INFLUENCE OF TILTH ON SOIL- AND AIRTEMPERATURE [1]

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Summary

The influence of tilth on the temperature near the surface of the soil has been given for sine shaped yearly and daily temperature waves. The cultivated soil is considered to consist of two homogeneous layers with different thermal properties (fig. 1b). This is applied quantitatively to a sandy soil, on the assumption that the heat flux into the soil is the same before and after cultivation, so cultivation only affects the distribution of heat with depth. If the upper layer has a looser density than the sublayer, the amplitude of the variation of temperature increases with increasing depth of the upper layer, till a constant value is reached, which for the daily variation occurs when the depth of the upper layer is about 10 cm (fig. 2). For the yearly variation the corresponding depth is $\sqrt{365}$ as large. The daily mean temperature of the cultivated layer appears to be lower during autumn and winter, and higher during spring and summer than the temperature of the uncultivated layer at the same depth (fig. 3). Deep fall plowing appears not to be desirable if winter-crops are grown that are sensitive to cold, while deep cultivation from the end of January stimulates germinating of summer crops. Because of the increased daily amplitude however, lower minima may occur, so the risk of nightfrost increases.

How far cultivation increases the risk of nightfrost is also investigated for shallow cultivation considering the fact that cultivation also influences the heat flux into the soil. The influence of loosening a moist and dry soil (fig. 4) on the minima that will occur during a bright and calm day in the beginning of May are represented in table 3. Loosening a moist surface layer of 2 cm decreases the minimum with about 1° C, and loosening a dry surface layer with about 3° C.

The influence of cultivating on the energy used in evaporation and transpiration, and its effect on the heat flux into soil and air is briefly discussed.

1 Introduction

The plant needs water and ions, which are taken from the soil by the roots. This uptake is closely connected with the presence of oxygen. At the same time some requirements concerning temperature and moisture content must be satisfied, while noxious influences such as a high concentration of carbondioxide, must be excluded. These factors, which vary with distance to the surface and with time, are also important for the micro- and macro-organisms in the soil and the oxidation of organic matter.

The condition of the soil, especially of the upper layer, is very important for the interchange of heat, water and gas between soil and air. To what extent it is desirable to cultivate this layer to get optimum yields, is still a problem which remains to be solved. This comes to expression in a statement of the Joint Committee on soil tilth: "Despite all that has been said, and all that has been recommanded, there has been very little done in the way of improving our situation with regard to measuring soil tilth and the effect on plantgrowth" (Shaw, 1952).

The objectives of cultivation are:

1 To kill weeds,
2 To turn under stubble and manure,
3 To improve drainage of the soil,
4 To provide a good seedbed,
5 To obtain a favourable microclimate,
6 To facilitate harvesting.

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Killing weeds is one of the most important factors, especially in preparing a seed-bed, so that the young crop can grow without competition of weeds (RUSSELL, 1953). It further conserves water and the heat that is consumed in the transpiration of the weeds, when the soil lays fallow between successive crops, resulting in a higher temperature of the soil.

Turning under organic matter stimulates the growth of organisms in the soil, which e.g. are of importance to soil structure and supply with nitrogen.

Cultivation also affects the quantity of available ions and water at a certain depth. Concerning the first point it is clear that cultivation may reduce the quantity of available ions on fixating soils. It is also observed that any shortage of plant food in the subsoil brought to the surface must be compensated (RUSSELL, 1953), and that in dry seasons less soluble fertilizers must be placed several centimeters beneath the surface (VERVELDE and MEYERMAN, 1950).

The physical condition of the soil is changed by a variation in the arrangement of the soil particles. This influences the resistance against root growth and the bearing strength of the surface, the water content and the water permeability, the aeration, the warming and cooling of the soil, and the microclimate. These influences are connected with the kind and depth of the cultivation, and the kind and condition of the soil. Regarding these physical changes and its effect on crop yield, three points must be enquired :

1 The structural changes of the soil, i.e. the volume of the pores and their dimensions : "if all the crumbs were between about 3 and 0.5 mm in size, there should be an excellent system of spaces between the crumbs" (RUSSELL, 1953).
2 The influence of these structural changes on the above mentioned conditions of the soil and the adjacent air layer.
3 The effect of these conditions on plant growth.

So far as the last point is concerned, only incidental data are known. In consequence of this lack of information the utility of a method of cultivation is usually tested by yield. The yield however also depends on other variable circumstances, as the quality of the seed, the temperature during the growing period, and the supply with water and fertilizer. Moreover the effect of soil tilth is connected with the weather and the kind of crop and soil. So even after a number of years, such experimental fields have only a limited significance, as long as the different sides of the problem are not analysed. As a contribution to a consideration of the different factors seperately, a certain physical aspect will be discussed in the present paper, namely the influence of cultivation on the temperature of the soil and the adjacent air layer.

2 THE ENERGY-BALANCE

The net amount of radiation reaching the surface of a large homogeneous field heats the ground and air, and causes evaporation. This is expressed by the equation :

$$H - E = q_a + q_s = q_{as} \tag{1}$$

H = radiation that reaches the earth, minus reflection and outgoing long-wave radiation.
E = energy used in evaporation.
q_s = heat flux into the soil.
q_a = heat flux into the air.

The ratio between q_a and q_s depends on the thermal properties of the soil, viz. the thermal conductivity λ and the heat capacity per unit volume C, and on the corresponding magnitudes in the air.

3 THE TEMPERATURE WAVE IN A HOMOGENEOUS SOIL

If λ and C are constant with depth and time (fig. 1a), the temperature at the surface ($z = 0$) in course of time is given by :

$$T\ (o,t) = \overline{T} + A \sin\ (\omega t - \pi/4) \tag{2}$$

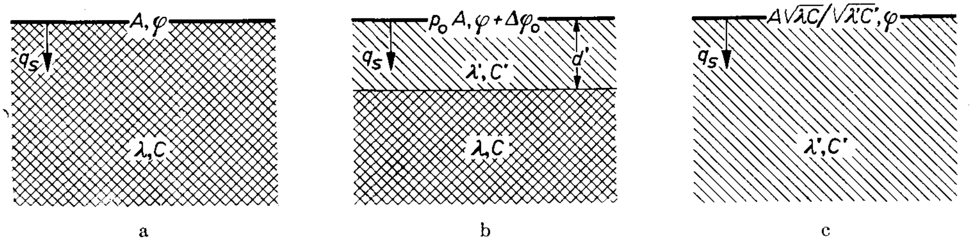

FIG. 1. AMPLITUDE AND PHASE OF THE TEMPERATURE WAVE AT THE SURFACE OF HOMOGENEOUS (FIG. 1a AND 1c) AND LAYERED SOIL (FIG. 1b), PROVIDED THAT THE HEAT FLUX q_s IS INDEPENDENT OF THE THERMAL PROPERTIES OF THE SOIL.

and the heat flux into the soil by:

$$q_s\ (o,t) = Q_s \sin \omega t \quad \text{with} \quad Q_s' = A \sqrt{\lambda C \omega}, \tag{3}$$

T = average temperature at the surface,
A = amplitude of the temperature wave at the surface,
ω = $2\pi/\tau$ is the circle frequency of a periodic fluctuation with period τ; in the case of the daily period τ = 86400 sec., for the yearly wave τ = 365 × 86400 sec.

If a soil is considered with thermal properties λ' and C' (fig. 1c), and the same heat flux q_s, thus $Q_s = A' \sqrt{\lambda' C' \omega}$, the expression of T (o,t) becomes:

$$T\ (o,t) = \overline{T} + A' \sin (\omega t - \pi/4) = \overline{T} + A\ (\sqrt{\lambda C}\ / \sqrt{\lambda' C'}) \sin (\omega t - \pi/4). \tag{4}$$

The phase of the temperature wave is $\pi/4$ radians behind the heat flux into the soil; this corresponds to one and half a month for the yearly, and three hours for the daily variation. The mean values of the yearly temperature wave at the surface occur about the middle of April and October, those of the daily wave about 7 and 19 h in summer and 8 and 20 h in winter; at these times $\sin (\omega t - \frac{\pi}{4}) = 0$.

The temperature at a depth of z cm is given by:

$$T\ (z,t) = \overline{T} + A\ e^{-z/D} \sin (\omega t - z/D - \frac{\pi}{4}). \tag{5}$$

So the amplitude decreases with increasing depth by a factor exp $(-z/D)$ and the phase shifts with $-z/D$ radians. A small value of the damping depth $D = \sqrt{2\lambda/\omega C}$ results in a rapid decrease of the fluctuations of the temperature with depth, so the influence of the temperature wave is limited to a small depth.

4 THE TEMPERATURE WAVE IN A CULTIVATED SOIL

In this section the influence of cultivation on the temperature wave in the soil will be analysed with the assumption that cultivating does not influence the heat flux into the soil. So q_s is considered to be independent of the thermal properties of the soil, and cultivating only affects the distribution of heat with depth. To enable the temperature wave in a cultivated soil to be calculated, the latter is assumed to consist of a lower layer (extending to infinity) with the thermal properties λ and C of the original uncultivated, homogeneous soil, and a cultivated upper layer with depth d' and thermal properties λ' and C' (fig. 1b).

If the temperature wave at the surface of the noncultivated soil is again represented by eq. (2), that of the cultivated soil is given by:

$$T\,(o,t) = \overline{T} + p_0\,A\,\sin\,(\omega t - \pi/4 + \triangle\varphi_0),\ \text{with}\ A = \frac{Q_s}{\sqrt{\lambda C\omega}} \tag{6}$$

So if A is the amplitude of the temperature wave at the surface of a homogeneous soil, then $p_0 A$ is the amplitude at the surface of a layered soil of which the thermal properties λ and C of the lower layer equal those of the homogeneous soil, while the phase difference between the temperature and the heat flux at the surface decreases by an amount $\triangle\varphi_0$. Thus the influence of the layering on the temperature wave is expressed mathematically by the quantities p_0 and $\triangle\varphi_0$. The theoretical expressions of p_0 and $\triangle\varphi_0$ which are determined by the thermal properties of both layers and the thickness of the upper layer, are given in the appendix, as well as the values of p_z and $\triangle\varphi_z$ which correspond to p_0 and $\triangle\varphi_0$, and represent the influence of cultivation on the temperature wave in the upper layer at a distance z from the surface ($0 \leqq z \leqq d'$). The value of p_0 is 1 if $d' = 0$ (fig. 1a) and $p_0 = \sqrt{\lambda C}/\sqrt{\lambda' C'}$ if $d' = \infty$ (fig. 1c); in this case eq. 6 becomes identical with eq. 4. The phase shift $\triangle\varphi_0$ is zero if $d' = 0$ and $d' = \infty$. When the upper layer has a looser packing than the subsoil, and its moisture content is not remarkably higher, $\sqrt{\lambda C}\,/\sqrt{\lambda' C'} > 1$, thus after ploughing, harrowing and similar operations the amplitude of the temperature wave near the surface will be increased, and the phase advanced.

Example

This theory is applied to the temperature wave in a sandy soil (8% $< 16\,\mu$; 3.5% organic matter) with the following volume fractions of solid material X_s, and water, X_w, and corresponding thermal properties [2]:

upper layer: $X_s{}' = 0.40$; $X_w{}' = 0.125$; $\lambda' = 1.70.10^{-3}$ cal/cm sec °C;
$C' = 0.31$ cal/cm³ °C; $D' = 235$ cm for the yearly wave;
lower layer: $X_s = 0.57$; $X_w = 0.175$; $\lambda = 3.40.10^{-3}$ cal/cm sec °C;
$C = 0.44$ cal/cm³ °C; $D = 280$ cm.

Concerning the moisture content both layers are supposed to be at field capacity, which in this soil corresponds to about 12.5% by weight at a density of the solid material of 2.56.

The yearly temperature wave

Fig. 2 represents the course of p and φ for $z = 0$ cm and $z = 8$ cm in dependence of the thickness of the upper layer. The value of p_0 increases from 1 when $d' = 0$ to $\sqrt{\lambda C}\,/\sqrt{\lambda' C'} = 1.68$ when $d' = 185$, while $\triangle\varphi_0$ reaches its maximum when $d' = 90$ cm.

[2]) The data of the thermal conductivity in dependence of the volume fractions of solid material and water are taken from determinations on a sandy soil by VAN DUIN and DE VRIES (1954); the heat capacities per unit volume are calculated with the approximate formula (DE VRIES, 1953): $C = 0.46\,X_s + X_w$.

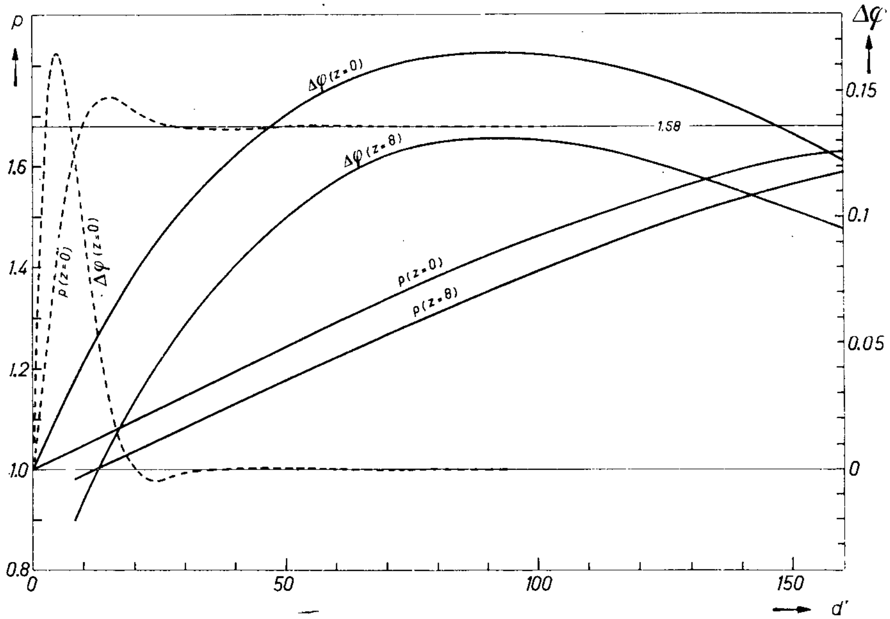

FIG. 2. INFLUENCE OF THE THICKNESS OF THE UPPER LAYER d' ON THE AMPLITUDE (p) AND PHASE ($\triangle\varphi$) OF THE TEMPERATURE WAVE AT THE SURFACE ($z = 0$) AND AT A DEPTH $z = 8$. IN THE PRESENT EXAMPLE $\sqrt{\lambda C} / \sqrt{\lambda' C'} = 1.68$.

- - - - daily wave ; ——— yearly wave.

Table 1.

	$A = 11.2$ °C	$d' = 0$	$d' = 16$	$d' = 36$	$d' = \infty$
$z = 0$ cm	p_0	1.000	1.078	1.175	1.682
	$p_0 A$ (°C)	11.2	12.1	13.2	18.8
	$\triangle\varphi_0$ (rad.)	0	+0.064	+0.116	0
	$\triangle\varphi_0$ (days)	0	3.7	6.7	0
$z = 8$ cm	p_z *)	0.972	1.019	1.111	1.675
	p_z A (°C)	10.9	11.4	12.4	18.7
	$\triangle\varphi$ (rad.)	–0.0286	+0.0155	+0.0714	–0.034
	$\triangle\varphi$ (days)	–1.67	+0.89	+4.15	–1.98

*) The factor p_z refers to the amplitude ,A, at the surface of the noncultivated soil.

Some numerical values illustrating the influence of an upper layer on the yearly temperature wave at the surface and at a depth of 8 cm are given in table 1, while the yearly temperature waves at the surface for $d' = 0$ and $d' = 36$ cm are given in fig. 3. The magnitude of the amplitude of the yearly variation at the surface of noncultivated soil ($A = 11.2$ °C) has been taken from observations at Groningen (BRAAK, 1941), as well as the dates on which the temperature reaches the mean value of 10.0 °C. The amplitude at a depth of 8 cm is $11.2\, e^{-8/280} = 10.9$ °C if $d' = 0$, and $11.2 \times 1.682\, e^{-8/235} = 18.2$ °C if $d' = \infty$ (cf eq. 4); the corresponding phase shifts are $-z/D = -8/280 = -0.0286$ and $-8/235 = -0.034$ radians.

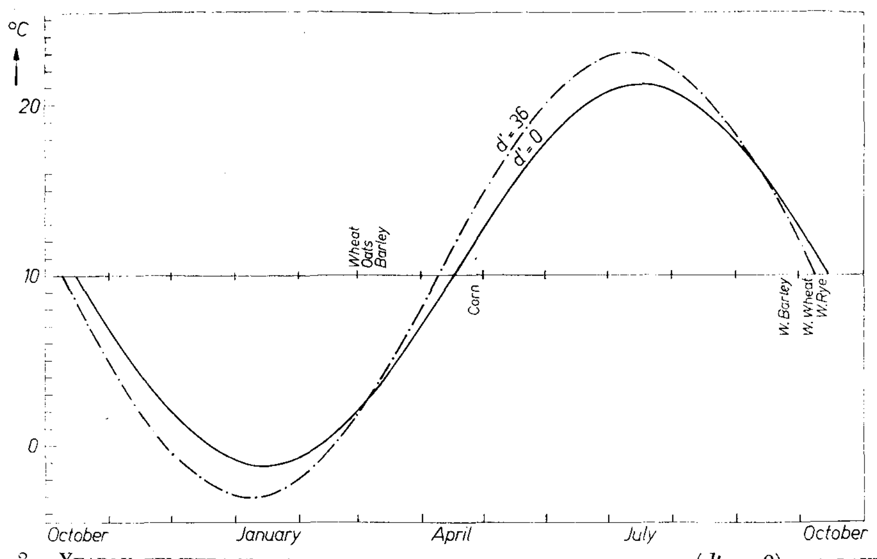

FIG. 3. YEARLY TEMPERATURE WAVE AT THE SURFACE OF HOMOGENEOUS ($d' = 0$) AND LAYERED ($d' = 36$) SOIL, PROVIDED THAT THE HEAT FLUX q_S IS THE SAME IN BOTH CASES. THE TEMPERATURE WAVE FOR $d' = 0$ IS TAKEN FROM OBSERVATIONS AT GRONINGEN (BRAAK, 1941). FOR SEVERAL CROPS THE SOWING TIME IS DENOTED.

From the beginning of March the surface of the cultivated soil is warmer than the homogeneous soil, and the mean yearly temperature $\overline{T}$ is reached about one week earlier for $d' = 36$ cm (fig. 3). At the beginning of May the mean daily temperature is 2 °C higher; the same temperature in the non-cultivated homogeneous soil is reached one decade afterwards. The upper layer of the cultivated soil is warmer in spring and summer, and colder in autumn and winter.

The daily temperature wave

The damping depth of the temperature wave is proportional to $\sqrt{\omega}$, thus the damping depth of the daily wave is $\sqrt{365} = 19$ times as small as that of the yearly wave. The damping depths of the daily waves are 12.3 cm for the upper layer, and 14.6 cm for the lower layer, in the present example. Because of this small value of the damping depths, the daily variation of temperature is much more influenced by cultivation than the yearly one since this influence decreases with decreasing values of the quotient d'/D' (eq. 9 and 10).

For the daily variation the relation between p_0 and d' is illustrated in fig. 2 where p_0 becomes equal to $\sqrt{\lambda C} / \sqrt{\lambda' C'} = 1.68$ when $d' = \pi D'/4 = 9.7$ cm. The maximal value of p_0, viz. 1.73, is reached when $d' = 15$ cm. With respect to the amplitude at the surface, the soil may be considered as if it were homogeneous, with the thermal properties of the upper layer if $d' > 9$, since changes in p_0 remain small for higher values of d'.

WEST (1932) observed at a depth of 3 cm a difference of 7 °C between the daily amplitudes in a loosened soil with an upper layer of 13 cm, and the original soil, while the daily mean temperature was about 2 °C higher. The latter agrees with the theory, since the observations were done when the yearly temperature wave reaches its maximum value.

Discussion

From the foregoing theory it follows that as far as soil temperature is concerned fall plowing is not desirable if wintercrops are grown that are sensitive to cold, in view of the lowering of the average temperature in winter, and the increase of the daily amplitude. For this reason considerable lower minima will occur after deep fall plowing, especially during cloudless nights. Loosening the soil from the end of January advances germinating of summer crops, especially if a strongly fluctuating temperature is favourable. This may be important when the duration of the growing season is critical, e.g. with growing of corn in Holland. The chance of nightfrost to occur increases considerably, as is explained in the next section. In general however, cultivating has only a slight numerical influence on the yearly temperature wave in the cultivated layer, the more so as in reality the heatflux into the soil diminishes when the upper layer is loosened (section 5). Changes in the evaporation rate are left out of account (section 7).

5 The distribution of heat between soil and air

In the foregoing section the same heat flux was assumed to penetrate into the soil before and after cultivation. It will be investigated now how the heat flux changes owing to cultivation, and what are the consequences on soil and air temperature.

The reduced heat flux into the soil caused by cultivation follows from a consideration of the ratio of the heat fluxes into soil and air. If the thermal properties of both soil and air are constant with time and distance to the surface this ratio is given by:

$$q_a / q_s = \sqrt{\lambda_a C_a} / \sqrt{\lambda C}$$

in which the index a refers to air.

Loosening the soil results in a decrease of the product λC. If the sum $q_{as} = q_a + q_s$ is not influenced by cultivation the heat flux into the air will therefore increase to the cost of the flux into the soil. The magnitude of A, corresponding with the new value of q_s is smaller than the original value, as follows from eq. (3). The values of p and $\triangle\varphi$, however, are independent of the heat flux into the soil. So it is to examine now how far cultivation influences the distribution of q_s between soil and air. The heat transfer in the air is caused mainly by turbulent air motion, the theory of this transfer of heat still being in a stage of development. In analogy to the thermal diffusivity coefficient λ/C in the theory of molecular heat conduction, a coefficient of turbulent diffusivity ,K, is introduced. The heatflux into the air is then given by:

$$q_a = -KC_a \frac{\delta T}{\delta z} \tag{7}$$

The turbulent diffusion coefficient K (in cm^2/sec) depends on the influence of friction near the earth and the stability of the air. Near the surface the frictional part almost always predominates, for which reason K may be considered to be independent of stability to a first approximation. From the theory of turbulent motion now follows (LETTAU, 1949):

$$K = k\, u_* \,(z + z_0) \tag{8}$$

k = 0.40 (constant of VON KÁRMÁN),

u = friction velocity; this is a measure of the turbulent force of the wind, with the dimension of a velocity (cm/sec),

z_0 = roughness parameter of the surface, varying between 0.01 cm for smooth surfaces and 10 cm for long grass.

Both u_* and z_0 depend on the properties of the surface; they will of course be changed by cultivation, especially by ploughing or ridging.

The theory of the distribution of available heat at the interface between a homogeneous soil and the air, assuming that K varies linearly with the distance to the surface has been elaborated by LETTAU (1953). This theory has been extended by the present author to the case of a layered soil (λ and C not independent of z), making use of the considerations of section 4. The formulas which enable a numerical solution of this problem are given in the appendix.

6 THE DAILY WAVE OF THE TEMPERATURE IN THE AIR LAYER ADJACENT TO THE SURFACE OF A CULTIVATED SOIL

The above denoted influence of cultivation on the heat fluxes into soil and air is taken into consideration to analyse the influence of a shallow upper layer on the daily wave of temperature at the surface, and at a height of 5 cm, during a bright and calm day in the beginning of May. The daily mean temperature at the surface is supposed to be 14 °C (fig. 3). The properties of the air have been suitably chosen [3]) to be: $C_a = 3.0.10^{-4}$ cal/cm³ °C; $u_{200} = 150$ cm/sec, $z_0 = 0.7$ cm (SUTTON, 1953), $u_* = 10.7$ cm/sec, which follows from the velocity profile for fully rough flow and neutral stability:

$$u_z / u_* = (1/k) \ln \frac{z + z_0}{z_0}.$$

The daily amplitude Q_{as} of the available heat flux into soil and air was about $7.2.10^{-3}$ cal/cm² sec if the evaporation term $E = 0$, and $4.8.10^{-3}$ cal/cm² sec if this term equals the calculated potential evaporation (PENMAN, 1950).

The four conditions of the soil that are considered, are represented in fig. 4; the corresponding thermal properties are given in table 2:

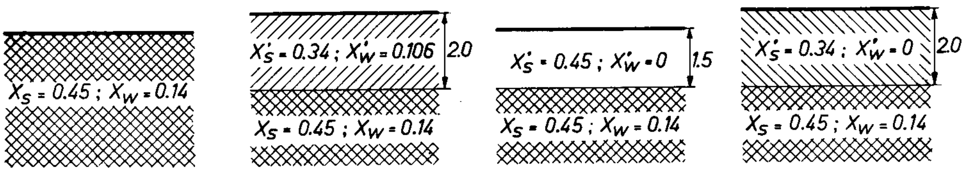

FIG. 4. CONDITIONS OF THE SOIL CORRESPONDING TO TABLE 2.

[3]) The values of u_{200} and Q_{as} were taken from observations at Wageningen dd. 8th May 1954.

Table 2.

Conditions of the soil	d'	$10^3\,\lambda'$	C'	D'	$10^3\,\lambda$	C	D	$\frac{\sqrt{\lambda C}}{\sqrt{\lambda' C'}}$	d'/D'	p_0
a) soil homogeneous, moisture content at fieldcapacity	0	–	–	–	2.20	0.35	13.2	–	0	1
b) upper layer loosened *), both layers at field-capacity	2.0	1.35	0.26	12.0	2.20	0.35	13.2	1.48	0.167	1.14
c) upper layer dried, lower layer at fieldcapacity	1.5	0.39	0.21	7.2	2.20	0.35	13.2	3.06	0.208	1.66
d) dried layer loosened *), lower layer at field-capacity	2.0	0.28	0.16	7.0	2.20	0.35	13.2	4.15	0.286	2.34

*) The depth of the upper layer follows from the volume fraction of solid material before and after cultivation and the working depth, so $d' = 1.5 \times 0.45 / 0.34 = 2.0$ cm.

The result of the calculations are summed up in table 3.

Table 3.

$\overline{T} = 14.0$ °C			I: $Q_{as} = 4.8.10^{-3}$ cal/cm^2 sec				II: $Q_{as} = 7.3.10^{-3}$ cal/cm^2 sec			
			a	b	c	d	a	b	c	d
q_s = constant	$z = 0$	p_0	1.00	1.14	1.66	2.35	1.00	1.14	1.66	2.35
		p_0 A	14.0	16.0	23.2	32.9	21.2	24.0	35.2	49.8
$q_s + q_a$ = constant	$z = 0$	A	14.0	15.1	18.5	22.2	21.2	22.9	28.2	33.8
		$T_{min} = \overline{T}$ -A	+0.0	–1.1	–4.5	–8.2	(–7.2)	(–8.9)	(–14.2)	(–19.8)
		A	11.2	12.1	14.8	17.8	17.0	18.3	22.6	27.0
	$z = +5$	$T_{min} = \overline{T}$ -A	+2.8	+1.9	–0.8	–3.8	(–3.0)	(–4.3)	(–8.6)	(–13.0)

From these calculations follows, that loosening a small surface layer of a wet soil (moisture content at fieldcapacity) results in a slight increase of the daily amplitude (situation $I_a \longrightarrow I_b$), which is more pronounced when this layer is dry (situation $I_c \longrightarrow I_d$). In this case however the evaporation term E will decrease, so the amplitude of the available heat will increase from $Q_{as} = 4.8.10^{-3}$ to $Q_{as} = 7.3.10^{-3}$ cal/cm^2 sec in the present example, provided that $E = 0$. In this most extreme case the amplitudes before and after cultivation are given by situation II*c* and II*d* respectively. In reality the daily mean temperature $\overline{T}$ is also influenced by changes in the evaporation rate, but it is not possible to calculate the new values of $\overline{T}$ with the theory described in this article.

In the present example the increase of the amplitude under the assumption $q_s + q_a$ being constant appears to be about half the increase as calculated with q_s being constant.

With the thermal properties of the homogeneous and layered soil in the former example (section 4), and $d' = 16$ cm the calculated amplitude of the daily variation at the surface is respectively 11.1 °C and 16.1 °C before and after cultivation, for $Q_{as} = 4.8.10^{-3}$ cal/cm^2 sec. If q_s is considered to be constant the amplitude would have been 11.1 °C and $p_0\ A = 1.68 \times 11.1 = 18.7$ °C respectively.

7 Influence of cultivation on evaporation and transpiration

At first the heat flux into the soil q_s was assumed to be independent of the tilth (sections 3 and 4), which postulation was substituted for $q_a + q_s$ being constant (sections 5 and 6). In humid climates however about 0.5 to 0.6 of heat budget H is consumed by evaporation and transpiration (Albrecht, 1930; Peerlkamp, 1944). So it is important to see how far cultivation influences this term of the energy balance. This influence is connected to the way in which water is transferred to the surface, e.g. by the plantroots, by capillarity or by diffusion of vapour.

Starting from a wet soil, the evaporation by diffusion is given by $E = c\sqrt{t\,(1-X_s)\,X_w}$ and the depth of the dry layer by: $d = c\sqrt{t\,(1-X_s)/X_w}$ where c is a factor, depending on the vapour gradient and the coefficient of diffusion (Woodruff, 1941). The evaporation appears to be as good as independent of the tilth, since X_s and X_s' vary between 0.60 and 0.30 maximal, and the initial moisture content (f.c.) is almost proportional to X_s, thus $E'/E = \sqrt{(1-X_s')\,X_w'}/\sqrt{(1-X_s)\,X_w} \approx 1$.

The depth of the dry layer however is more dependent on the packing of the soil, since $d'/d = \sqrt{(1-X_s')\,X_w/(1-X_s)\,X_w'}$.

With the numerical values of the example in section 4 e.g. these quotients are $E'/E = 1.0$ and $d'/d = 1.4$. In reality the drying of the soil is limited to a surface layer of some centimeters, and since the water content of such a layer is small (maximal 1 to 2 cm), the evaporation depends to a large extent on the frequency of showers.

Much more water can evaporate from a soil that is grown over, so killing weeds between successive crops saves water, and thus less energy is used in vaporization. So a bare soil will in general be warmer, especially during periods with few showers.

If water transport to the surface takes place by capillary forces from a groundwater level, loosening the surface layer can diminish the evaporation considerably, as was found by King (1907), who measured the evaporation from various soil columns in contact with a free-water surface, in relation to the depth of tillage. This is a consequence of the rapid decrease of capillary conductivity with increasing values of X_a (cf. Childs and Collis-George, 1950).

It is clear that as far as cultivation influences evaporation and transpiration, the available heat flux q_{as} increases. This may result in an increased value of the amplitude of the temperature wave, and a somewhat higher mean temperature.

Appendix

The quantities p_0 and $\Delta\varphi_0$ (eq. 5) that are introduced because of the layering of the soil, under the assumption that the heat flux into the soil, q_s, is independent of this layering, are given by:

$$P_0=\left\{\frac{\lambda C}{\lambda' C'}\,\frac{r^2 e^{-4d'/D'}+2re^{-2d'/D'}\cos 2d'/D'+1}{r^2 e^{-4d'/D'}-2re^{-2d'/D'}\cos 2d'/D'+1}\right\}^{\frac{1}{2}} \quad (9) \quad \text{where} \quad r=\frac{1-\sqrt{\frac{\lambda' C'}{\lambda C}}}{1+\sqrt{\frac{\lambda' C'}{\lambda C}}}$$

$$\Delta\varphi_0=\operatorname{arctg}\frac{2re^{-2d'/D'}\sin 2d'/D'}{r^2 e^{-4d'/D}-1}\quad , (10)$$

The values of these quantities in the region $0 \leqslant z \leqslant d$, are given by:

$$P_z=\left\{\frac{\lambda C}{\lambda' C'}\left(r^2 e^{-4d'/D'}-2re^{-2d'/D'}\cos 2d'/D'+1\right)\left(r^2 e^{-4d'/D'}e^{2z/D'}+e^{-2z/D'}\right)+2re^{-2d'/D'}\cos\left(2d'/D'-2z/D'\right)\cdot\right.$$

$$\left.\cdot\left(r^2 e^{-4d'/D'}-re^{-2d'/D'}\cos 2d'/D'+1\right)+2r^2e^{-4d'/D'}\sin 2d'/D'\sin\left(2d'/D'-2z/D'\right)-2r^2e^{-4d'/D'}\cos 2z/D'\right\}^{\frac{1}{2}}:$$

$$:\left(r^2 e^{-4d'/D'}-2re^{-2d'/D'}\cos 2d'/D'+1\right) \qquad (11)$$

$$\Delta\varphi_z=\operatorname{arctg}\frac{\left(r^2e^{-4d'/D'}e^{z/D'}+e^{-z/D'}\right)\sin z/D'+re^{-2d'/D'}\left(e^{z/D'}+e^{-z/D'}\right)\sin\left(2d'/D'-z/D'\right)}{\left(r^2e^{-4d'/D'}e^{z/D'}-e^{-z/D'}\right)\cos z/D'-re^{-2d'/D'}\left(e^{z/D'}-e^{-z/D'}\right)\cos\left(2d'/D'-z/D'\right)} \qquad (12)$$

These formulas follow from the heat conduction in an inhomogeneous medium, which has been applied to the soil by PEERLKAMP (1944). If the amplitude of the total heat flux into soil and air q_{as} has a fixed value Q_{as} and if further the soil is homogeneous, while K is a linear function of z, the amplitudes Q_a and Q_s, and phases α and β of the heat flux into air and soil can according to LETTAU (1952) be found from:

$$\frac{Q_s}{Q_a}=\frac{\pi\left\{\lambda C\omega(j^2+0.25)\right\}^{\frac{1}{2}}}{ku_*C_a} \quad (13)$$

$$Q_{as}=Q_a\cos\alpha+Q_s\cos\beta \quad (14)$$

$$\alpha=\varphi+\operatorname{arctg}1/2\,j \quad (15)$$

$$\beta=\varphi+\pi/4 \quad (16)$$

where φ is the phase of the temperature wave at the surface, which is given by:

$$-\varphi=\operatorname{arctg}\frac{\frac{Q_s}{Q_a}\sqrt{0.5}+\sin\left(\operatorname{arctg}1/2j\right)}{\frac{Q_s}{Q_a}\sqrt{0.5}+\cos\left(\operatorname{arctg}1/2j\right)} \qquad (17)$$

The quantity j is dependent on the parameters of the windprofile, according to the expression:

$$j=-0.367+\frac{1}{\pi}(\ln k+\ln u_*-\ln z_0-\ln\omega), \quad (18)$$

The temperature at the surface follows from:

$$T(o,t)=\overline{T}+A\sin(\omega t+\varphi),\ \text{where}\ A=\frac{\pi Q_a\sqrt{(j^2+0.25)}}{ku_*C_a}$$

The temperature at a height z (if $0\leqslant z\leqslant 100$ cm) is given by:

$$T(z,t)=\overline{T}+Ah\sin(\omega t+\varphi-\psi),\ (20)\ \text{where}\ h=\frac{\left\{(jJ+0.25)^2+0.25(j-J)^2\right\}^{\frac{1}{2}}}{j^2+0.25} \quad (19)$$

and $\psi=\operatorname{arctg}(j-J)/(2jJ+0.50)$. (22).

The quantity J denotes the dependence of the solution on the height, since $J = j - \frac{1}{\pi} \ln \frac{z + z_0}{z_0}$, (23). For a full discussion of the distribution of heat between a homogeneous soil and the air the reader is refered to LETTAU (1954).

In a layered soil with thermal properties λ' and C' for $0 \leqslant z \leqslant d'$ and λ and C for $z \leqslant d'$, eq. 13 and 16 must be changed, because the temperature wave at the surface has a different relation to the heat flux into the soil (cf. eq. 6).

The amplitude of the temperature wave at the surface is now given by: $A = p_0 \; Q_s / \sqrt{\lambda C \omega}$, and the phaseshift between the heat flux into the soil, and the temperature wave at the surface decreases with $\triangle \varphi_0$ radians. Owing to this eq. 13 and 16 change to:

$$\frac{p_0 \, Q_s}{Q_a} = \frac{\pi \left\{ \lambda C \omega \left(j^2 + 0.25 \right) \right\}^{\frac{1}{2}}}{k \, u_* C_a}, \; (13a); \; \beta = \varphi + \frac{\pi}{4} - \triangle \varphi_0. \; (16a)$$

The values of p_0 and $\triangle \varphi_0$ are represented by eq. 9 and 10 respectively. The formulas 14 and 15, and 17 to 23 remain unchanged, but for the new values of the quotient Q_s / Q_a and the phase β.

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List of symbols and units

Symbols		Units
A[4])	— amplitude of variation of temperature at the surface of a homogeneous soil with thermal properties λ and C	°C
C[5])	— volumetric heat capacity of soil	cal/cm^3 °C
D	— damping depth	cm
E	— energy consumed in evaporation or transpiration	cal/cm^2 sec
H	— net gain of radiation energy at the surface	cal/cm^2 sec
Q_s	— amplitude of heatflux into the soil	cal/cm^2 sec
Q_{as}	— amplitude of the available heat q_{as}	cal/cm^2 sec
T	— temperature	°C
$\overline{T}$	— average temperature at the surface	°C
X_a	— volume fraction of air-filled pores	—
X_s	— volume fraction of solid material	—
X_w	— volume fraction of water	—
d'	— depth of a layer with thermal properties λ' and C'	cm
k	— constant of von Kármán $= 0.40$	—
p_0[6])	— influence of cultivation on the amplitude A	—
q_s	— heat flux into the soil	cal/cm^2 sec
q_{as}	— available heat $= q_a + q_s$	cal/cm^2 sec
t	— time	sec
u	— windvelocity	cm/sec
u_*	— friction velocity	cm/sec
z	— distance to the surface	cm
K	— coefficient of turbulent diffusivity	cm^2/sec
z_0	— roughness parameter	cm
α	— phaseconstant of the heatflux into the air	radians
β	— phaseconstant of the heatflux into the soil	radians
λ[5])	— thermal conductivity of soil	cal/cm sec °C
τ	— period of variation	sec
φ	— phaseconstant of temperature wave at the surface	radians
$\Delta\varphi$[6])	— phaseshift caused by the layering of the soil	radians
ω	— circle frequency	sec^{-1}

4) The dashed symbols refer to a soil with thermal properties λ' and C'.
5) The symbols with index a refer to the properties of the air.
6) The symbols with index z refer to a depth z.