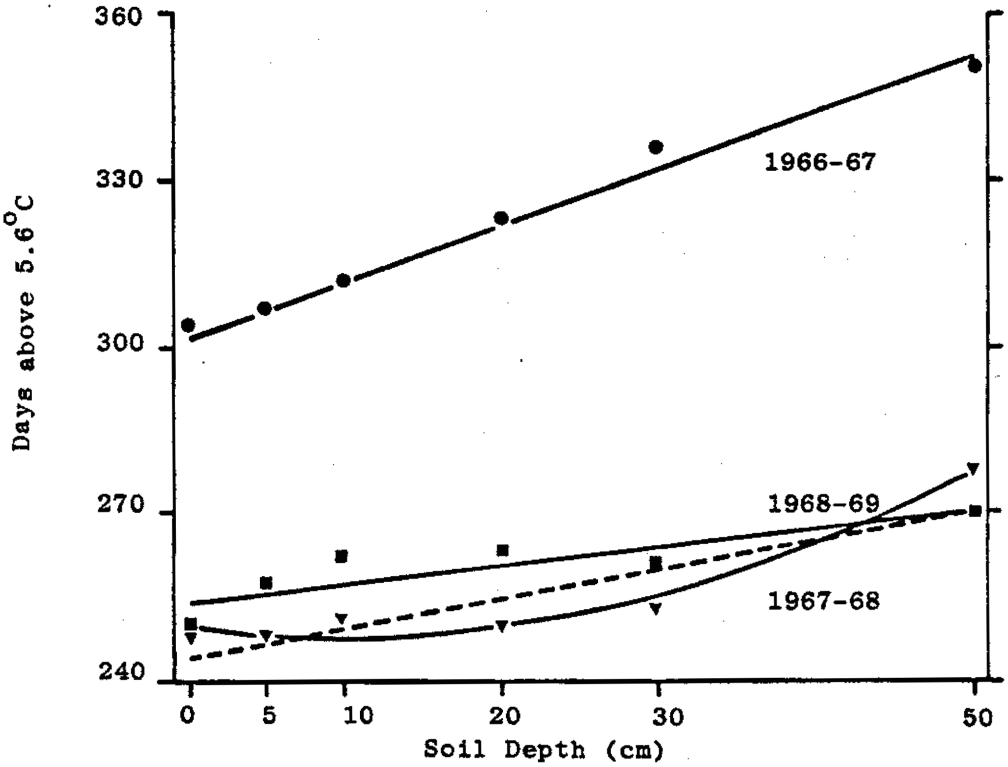


Aspects of soil temperature for 1 C^{o} intervals from minimum to maximum mean temperatur for individual days at 0 cm soil depth, ● 1966-67, ▼ 1967-68, ■ 1968-69.

a) Number of days on which the mean temperature exceeded specified temperatures.

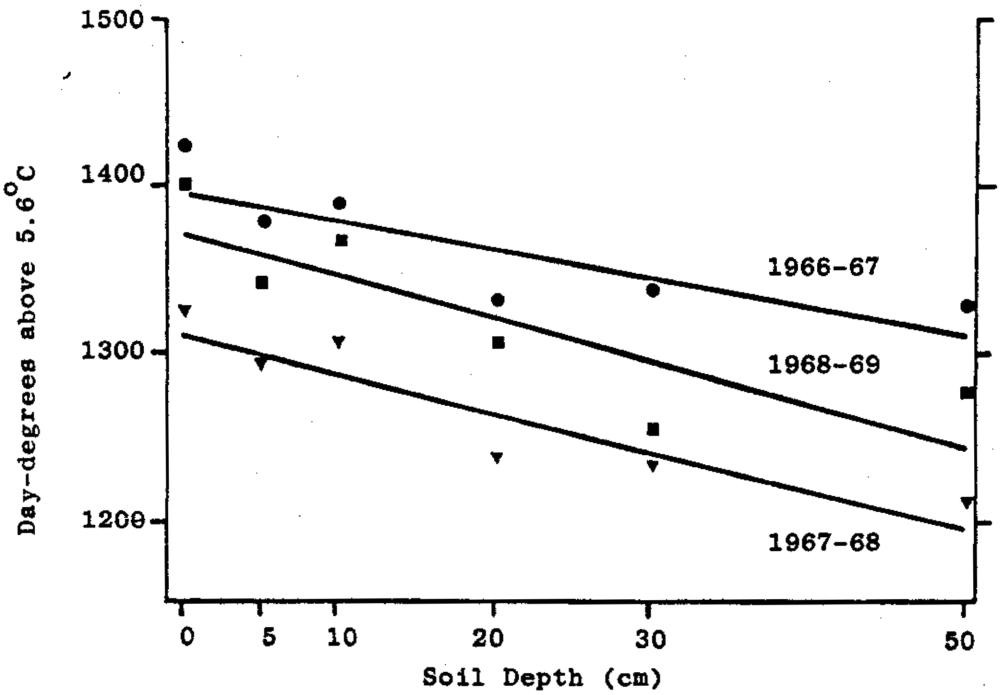
b) Number of day degrees above specified temperatures.

Figure 8.



Change with soil depth in the number of days with mean soil temperature above 5.6°C for years August - July. ——— Line of best fit, ------ linear regression line where line of best fit is curvilinear. Comparable data for screen air temperature were 261, 241 and 227 days.

Figure 9.



Change with soil depth in the number of day degrees above 5.6°C for years August - July. Comparable data for screen air temperature were 1196, 1181 and 1063 day degrees.