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Mulch influence on soil temperature and corn growth

William Chapel Burrows

Iowa State University

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MULCH INFLUENCE ON SOIL TEMPERATURE AND CORN GROWTH

by

William Chapel Burrows

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of The Requirements for the Degree of DOCTOR OF PHILOSOPHY

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Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University Of Science and Technology Ames, Iowa

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INTRODUCTION

Mulching, for various purposes, is a widely used practice in agriculture. Materials used for mulch vary from man-made materials such as plastic films and paper to natural materials such as the residues derived from the preceding year's crop. Only mulches of crop residues will be considered in this thesis.

In tropical areas and in the southern United States crop residues on the soil surface have been used to lower the soil temperature, although this phenomenon has never been subjected to more than a cursory examination. In the western and southwestern United States mulches have been used to conserve moisture and prevent wind erosion. Mulch may or may not increase yields. In both the areas mentioned above, however, the effects of mulching on the final product, crop yield, have been satisfactory from the standpoint that the yield was either increased or was unaffected by mulch.

Many authors have pointed out the potentiality of mulching in the north-central and north-eastern United States as a method for conserving moisture and preventing water erosion. The practice has not gained widespread acceptance because decreased crop yields frequently occur.

In order to gain an understanding of some of the causes of the detrimental effects of mulches of plant residues on crop growth and yield, several lines of research have been
followed. The lowered nitrogen availability to plants in mulched soil was perhaps the best-known phenomenon and received early attention. Heavy applications of nitrogenous fertilizer did not alleviate completely the poor growth responses noted where mulches were used. While it has not been demonstrated in the field, laboratory studies have indicated the existence of growth-inhibiting substances due to the mulch.

It has been known for some time that a mulch of crop residues decreases the soil temperature in the spring or early part of the growing season. Soil temperature, in corn production, received little attention as a possible cause of the mulch effects on the crop's growth until Willis, in Iowa, studied the problem. Willis' work showed that the lowered soil temperature under a mulch, provided other growth conditions were optimum, could be responsible for the decreased growth of corn when crop residues were left on the soil surface rather than plowed under.

The experiments described in this thesis amplify Willis' work. They were carried out to obtain a quantitative measure of the interaction of mulch, soil temperature and corn growth, and to obtain data which could be used in a theoretical approach to predict the effect of mulches on soil temperature.
LITERATURE REVIEW

Mulches have been used for many years to conserve soil and water for agricultural uses. Harris and Robinson (1916) reported that mulches of various organic materials, if kept dry, retard evaporation and that coarse mulches are better than fine for this purpose. Duley and Russel (1939) were the first to report a method of tillage for crops whereby the residues of the crop from the previous year are left on the soil surface. This tillage method has come to be called stubble-mulch tillage or just mulch tillage. Duley and Russel showed that mulch tillage in Nebraska increased infiltration of rainfall and thereby also reduced runoff and water erosion. They also reported a reduction in evaporation of soil moisture. As a direct consequence of the higher moisture, and also the increased roughness of the soil surface, due to the mulch, soil erosion by wind was decreased. Duley and Russel found no essential differences in yields due to mulch.

Alderfer and Merkle (1944) found that a mulch, as compared to incorporation of residues in the soil, increased soil moisture and improved soil structure, the measure of the soil structure being the size and frequency of the larger soil granules. Browning, as will be cited, has studied and compared various tillage methods, including
mulch tillage. Browning et al. (1944) and Browning and Norton (1947), in comparing mulch tillage with conventional plowing and listing of corn, reported that mulch tillage gave the least amount of runoff. The runoff was less than one-half that from the other two methods. Corn grain yields under mulch tillage were greater than for listing, but were less than under conventional plowing tillage. There thus appeared to be some difference between the results of Duley and Russel (1939), who had found no essential difference between yields obtained under mulch tillage and the conventional tillage systems, and the results of Browning and co-workers.

White (1947) and White et al. (1947) reported beneficial results in terms of growth and yield of tropical plants from mulching the soil. They listed the following effects of mulching which appeared to cause the better growth and yield: (1) more moisture conserved; (2) additional nutrients in the mulch; (3) soil structure improvement; (4) reduced erosion; (5) reduced weeding time; and (6) lowered soil temperature. Kruger (1947) applied 2 to 3 inches of straw mulch to fruit trees in South Africa. Water penetrated to 30 inches in the mulched soil but only to 18 inches in unmulched soil. Soil temperature of the mulched soil was 60 to 65°F and of the unmulched soil up to 130°F. On sandy soil in Texas, Moldenhauer (1959) found that the moisture conserved by
mulches was a critical amount and was the difference between establishment and non-establishment of grasses. Verma and Kohnke (1951) found increased yields of soybeans under mulch, which they attributed to 3.3% more available moisture.

Schaller and Evans (1954) have reviewed the literature on mulch tillage and give eight general effects of mulch tillage in the Corn Belt. They are: (1) improvement of soil structure; (2) more moisture in the soil (higher infiltration and less evaporation); (3) reduced soil temperature; (4) unknown but real effects on tilth and aeration; (5) lowered availability of nitrogen and potassium; (6) alteration of effectiveness of fertilizer placement; (7) greater microbial activity; and (8) lowered stands with more weeds. These eight effects provide a starting point for the search for causes of lowered yields under a mulch tillage system.

Of the factors affected by mulch, soil fertility and nutrient availability have received some attention. Early investigations by Albrecht and Uhland (1925) in the greenhouse showed that the failure of nitrates to accumulate under mulch is not due to a shortage of ammonium, since ammonium is higher in mulched soils than in bare. They were able to obtain substantial increases in nitrate accumulation in a mulched soil by aeration and wetting and drying. With a constant moisture content, application of mulch to a bare soil decreased the nitrate content of the soil, while re-
moval of the mulch caused an increase in nitrate content.

Browning and Norton (1945), reporting the results of a number of tillage trials in Iowa, showed that nitrogen and potassium deficiencies were evident under mulch tillage and listing on poorly drained or eroded soils, but showed further that in the trials described, there was no interaction of fertility level with tillage treatment.

In an experiment carried out in Iowa and described by Willis (1956), studies of ten tillage methods with four fertility treatments over a period of 4 years showed little tendency for an interaction of tillage method and fertility level for a number of measurements other than yield. Mulch tillage was one of the treatments in this experiment. Fertilizer addition on mulch increases yields on mulch treatments; but all of the evidence accumulated from experiments on mulching corn in the Corn Belt points to a decrease in growth and yield due to mulching which cannot be completely overcome by fertilizer additions.

Outside of the Corn Belt, Newton (1953, 1956) in Canada reports that mulching of grain crops had beneficial effects on the long-term average yield. The initial depressing effects of straw mulch on nitrates and soluble nitrogen were likely to be overcome by nitrogen fertilizer dressings to the mulch. Recently, Moody et al. (1957) have reported that proper placement of fertilizer will overcome the detrimental
influence of mulch tillage for corn in Virginia. It thus appears that geographical location is a prime factor in deciding whether or not a system of mulch tillage will be feasible.

Decomposition of the mulch has been advanced as a possible factor in producing the effects noted on growth and yield of crop plants. Hallam and Bartholomew (1953) showed that the decomposition of soil organic matter is accelerated by mixing green residues with the soil rather than leaving them on the surface, and that the decomposition process is also significantly affected by the rate of addition of such residues. Denisen et al. (1953) reported the effect of summer mulches on yields of strawberries. Yields were in direct proportion to the decomposition rate of the mulches, and while soil moisture was higher in mulched than unmulched plots, there was no difference in soil moisture under the various mulches used (sawdust, chopped corncobs and straw). The 4 p.m. soil temperature was 8 to 10°F cooler under the mulches but there was little difference observed in minimum temperatures. McCalla (1958) feels that the effect of mulch on microbial activity, rather than temperature per se, is the main determining factor in the growth of crops under a mulch tillage system.

McCalla and Duley (1948, 1950) have suggested that
growth inhibitors may be present in the mulch and are ex-
tracted by rainwater. In one study they used water extracts 
of decomposing sweetclover and wheat straw, both with added 
nitrogen, and got a reduction in germination of corn. Growth 
inhibitors have not been studied as yet to the point where 
any conclusions may be drawn; however, it must be borne in 
mind that this distinct possibility does exist. Even though 
it is known that such substances are found under certain 
conditions in the laboratory, it is not known whether or not 
these conditions are met in the field.

It was noted previously that the soil under a mulch of 
crop residues is cooler than the same soil without residues. 
McCalla and Duley (1946) investigated this facet of the prob-
lem and stated that with the amounts of residue likely to be 
grown on the field, the reduction in soil temperature is not 
likely to be great enough to cause decreases in growth. 
Drouineau et al. (1952) reported that the marked reduction 
in mineralization of nitrogen under a straw mulch was believed 
due to a decrease of the soil temperature during the dry sea-
son. Willis et al. (1957) have shown that in central Iows 
the addition of crop residues to the soil surface as a mulch 
causes a definite decrease in growth and yield of corn and 
that this decrease may be ascribed to the decrease in soil 
temperature, if other factors are considered optimum. Willis 
et al. (1957) were the first investigators to attempt to hold
factors such as soil moisture and fertility constant while varying the soil temperature in the field.

Air temperature has long been considered one of the best indicators of planting and harvest dates. Abbe (1905) considered air temperature and rainfall as possibly the two most important climatic factors affecting crops. The ease with which air temperature and rainfall may be measured has led to the establishment of weather stations collecting only that data, with the consequence that most studies of the climatic effect on crops have used air temperatures rather than soil temperatures. In many instances use of air temperature rather than soil temperature may be satisfactory, since the air temperature is controlled in the main by the energy balance at the soil surface so that air temperature follows the soil temperature. Rose (1936), in speaking of corn, states:

Corn yield in the center or core of the Corn Belt generally fails to correlate significantly with the climatic factors investigated. This is less true for the coefficients of multiple correlations, in which several factors are considered, than for the coefficients of simple correlations. Presumably corn yield in this core area is somewhat affected by the factors significant on the surrounding margins; but with several factors operative - perhaps first on one, then on the other, side of the optima, and thus with conditions generally favorable - variation in any one factor has little effect by itself.

Livingston and Livingston (1913) considered that the growth of plants followed the van't Hoff law that for each \(10^\circ \text{C}\) (\(18^\circ \text{F}\) ) rise in temperature, the growth rate would be
doubled. They then calculated a temperature efficiency index which is nothing more than a mathematical statement of the above law, with the exception that they also considered that plant growth would cease at 40° F. The temperature efficiency index is thus expressed as $u = 2\left(\frac{T-40}{18}\right)$, with $T$ being the average daily air temperature in degrees Fahrenheit. This index was compared to a direct index. The direct index was the sum of the number of degrees above 40° F. for the number of days in the time period concerned. The latter index is still used and is called variously "heat units" and "degree days". Lindsey and Newman (1956) have published a lengthy article on calculating heat units from official weather data.

A classic work in the field of temperature effects on plant growth is that of Lehenbauer (1914). He presented curves and data on the growth rate of corn seedlings at various temperatures and lengths of exposure to those temperatures. The curves are plots of corn growth rate versus soil temperature. The growth rate is determined for his "3-hour curve" by dividing the growth made in 3 hours by 3 for each of the many temperatures considered. For the "6-hour curve" the growth made in 6 hours is divided by 6, etc.

Livingston (1916) used the 12-hour curve of Lehenbauer (1914) to get an index of temperature efficiency by dividing Lehenbauer's growth rates by the growth rate at 4.5° C.
Since Lehenbauer's curves show a minimum, an optimum and a maximum temperature for growth, Livingston's index can be the same for two widely different temperatures. More recently Gilmore and Rogers (1958) have investigated various indexes of temperature. They used air temperatures and computed the indexes for the period from planting to silking of corn in Texas. Analysis of variance of the indexes for a number of different planting dates for corn showed that an "optimum day" has the lowest coefficient of variation. A day is called one optimum day if the average daily temperature, computed as the average of eight temperatures, taken every 3 hours of the day, corresponds to the temperature which gives the maximum growth rate on Lehenbauer's 6-hour curve. The number of optimum days from planting to silking for a variety is about the same for all planting dates, whereas calendar days give no information of value.

There has been only one investigator who has attempted to correlate soil temperature, rather than air temperature, as a climatological factor, with corn yield in central Iowa. Riley (1957) has obtained a multiple regression equation for prediction of average county corn yield from three soil temperature variables. He uses the mean June soil temperature at 72 inches depth, the departure from the mean June soil temperature reading at 7 a.m. at 1-inch depth and the mean August soil temperature reading at 7 a.m. at 1-inch
depth. The standard error of estimate for this equation is 5.68 bushels, and the coefficient of multiple correlation is 0.811. It should be realized in connection with studies of this type that no account has been taken of variations in plant population, fertility, method of tillage, weather conditions at planting and harvest times, soil moisture at planting and harvest times and other factors, any one or all of which might be used to explain much of the variation in corn yield.

There is disagreement among scientists as to the cause of apparent temperature effects on plant growth. McCalla (1958) feels that soil temperature is important only insofar as the biological properties of the soil are affected. Different organisms are prevalent at different temperatures, and thus there may be different amounts and types of by-products formed and also different nutrient regimes. This view is supported by the work of Sabey et al. (1956), who report that the amount of nitrate nitrogen produced in the soil varies directly with the mean temperature of the soil. Parker (1957) also reports a large influence of soil temperature upon nitrification.

Ketcheson (1957) studied young corn plants in the greenhouse and concluded that the phosphorus requirement appears to be increased by cool temperatures. More work is necessary on the effect of temperature on the nutrition of the plant
before further conclusions can be drawn.

A number of investigations seem to show that temperature affects the plant directly, regardless of side effects on the soil. Cannon (1915) states that with desert plants, rooting habits are directly affected by the temperature of the soil. Went (1953) notes that the appearance at different times of various desert plants is due to temperature and rainfall conditions. Mederski and Wilson (1955) in a study of the manganese absorption of soybeans, felt that their data indicated a physiological response of the plant to changes in root temperature. While working with legumes, Jones and Tisdale (1921) found that the weight of roots, tops and nodules increases from minimum to maximum and back to minimum as the temperature is increased from some minimum to optimum and up to maximum. Earley and Gartter (1945) also found similar results with soybeans. Sprague (1944) allowed the temperature to vary within limits of 15 °F. and found that the ranges 55 ° to 70 °F. and 70 ° to 85 °F. were both suitable for emergence and growth of several pasture grass species. Root to top ratios were reduced at temperatures above the optimum for dry matter production and were increased below the optimum.

On the subject of the effect of temperature on the growth of corn, there appears to have been no more complete nor more widely quoted study than that of Lehenbauer (1914).
He used constant temperature chambers in which he placed corn seedlings. The heights of the seedlings were determined at the time of placement in the temperature chambers and at different times later. The temperatures used were from 12° to 43° C. (53.6° to 109.4° F.), generally in steps of 1° C.

Lehenbauer recognized that the plant responds not only to the actual temperature, but to the length of exposure as well. For this reason he prepared curves showing the mean hourly growth rate in mm. per hour vs. the various temperatures for several different times of exposure to the temperatures. For example, if the temperature in question were 25° C., the plant height was measured every hour for a total of 21 hours. The mean hourly growth rates for 3, 6, 9, 12, 15 and 21 hours were then calculated and plotted versus 25° C. When this procedure had been followed for all of the temperatures, six curves, one for each of the time periods, had been generated. The growth rates for the 3-hour curve were lowest and increased with longer times of exposure. All of the curves, however, do have three temperature points in common: the temperature point at which the growth rate was maximum, called the optimum, about 87° F.; and the two temperature points for which the growth rate is zero, regardless of the length of exposure. The latter two temperatures are called the minimum at the cold end and the maximum at the hot end and are about 50° F. and 110° F., respectively.
When applying Lehenbauer's results there are several points that should be kept in mind regarding their applicability to the problem at hand. First, the plants were grown in nutrient solution and may have reacted differently than in soil. Both the aerial parts and the roots were subjected to the same constant temperature; thus there may have been abnormal relations between leaf and air temperatures. The plants were grown in subdued light so that there may have been no chance for observation of an interaction between light and temperature (if it does exist) such as Went (1944) has found to exist with tomatoes. Even though the above limitations must be recognized, other investigators, as quoted by Richards et al. (1952), have found much the same relationships as did Lehenbauer. Willis (1956) grew corn plants in the greenhouse where normal leaf-air temperature relationships existed, where the photoperiod was normal and air temperature was not controlled but allowed to fluctuate. These results confirm the results of Lehenbauer in every respect. The actual rates and amounts of growth as found by Lehenbauer are not directly applicable in the field, but the shape of Lehenbauer's curves with the maximum growth rate occurring at 86° to 89° F. is important; and it appears that it may be used to explain the results of soil temperature experiments in the field (Livingston, 1916; Gilmore and Rogers, 1958; van Wijk et al., 1959).
In order to study the interrelationships of soil temperature, mulches and plant growth, it is necessary to know what factors affect soil temperature, how these factors affect soil temperature, and their relationship to each other. The earliest work on soil temperature was the 1824 mathematical treatise of Fourier (1955). There have been whole books written on Fourier's methods of analysis and what have come to be called Fourier series. Essentially the method consists of the application of trigonometric series to obtain an approximation of some function. Soil temperature varies nearly sinusoidally with time and thus Fourier series analysis is suitable for obtaining a mathematical expression of a time-temperature curve. Fourier (1955, p. 3) realized that the soil temperature is controlled primarily by the amount of incident solar radiation.

Bouyoucos (1913) made extensive investigations of the thermal properties of soils in the field and in the laboratory. He was handicapped by the lack of modern equipment and techniques; however, his methods were sufficient to enable him to state the basic principles of soil temperature factors. He studied the absorption of heat by soil and the reradiation of this heat from the soil when the heat source is removed. The results of this study were the first to give proof of the fact that soil color affects the amount of heat absorbed but has little effect on the amount of heat radi-
ated. This is an important point, since it may be predicted that a soil covered by mulch will have a lower temperature than the same soil not covered. This is so because the light colored mulch reflects much of the energy from the sun that the uncovered soil can absorb, but the soil under the two conditions can lose similar amounts of radiation at night depending mainly upon thermal conductivity. Bouyoucos (1913) also measured specific heats and thermal conductivities of various soils, but he realized that the results were only qualitative, as were Patten's (1909), due to complications from soil moisture.

The thermal conductivity is defined as the quantity of heat (cal.) which passes through a surface of unit area (1 cm²) in the direction normal to the surface per unit time (1 sec.) under a unit temperature gradient (1° C. per cm.); its units are thus cal. cm⁻¹ sec⁻¹ °C⁻¹. Most recent authors use the greek lambda, \( \lambda \), as the symbol for thermal conductivity. Smith and Byers (1938) studied the thermal conductivity of dry soils and attempted to relate it to some of the physical properties of soil. Later, Smith (1939) used moist soils to determine conductivities. He found, as did Patten and Bouyoucos, that moisture movements due to thermal gradient affected the measurements. De Vries (1950) separated the thermal conductivity of soil into two components, the real conductivity and that due to water vapor transfer.
under the thermal gradient. The main problem in the determina-
tion of thermal conductivity, that of separating the two components, was solved by de Vries (1952a). He described a very thin probe which is alternately heated and allowed to cool while the temperature of the probe is observed. A graph of temperature variation with time gives a measure of the thermal conductivity of the material with a negligible amount of water vapor movement. The theory for this probe was worked out in part, but not until very recently (de Vries and Peck, 1958a, 1958b) did the theory become exact. Van Duin and de Vries (1954) made a recorder for use with the probe so that a continuous record of the manner in which thermal conductivity varies with time and moisture content in the field may be had. Jackson and Kirkham (1958) also report measurements of the real thermal conductivity of moist soil; however, their method can not be used in the field, although it is also a non-stationary method.

The heat capacity of the soil, defined as the product of the soil density and the specific heat, is symbolized by C and has units cal. cm⁻³ °C⁻¹. It is the amount of heat required to raise a unit volume of the soil by one degree. The thermal diffusivity, \( \alpha \), is the quotient of the thermal conductivity divided by the heat capacity and has units of cm² sec⁻¹. The physical properties of the soil affecting soil temperature include texture, structure and color. Texture
and structure affect the moisture content and thermal diffusivity; color affects the amount of heat absorbed from solar radiation. Other factors which affect the soil temperature are those such as mulching or tillage, which affect the color of the absorbing surface, the soil moisture content, the amount of solar energy which strikes the soil surface and the organic matter content. External factors include the climatic factors of rainfall, cloud cover, solar radiation, wind and sometimes cold or warm air masses which suddenly change the weather of an area. Crabb and Smith (1953) state that one of the most important factors affecting soil temperature is the state of ground cover. They give as the principal modifications brought about by various covers: (a) shielding of solar energy; (b) changes in soil moisture content; (c) changes in porosity and permeability of the soil; and (d) changes in the soil color and organic matter content.

A great deal of work has been done on the "classical" theory of soil temperature. This is the approach used by van Duin (1956). Essentially the theory is as follows. The differential form of the equation of heat conduction states that the sensible heat (cal. cm\(^{-2}\) sec\(^{-1}\)) conducted in the downward (z-coordinate) direction at depth z, that is, the vertical heat flux, \(F\), is proportional to the thermal gradient at z. The thermal conductivity is the proportionality constant in the equation of Fourier's law which equation is:
\[ F = -\lambda \frac{\partial T}{\partial z} \]  

(1a)

where \( T \) is the temperature at depth \( z \).

If it is assumed that there is no vertical advection, that is, if it is assumed that there is no heat carried by mass movement of water or air, then equation (1a) is the definition of thermal conductivity \( \lambda \). The equation of continuity is written:

\[ \frac{\partial F}{\partial z} = -C \frac{\partial T}{\partial t} \]  

(1b)

If it is assumed that there are no horizontal components of heat conduction and that no heat sources or sinks occur at any depth except the surface, then equation (1b) is the definition of the volumetric heat capacity, \( C \). The problem is a boundary value problem and the equation to be solved is,

\[ C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) \]  

(2a)

The solution of equation (2a) depends upon the assumptions made heretofore, and also on assumptions about the thermal conductivity. The "classical" theory is based mainly on the assumption that there is no vertical variation of thermal conductivity, that is \( \frac{\partial \lambda}{\partial z} = 0 \). Equation (2a) may then be written

\[ C \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} \]  

(2b)

The solution to this differential equation is easily obtained
and may be found in Carslaw and Jaeger (1959, p. 64), and in van Wijk et al. (1959) where it is used in connection with computing soil temperatures as affected by mulch. The solution takes the form

\[ T(z,t) = T_{\text{av}} + A_0 \exp(-z/D) \sin(\omega t - z/D + \phi) \]  

\[ (3) \]

where \( T(z,t) \) is the soil temperature at depth \( z \) and time \( t \),

\( T_{\text{av}} \) is the average temperature,

\( A_0 \) is the amplitude of the temperature wave at the soil surface,

\( D \) is a length, defined by equation (4) below, called the damping depth and is characteristic for the propagation of the temperature wave in the soil,

\( \omega \) is the circle frequency or \( 2\pi/\tau \) where \( \tau \) is the period of variation,

\( \phi \) is a phase constant determined by the time scale used.

The damping depth, \( D \), is related to the thermal constants of the soil by the equation

\[ D = \left[ \frac{2 \lambda}{(C \omega)} \right]^{1/2}. \]  

\[ (4) \]

The reason \( D \) is called the damping depth is that it is the depth in the soil where the amplitude of the temperature wave is \( 1/e \) of the amplitude of the temperature wave at the soil surface.

Equation (3) was found by assuming (a) that the soil is homogeneous both with respect to space and time; (b) that the
only source of heat is the sun, and that the heat flux at the soil surface varies sinusoidally with time; and (c) that the temperature at great depth is finite. With respect to actual conditions, assumption (c) is always met while assumption (a) is rarely true and assumption (b) is true only on a cloudless day at the equator when night and day are of the same length if one is considering the diurnal course of temperature. Even though the assumptions necessary for a solution of the problem seem to be extremely restrictive, equation (3) does give a fair approximation to the daily variation in temperature and does even better for yearly temperatures. At any rate, this relatively simple solution does provide a physical picture of heat flow in the soil.

In equation (3) the term \( A_0 \exp(-z/D) \) indicates that the amplitude of the temperature wave decreases exponentially with depth. Within the argument of the sine function, the term \(-z/D\) assures that some point on the temperature curve, for example the maximum, occurs later at depth \( z \) than at the surface, \( z = 0 \). Also, at depth \( D \) such a point will be 1 radian (corresponding to \( 12/\pi \) hours of time in the case of diurnal variations) out of phase with the time of occurrence of the same point at the surface. Values of the constants for the case of the diurnal temperature wave are: \( \omega = 2\pi/24 = 0.262 \text{ hr}^{-1} \), \( \phi = -\pi/2 \), if \( t \) is chosen so that the maximum temperature occurs at \( t = 12 \), or \( \phi = 0 \) if \( t \) is chosen
so that the maximum temperature occurs at \( t = 0 \).

The difficulty which arises when attempting a solution of equation (2a) is that it is seldom if ever known in what manner the thermal conductivity varies with depth. McCulloch and Penman (1956) have given a method by which a solution may be obtained using soil temperature data from the field. Their analysis resulted in values for the variation of thermal diffusivity with depth. Their method is essentially as follows: first new parameters \( p \) and \( q \) are defined by

\[
p = \frac{\partial (a'z)}{\partial z}; \quad q = \frac{\partial (b'z)}{\partial z}
\]

(5)

where \( a' \) and \( b' \) are unknown variables which vary with \( z \) but not \( t \). Assuming that a solution similar to equation (3) holds,

\[
T = T_{av} + A_0 \exp(-a'z) \cos(\omega t - b'z) \tag{6a}
\]

and

\[
\frac{\partial T}{\partial z} = -A_0 \exp(-a'z)(p^2 + q^2)^{1/2} \cos(\omega t - b'z + \delta), \tag{6b}
\]

where \( \tan \delta = q/p \), one may then find values for \( p \) and \( q \) at the observation levels from equations (6a) and (6b) and observed temperatures. For values of \( p \) and \( q \) midway between two observation levels the formulas

\[
p = \ln(A_1/A_2)/(z_2 - z_1); \quad q = \omega(t_2 - t_1)/(z_2 - z_1)
\]

(7)

are used. A curve may then be drawn to determine \( \partial p/\partial z \).
and \( \partial q/\partial z \) for use in the formulas

\[
a = \frac{\lambda}{C} = \frac{\omega p}{q(p^2 + q^2) - (p \frac{\partial q}{\partial z} - q \frac{\partial p}{\partial z})} \quad (8a)
\]

and

\[
\frac{\partial \ln \lambda}{\partial z} = \frac{1}{\lambda} \frac{\partial \lambda}{\partial z} = \frac{p^2 - q^2}{p} - \frac{\partial p}{\partial z} \quad (8b)
\]

Values of the thermal diffusivity obtained in this way are given by McCulloch and Penman (1956) for one day. The values for their soil vary from \( 0.5 \times 10^{-2} \text{ cm}^2 \text{ sec}^{-1} \) at \( z = 0 \), to \( 6.9 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1} \) at \( z = 7.5 \text{ cm} \) and become nearly constant from \( 12.5 \text{ cm} \) to \( 30 \text{ cm} \), with an average value of \( 4.6 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1} \). The values indicate that the phase lag method of estimating thermal diffusivity, \( a \), is more reliable than the amplitude ratio method in the case of a rapid change in diffusivity with depth.

Fluker (1958) used the "classical" theory to compute the annual variation in soil temperature at a number of depths. This theory was also used by van Duin (1954, 1956) to compute the effect of tillage on soil temperature. His procedure was to consider a layered soil, the upper layer of depth \( d \) composed of material with a damping depth \( D_1 \), thermal conductivity \( \lambda_1 \), and heat capacity \( C_1 \), and the lower layer of infinite depth with thermal properties \( \lambda_2 \), \( C_2 \) and \( D_2 \). All of the thermal properties of both layers are assumed to be invariant with time and depth within the layer. The ex-
pression for the temperature wave in such a soil is easily
derived, and from such an expression one may obtain the ratio
between the amplitude for the layered soil and the amplitude
for the non-layered soil. The two cases correspond to a
mulched soil and unmulched soil or to a cultivated soil and
an uncultivated soil. The ratio of the amplitudes for
mulched to unmulched soil at depth $z = d$ is given by (van
Wijk et al., 1959)

$$\frac{A_m}{A_u} = \frac{(r^2 \exp(-2d/D_1) + 2r \exp(-2d/D_1) + \exp(-2d/D_1))(\lambda_2 c_2)^{1/2}}{(r^2 \exp(-4d/D_1) - 2r \exp(-2d/D_1) \cos(2d/D_1) + 1)(\lambda_1 c_1)^{1/2}}$$

(9)

where

$$r = \frac{(\lambda_1 c_1)^{1/2} - (\lambda_2 c_2)^{1/2}}{(\lambda_1 c_1)^{1/2} + (\lambda_2 c_2)^{1/2}}.$$  

For the purpose of the above analysis it must be assumed
that the heat flux into both soils is the same. This is not
true in the strict sense where mulches are concerned, since
the properties of the mulch change the heat balance at the
surface.

The heat balance at the surface of the soil may be ex­
pressed simply as

$$H - E = q_a + q_s$$  

(10)
where $H$ is the solar radiation less reflected energy and outgoing long-wave radiation, $E$ is the energy used in evaporation, $q_a$ is the heat flux into the air and $q_s$ is the heat flux into the soil. It is evident that addition of a mulch of crop residues which are in general lighter in color than the soil will increase the amount of reflected energy; thus the net radiation will be changed. Van Wijk et al. (1959) have given an example of this effect and calculated that addition of a mulch should bring about a lowering of about 2° F. in the soil temperature at the 4-inch-depth in June in southern Iowa. The amount of reflected radiation from various materials used as mulches in agriculture has not been widely reported in spite of its obvious significance. Moore and Bruce (1958) measured reflection with a light meter and found the following values for the percent of incident light reflected: white plastic 44%, soil (dust mulch) 13%, sawdust 11%, black plastic 10% and pine straw 6%. Van Wijk et al. report a reflection coefficient for short wave radiation of 18% for chopped corn stalks and 8% for a dark-colored (Colo clay loam) soil.

It has been shown by de Vries (1956) that the procedure of van Duin, outlined above, of applying the theory for a homogeneous medium to successive layers of a non-homogeneous soil may lead to values of thermal diffusivity that are in error by more than a factor of ten. Even though it is not
proposed to obtain values of thermal diffusivity, or of conductivity, from the data taken in this study, the "classical" theory as extended by van Duin (1954, 1956) can be useful in obtaining a picture of the effect of mulching on soil temperature. More precise methods for obtaining a mathematical expression of the diurnal course of soil temperature depend upon Fourier series. The Fourier sine series expressing the temperature wave in soil may be written

\[ T = T_{av} + A_1 \sin(\omega t + \phi_1) + A_2 \sin(2\omega t + \phi_2) + A_3 \sin(3\omega t + \phi_3) + \ldots \]  

(11)

For the daily curve of temperature where observations are taken once each hour, it is possible, as shown by Bliss (1958), to get only the three sine terms shown in equation (11).

Fourier series analysis of temperature records was done by West et al. (1920) and by Lettau (1954). Of particular interest is Lettau's (1954) approach. He applies a mean trend correction to the temperature data before using the Fourier analysis. The mean trend correction is necessary because the course of soil temperature is not exactly periodic, that is, the temperature at the end of a period is usually different than the temperature at the beginning of the same period. Because of this, the line which represents the mean temperature will appear to have been rotated around the origin of the time vs. temperature coordinates. To make
the mean trend correction, the change in mean temperature for the period (i.e. \( T_{24} - T_1 \)) is divided by the period (i.e., 24 hours) and then multiplied by the time of observation (i.e., \( t = 1, 2, 3, \ldots \)). As an example, Lettau (1954) gives a mean trend of 2.4°C per 24 hours at a 10 cm. soil depth. This gives 0.1°C per hour and for \( t = 10 \) gives a correction of 1°C to be subtracted from the observed temperature at that time. Lettau's (1954) Fourier series then may be expressed by

\[
T = T_{av} + t \frac{dT}{dt} + A_1 \cos(\omega t - \phi_1) + A_2 \cos(2\omega t - \phi_2) + \ldots
\]

(12)

He continues through the use of MacLaurin series to obtain numerical values of various derivatives of the temperature expression which are then used to determine depth or depth-time dependent values of the thermal diffusivity. He also points out that it is not correct to speak of two thermal diffusivities derived by the use of the "classical" theory, one from the phase shift, the other from the logarithmic decrement of amplitudes, such as did McCulloch and Penman (1956).

From the foregoing review it is seen that there has been work on the interactions of mulch with crop yield, temperature with plant growth, mulch with soil temperature and a small amount of work on the relationship of each one to the others. It appears that workers interested in the
theory of soil temperature as it might apply to mulching have not been interested in plant growth or in mulches, while the plant growth investigations have not included the theoretical aspects of soil temperature. There exists a need for experimentation to produce data which can be used to show how soil temperature affects plant growth and is affected by mulching, and which at the same time can be used in the models of the temperature theories to enable prediction of mulch effects. It is with this need in mind that the following experiments were performed.
EXPERIMENTAL

The experiments outlined below were performed to give information which would lead to a quantitative expression of the relationships between soil temperature, plant growth and mulching practice.

Heating Cable Experiment

An experiment was designed as an extension of the work of Willis (1956). The objectives were (1) to attempt to alleviate unfavorable soil temperature effects by heating the soil artificially, by electric heating cables, under a crop residue mulch, and (2) to ascertain if the heating is effective only during the early growth of the plants or if heating for the whole growing season is beneficial. Seven treatments were arranged in a randomized complete block design with four blocks. Soil temperatures, when established, were either 71° F. or 75° F. The treatments were: (1) bare soil, unheated; (2) bare soil, heated (75° F.) all season; (3) bare soil, heated (75° F.) until June 17; (4) mulched soil, heated (71° F.) all season; (5) mulched soil, heated (75° F.) all season; (6) mulched soil, unheated; and (7) mulched soil, heated (75° F.) until June 17. The temperatures indicated for the heated treatments are the temperatures below which the heaters were automatically turned.
on, that is, the theoretical minimum soil temperatures allowed to be reached in the heated treatments.

The thermostatic control used is called Thermoswitch and is manufactured by Fenwall, Inc., Ashland, Mass. These regulators were preset in the laboratory to close the circuit to the heaters when the temperature dropped to the level indicated in the above listing of the treatments. The Thermoswitches, about 3 1/2 inches long and about 3/4 inch in diameter, were buried vertically in the soil in the corn row so that the top of the switch was level with the soil surface.

The heaters used were lead-sheathed heating cables, manufactured by General Electric, such as are commonly used to keep sidewalks and pipes free of ice. Each cable is 60 feet long, bent into a hairpin shape with 30-foot legs. In a heated plot, the cable was placed with each 30-foot leg 4 inches from each side of a corn row and 5 inches deep in the soil.

The experimental area was at the Agricultural Engineering Farm near Ames, Iowa on Webster silty clay loam soil. The area had been in alfalfa the previous year and the available nitrogen content of the soil was assumed to be high. Commercial 10-10-10 fertilizer at the rate of 1000 pounds per acre was added. It was intended to side-dress nitrogen on the mulch plots if evidence of nitrogen defi-
ciency became apparent, but no side dressing was necessary. Whole plant samples taken June 12, 1957, leaf samples on July 29 and corn grain samples on September 23, were analyzed for nitrogen, phosphorus and potassium by Mr. V. J. Kilmer of the Agricultural Research Service, Beltsville, Maryland.

The mulching material was chopped corn stalks applied at the rate of 3 tons of air-dry material per acre. The corn was planted on May 1, 1957 at 2 1/2 inches soil depth at the rate of three kernels every foot. The heating cables were in operation at the time of planting. Emergence counts were made on May 6 and May 8, 1957. Plant heights were taken on eight dates from May 17 until July 2, 1957. Soil temperature in the corn row at the 4-inch depth was measured with copper-constantan thermocouples attached to a modified Brown Electronik strip-chart recorder. The recorder was equipped with modifications as described by Larson et al. (1959). Air temperature at the 5-foot height was also measured. All temperatures were measured every hour on the hour generally for two days each week of the growing season.

Additional data taken included the date at which 75% of the plants in a treatment were silked, corn grain yields and one soil moisture sampling.

The following statements apply equally to the heating cable experiment just described and the mulch rate experiment to be described later. For the first 10 days after planting
there was no rainfall and soil moisture supplies had been depleted. A total of 18.05 inches of rainfall was measured during the 146 days from planting to harvest. Rain fell on 45 of the 146 days. Of the total rainfall, 6.16 inches fell in May, 5.56 inches in June, 3.17 inches in July, 3.39 inches in August and 1.19 inches in September. In a normal year this amount of rainfall would have been adequate; however, since soil moisture supplies were low at the beginning of the season, the amount of rainfall did not appear to be optimum.

**Mulch Rate Experiment**

An experiment was designed to investigate the effects of the amount of mulch present on the soil surface on soil temperature and the early growth of corn. Five rates of mulching were used: 0 (bare soil) and 1, 2, 4 and 8 tons per acre of chopped corn stalks on a dry weight basis. The experiment was located on Webster silty clay loam soil at the Agricultural Engineering farm south of Ames.

Plot size was four 40-inch corn rows, each 15 feet long. The plots were arranged in a randomized complete block design with four blocks. Mulch was applied to the plots on May 2. Thermocouples were buried at three soil depths, 1/4, 2 and 4 inches at two randomly selected sites in the two harvest rows of each plot, making a total of 120 (5 treatments x
4 blocks x 3 depths x 2 sites per plot) thermocouples for measurement of soil temperature. Air temperature at a height of five feet was measured at one point in the center of the experimental area. All temperatures were measured once each hour on the hour for at least two days of each week of the growing season from May 17 until harvest on September 23.

On April 13, 1957, there was applied 1000 pounds per acre of 10-10-10 commercial fertilizer. It was assumed that this rate of fertilizer application would take care of the requirements of the plants as well as being an ample supply for decomposition of the residue. In addition to the uniform fertilizer application, there was applied 4-16-8 fertilizer in the corn row as starter fertilizer at the rate of 80 pounds per acre when the corn was machine planted on May 1.

By May 17 the corn in all treatments had emerged above the soil and, with the exception of the 8-ton-per-acre rate, had emerged also above the mulch. On May 17 it was apparent that the corn in the 8-tons-per-acre treatment would die before it emerged from the mulch cover, which was about 5 inches thick, and so the mulch was pulled back from the rows in this treatment. Even with this precaution, some of the plants in the 8-tons-per-acre treatment did die and it was necessary to replant some bare spots on May 23.

Data other than soil temperature taken on the experiment
included plant heights (leaves extended) on seven dates from May 24 to July 2; the date on which 75% of the plants in each plot were silked; dry matter production; total nitrogen, phosphorus and potassium in whole plant samples taken at thinning on June 19; corn leaf samples for total nitrogen, phosphorus and potassium at 75% silking; corn grain yields and total nitrogen, phosphorus and potassium in the grain at the season's end.
RESULTS AND DISCUSSION

Heating Cable Experiment

The seven treatments of the heating cable experiment will be referred to as follows: 1) bare-unheated, 2) bare-heated-75°-all-season, 3) bare-heated-75°-early, 4) mulch-heated-71°-all-season, 5) mulch-heated-75°-all-season, 6) mulch-unheated and 7) mulch-heated-75°-early.

On May 6, 1957, six days after planting, about one-half of the plants in the bare-heated plots had emerged, while there were no other plants visible in any of the other plots. Plants in the mulch-heated plots had also emerged under but not through the mulch. On May 8 the plants of the bare-unheated and mulch-unheated treatments still showed no emergence; however, over three-fourths of the plants in the other plots were nearly three inches in height. These emergence data provide one index of the early growth of the plants, but there was no difference between mulch and bare plots, just between heated and unheated.

Table 1 shows the average of 40 observed plant heights in each treatment on each of eight dates, together with the standard error, as computed from analysis of variance, of a treatment mean for each date. Analysis of variance of the data in Table 1 shows that for each date there is a highly significant treatment effect. The data from Table 1 are
Table 1. Average of 40 plant heights at eight dates in the heating cable experiment, together with the standard error of a treatment mean for each date.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>May</th>
<th>June</th>
<th>July</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Bare-unheated</td>
<td>7.2</td>
<td>9.9</td>
<td>15.8</td>
</tr>
<tr>
<td>Bare-heated-75°C-all-season</td>
<td>13.4</td>
<td>15.6</td>
<td>18.9</td>
</tr>
<tr>
<td>Bare-heated-75°C-early</td>
<td>13.4</td>
<td>15.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Mulch-heated-71°C-all-season</td>
<td>13.8</td>
<td>15.3</td>
<td>17.9</td>
</tr>
<tr>
<td>Mulch-heated-75°C-all-season</td>
<td>14.6</td>
<td>17.2</td>
<td>20.8</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>6.0</td>
<td>8.4</td>
<td>14.0</td>
</tr>
<tr>
<td>Mulch-heated-75°C-early</td>
<td>15.2</td>
<td>16.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.37</td>
<td>0.34</td>
<td>0.38</td>
</tr>
</tbody>
</table>

plotted graphically in Figure 1 so that the various treatments may be easily compared. It is seen from Figure 1 that the height order of the treatments from high to low is bare-heated-75°C-all-season; bare-heated-75°C-early (a single curve for these two sets of data points); bare-unheated; mulch-heated-75°C-all-season, mulch-heated-75°C-early (a single curve
Figure 1. Plant height versus time for the heating cable experiment
CORN PLANT HEIGHT (cm.)

TIME (DAYS FROM MAY 1, 1957)

BARE-HEATED-75°-ALL SEASON
BARE-HEATED-75°-EARLY

BARE-UNHEATED

MULCH-HEATED-75°-ALL SEASON
MULCH-HEATED-75°-EARLY

MULCH-HEATED-71°-ALL SEASON

MULCH-UNHEATED
for these two sets of data points); and last, mulch-unheated. In general this is the order one might predict from an examination of the average soil temperatures during the period of height measurements. The mulch-heated and bare-heated treatments had the highest average temperatures, followed by the bare-unheated and mulch-unheated. The average temperatures referred to are the averages over two days of each week measured and are not the true weekly or monthly averages.

The heating cables were turned off in the heated-early plots on June 15 and the height measurements were continued until July 2. If differences in growth other than early growth were going to be apparent, then comparison of plant heights on the heated-all-season to those on the heated-early treatments should be significant, at least for the June 26 and July 2 measurements. The comparisons, bare-heated-all-season versus bare-heated-early, and mulch-heated-all-season versus mulch-heated-early do not even approach statistical significance for any of the measurement dates. Figure 1 shows a single curve for each of these two treatment pairs. Thus it appears that the main effect of mulch on the elongation of corn takes place during the early period of growth.

On June 12, the plots were thinned so that there was remaining only one corn plant for each foot. Twenty randomly selected plants from those removed from the plots were used
for dry-matter determinations. Table 2 gives the average oven-dry weight of 20 plants and the average 4-inch soil temperature. Each weight in Table 2 is the average of four observations (replicates) and each temperature the average of 36 temperature measurements.

Table 2. Dry matter production and average 4-inch soil temperatures on the heating cable experiment (samples taken at thinning time, June 19, 1957; weights are in grams and are for 20 plants; temperatures are in °F.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Weight per 20 plants (g)</th>
<th>Average 4-inch soil temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare-unheated</td>
<td>42</td>
<td>61</td>
</tr>
<tr>
<td>Bare-heated-(75°)-all-season</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Bare-heated-(75°)-early</td>
<td>55</td>
<td>70</td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>31</td>
<td>68</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>42</td>
<td>71</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>36</td>
<td>70</td>
</tr>
</tbody>
</table>

One sees in Table 2 that the highest temperatures occurred in the heated treatments. Furthermore a general relationship may be seen between dry-matter production and average temperature. The average temperatures in the heated treatments were 7 to 11 degrees higher than in the unheated
treatments. The mulch-heated treatments produced about as much dry matter as the bare-unheated treatment, but two to three times as much as the mulch-unheated. It is of interest to examine the experimental results on the assumption that only four treatments were used: bare-unheated; mulch-unheated; bare-heated-(75°)-all-season; and mulch-heated-(75°)-all-season. Comparing treatments on this basis leads to the conclusion that the undesirable effects of mulching are due to lowered soil temperature.

There have been occasions when visual observations indicated that plants grown in mulched soil are as tall as plants grown in unmulched soil, but that the stalk diameter is smaller under mulched conditions. The data from Tables 1 and 2 show that this is not necessarily the case. Plant heights for June 10 in Table 1 may be compared with the dry matter production until June 12 of Table 2. This comparison shows that the bare-heated treatments resulted in highest elongation (50.4 and 52.1 cm.) and highest dry weight (50 and 55 gm.); while the mulch-heated-71° and the mulch-unheated treatments resulted in the lowest elongation (41.3 and 34.5 cm.) and dry weight (31 and 15 gm.).

The whole plant samples, as well as subsequent plant samples, were analyzed for percentage of nitrogen, phosphorus, and potassium. Table 3 shows the content of these three nutrients in the whole plant samples of June 12.
Table 3. Percent nitrogen, phosphorus and potassium in whole plant samples taken June 12, 1957 from the heating cable experiment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Percent&lt;sup&gt;a&lt;/sup&gt;</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nitrogen</td>
<td>Phosphorus</td>
<td>Potassium</td>
<td></td>
</tr>
<tr>
<td>Bare-unheated</td>
<td>4.47</td>
<td>0.49</td>
<td>4.81</td>
<td></td>
</tr>
<tr>
<td>Bare-heated-all-season</td>
<td>4.54</td>
<td>0.54</td>
<td>5.01</td>
<td></td>
</tr>
<tr>
<td>Bare-heated-early</td>
<td>4.42</td>
<td>0.50</td>
<td>4.91</td>
<td></td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>4.03</td>
<td>0.53</td>
<td>4.70</td>
<td></td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>4.03</td>
<td>0.51</td>
<td>4.80</td>
<td></td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>4.04</td>
<td>0.54</td>
<td>4.47</td>
<td></td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>4.03</td>
<td>0.54</td>
<td>4.75</td>
<td></td>
</tr>
<tr>
<td>Standard error of treatment mean</td>
<td>0.12</td>
<td>0.03</td>
<td>0.12</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Each entry is an average of four replicates.

Analysis of variance of the data for Table 3 shows that nitrogen is the only one of the three nutrients upon which the treatments had statistically significant effects (0.05 probability level). It is readily apparent that the significance is due to mulching and not to heating by comparing the nitrogen levels of the plants from the bare treatments (4.47, 4.54 and 4.42 percent N) to those of the mulched treatments (4.03, 4.04 and 4.03 percent N). The nutrient status of the whole plant samples thus gives the same information that has
been observed by other workers, namely, that a mulch of crop residues lowers the nitrogen uptake of the plant.

Leaf samples for nutrient analysis were taken on July 29, 1957 when corn in all of the plots had reached approximately 75% silking. Table 4 shows the percentage nitrogen, phosphorus and potassium in the leaf immediately below and opposite the ear.

In connection with Table 4, it is pointed out that tentative values of the percentage of nitrogen and phosphorus in the corn leaf required for maximum yield have been estab-

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Percenta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Bare-unheated</td>
<td>3.14</td>
</tr>
<tr>
<td>Bare-heated-all-season</td>
<td>3.29</td>
</tr>
<tr>
<td>Bare-heated-early</td>
<td>3.16</td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>3.04</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>3.02</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>3.08</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>2.88</td>
</tr>
<tr>
<td>Standard error of treatment mean</td>
<td>0.04</td>
</tr>
</tbody>
</table>

aEach entry is the average of four replicates.
lished (Dumenil, 1958). These values are 3.16% nitrogen and 0.33% phosphorus. With regard to potassium, Dr. Dumenil and others have expressed the opinion to the writer that the potassium level should be 1.5 to 2.0% for maximum yield. All these values were obtained for conventional plow tillage. If it can be assumed that these values apply equally to the conditions of this experiment, then one sees from Table 4 that the plants on the bare treatments contained sufficient nitrogen to attain maximum yield while those on the mulched treatments did not. All treatments were slightly below the 0.33% level for phosphorus, but contained potassium in amounts larger than the 1.5 to 2.0% value. The differences in nitrogen percent among the various bare treatments probably mean little, as all the nitrogen values were above or nearly at the desired minimum level. The differences in nitrogen percent among the various mulch treatments are in general within the experimental error. The low value of nitrogen percent for the mulch-heated-75°-early treatment would lead to the conclusion that the differences in heating produced this low value; however, the coldest treatment, mulch-unheated, had the highest nitrogen percent. In the case of phosphorus, the theory that lowered temperature causes increased phosphorus uptake is not borne out here. Mulching produced the highest as well as the lowest phosphorus content. Even though the analysis of variance shows
that treatments had a significant effect on phosphorus content of the corn leaves, most differences are within the experimental error. Although in some cases the nutrient uptake by the plants appears to be slightly low, the amount of nutrient should have been sufficient for near-maximum yield if other factors were also near optimum. In general, it may be said from Tables 3 and 4 that the nitrogen status, but not the phosphorus and potassium, was affected by the mulch. In view of the growth data of Tables 1 and 2 and the data of Table 4, differences in nutrient amounts in the plants due to mulch did not result in growth differences.

The date that 75% of the plants in a treatment reach the silking stage of growth is considered to be a measure of relative maturity. This is the case if there are a constant number of days between silking and maturity. Table 5 shows the date on which 75% of the plants in each treatment had silked. Analysis of variance shows that the treatment effects shown in Table 5 are statistically significant (0.01 probability level). Usually the earliest possible maturity date is the best, since dangers from frost damage and delays from harvesting by inclement weather are then minimized. Although a difference of about two days may be considered statistically significant, a period of about five days would probably be required before attaching any practical significance to it. In the fall of 1957 an early snow prevented or
Table 5. Dates on which the treatments of the heating cable experiment had 75% of the plants silked

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Silking date (July)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare-unheated</td>
<td>20</td>
</tr>
<tr>
<td>Bare-heated-all-season</td>
<td>18</td>
</tr>
<tr>
<td>Bare-heated-early</td>
<td>17</td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>21</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>19</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>25</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>20</td>
</tr>
</tbody>
</table>

Standard error of a treatment mean = 0.96 day

Delayed harvest of much of the corn crop in central Iowa. Had a farmer been able to take advantage of five days prior to the snow, he might have saved some corn which was lodged by the weight of the snow. In Table 5 it is seen that heating the mulched soil resulted in four to eight days hastening of maturity. Merely putting a mulch on the surface delayed maturity by five days.

Soil moisture samples were taken from the experiment just before silking. Table 6 shows the results of this sampling. The highest soil moisture content occurred as expected in the mulch unheated treatment. The lowest soil moisture content, however, did not occur in the bare-heated-
Table 6. Soil moisture (percent of dry soil weight) on July 18, 1957 in the heating cable experiment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-6</td>
</tr>
<tr>
<td>Bare-unheated</td>
<td>12.9</td>
</tr>
<tr>
<td>Bare-heated-all-season</td>
<td>14.7</td>
</tr>
<tr>
<td>Bare-heated-early</td>
<td>13.8</td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>15.2</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>14.4</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>15.2</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>14.8</td>
</tr>
</tbody>
</table>

All-season treatment but in the bare-unheated treatment. A surprising result, and one that the author has no explanation for, is the small amount of moisture present under the mulch-heated-(75°)-all-season treatment.

Grain yields were variable. The small plot size contributed a large amount of this variation. Table 7 gives the corn grain yields for the heating cable experiment. Analysis of variance shows that the yield differences of Table 7 are significant at the 0.10 probability level. Comparison of the yield data with the soil moisture data of Table 6 reveals
Table 7. Comparison of corn yields from the present heating cable experiment and the heating cable experiment of Willis; average soil temperatures at 4-inch depth in the present experiment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Average soil temperature</th>
<th>Yield (bushels per acre)</th>
<th>Yields from Willis (1956)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare-unheated</td>
<td>68.7</td>
<td>117.2</td>
<td>116.2</td>
</tr>
<tr>
<td>Bare-heated-all-season</td>
<td>72.5</td>
<td>116.3</td>
<td>109.2</td>
</tr>
<tr>
<td>Bare-heated-early</td>
<td>72.1</td>
<td>106.3</td>
<td>--</td>
</tr>
<tr>
<td>Mulch-heated-(71°)-all-season</td>
<td>71.6</td>
<td>121.2</td>
<td>118.0</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-all-season</td>
<td>72.8</td>
<td>114.4</td>
<td>--</td>
</tr>
<tr>
<td>Mulch-unheated</td>
<td>67.6</td>
<td>127.1</td>
<td>114.8</td>
</tr>
<tr>
<td>Mulch-heated-(75°)-early</td>
<td>71.3</td>
<td>116.4</td>
<td>--</td>
</tr>
</tbody>
</table>

that the mulch unheated treatment had the highest moisture content and also the highest yield and that this pattern is generally followed for the rest of the treatments. In other words beneficial moisture effects of mulch of the later growing season have apparently overshadowed deleterious temperature effects of mulch, seen in former tables, of the early growing season. That moisture effects are in point is evident from the last column of the table, as this column contains data where moisture was not limiting. Willis was able to show that the lower yield from the bare-heated
treatment was probably due to soil temperature being higher than optimum. In the present experiment, it was not possible to irrigate as did Willis, and therefore yield differences may be ascribed to soil moisture differences as well as to soil temperature. The moisture problem probably did not enter into the early growth data reported in Tables 1 and 2.

Figures 2 and 3 show graphs of temperature during an average day of the season. The points were obtained for the graphs by averaging the hourly temperature readings at the 4-inch soil depth over replicates and days of the season. Each point on the soil temperature curves is thus an average of 108 observations and each point on the air temperature curve is the average of 27 observations. The temperatures in the bare treatments may be compared with each other and with the temperatures in the mulch-unheated treatment and with air temperatures in Figure 2. Figure 2 shows that with heating, the bare plots were maintained almost constantly 5°F warmer than the mulch-unheated treatment. The main difference between the bare-heated and bare-unheated treatments was at the minimum temperature. This difference was about 4°F, while at the maximum the difference was only about 2°F. This pattern is to be expected, since the thermostatic controls were set to close on a temperature fall below the setting. Thus the minimum temperature was the one to be changed. The temperature difference caused by
Figure 2. Seasonal average hourly temperatures at 4-inch depth for the bare-heated-early, bare-heated-all-season and mulch-unheated treatments and the 5-foot air temperature in the heating cable experiment.
HEATING CABLE EXPERIMENT
SEASONAL AVERAGE HOURLY TEMPERATURES,
at 4 inch depth for treatments indicated; air
temperature at 5 foot height.

![Graph showing seasonal average hourly temperatures](image-url)
Figure 3. Seasonal average hourly temperatures at 4-inch depth for the mulch-heated-71°-all-season, mulch-heated-75°-all-season and -early and mulch-unheated and the 5-foot air temperature in the heating cable experiment.
HEATING CABLE EXPERIMENT
SEASONAL AVERAGE HOURLY TEMPERATURES,
at 4 inch depth for treatments indicated; air
temperature at 5 foot height.
mulching was about 3° F. at the maximum and almost zero at the minimum. This effect also may be expected because the reflection of solar radiation during the day by the mulch prevents the soil under the mulch from warming as much as the bare soil. Therefore the maximum temperature of the bare soil is higher than that of the mulched soil. At night the radiation of heat from the soil is slowed by the insulating effect of the mulch. Thus the bare soil loses more heat and the minimum bare soil temperature falls to a value the same as or nearly the same as the soil temperature under the mulch.

**Mulch Rate Experiment**

The mulch rate experiment, where rates of 0, 1, 2, 4, and 8 tons per acre of mulch were used, was one for which more comprehensive data were taken than for the heating cable experiment. The experiment was planted on May 1, 1957 and the first emergence of corn was on the 0 and 1 ton per acre treatments on May 6. The corn on the rest of the treatments emerged between May 6 and May 17. On May 17 it appeared that the corn seedlings under 8 tons per acre of mulch were going to die and the mulch was pulled back from the rows so that some growth could take place. The mulch was put back in the rows on June 5 when the plants had a good start. For this reason some of the data for the 8-tons-per-acre treatment may
not strictly be compared with the data from the treatments with the other rates of application.

Plant height measurements were started on May 24 and the results of these measurements are presented in Table 8. One sees that the height decreases as amount of mulch in-

Table 8. Plant heights at various dates from the mulch rate experiment (each entry in the table is the average of 40 heights - 10 plants from each of four replicates)

<table>
<thead>
<tr>
<th>Treatment (mulch rate T/A)</th>
<th>May 24</th>
<th>June 1</th>
<th>June 10</th>
<th>June 20</th>
<th>June 26</th>
<th>July 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11.5</td>
<td>16.5</td>
<td>20.1</td>
<td>39.3</td>
<td>84.0</td>
<td>111.3</td>
</tr>
<tr>
<td>1</td>
<td>11.3</td>
<td>17.0</td>
<td>19.9</td>
<td>38.3</td>
<td>79.8</td>
<td>103.9</td>
</tr>
<tr>
<td>2</td>
<td>10.8</td>
<td>15.5</td>
<td>20.3</td>
<td>34.0</td>
<td>72.6</td>
<td>95.2</td>
</tr>
<tr>
<td>4</td>
<td>9.9</td>
<td>15.6</td>
<td>19.5</td>
<td>30.9</td>
<td>62.6</td>
<td>81.2</td>
</tr>
<tr>
<td>8</td>
<td>8.4</td>
<td>13.1</td>
<td>16.1</td>
<td>27.3</td>
<td>56.5</td>
<td>72.1</td>
</tr>
</tbody>
</table>

Standard error of a treatment mean

<table>
<thead>
<tr>
<th></th>
<th>May 24</th>
<th>June 1</th>
<th>June 10</th>
<th>June 20</th>
<th>June 26</th>
<th>July 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard error</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9</td>
<td>1.3</td>
<td>1.9</td>
</tr>
</tbody>
</table>

creases. Subtracting the height on one date from the height on another date and dividing the difference by the number of days in the period, one obtains an average growth rate for the period which may be compared among treatments. For example, considering the 0-ton-per-acre treatment, the
height on July 2 was 143.9 and on June 26 it was 111.3 for a difference of 32.6. There were six days in the period, giving an average growth rate of 5.4 cm./day. For the May 24 to July 2 period shown in the table, one finds that growth rates calculated in this manner increase as the season progresses and decrease with an increase in mulch rate. Growth rates calculated in this manner are not accurate and depend upon the actual height obtained. Figure 4 is a graph of the data in Table 8. Here the differences in height may be observed. The growth rates are the slopes of the curve, which get steeper with time.

It has already been noted that the growth rate (change in height with time) \( \frac{dH}{dt} \) is proportional to the height, \( H \), attained. It may then be assumed that the differential equation to be solved for the portion of the growth curves shown in Figure 4 is \( \frac{dH}{dt} = bH \), where \( b \) is a proportionality constant (Hammond and Kirkham, 1949). The solution is \( H = a e^{pt} \), where \( a \) is the constant of integration. Taking the logarithm of the solution gives a linear equation, \( \ln H = \ln a + bt \). From regression analysis of \( \ln H \) versus \( t \), the equations shown in Table 9 were obtained. The equation for the 8-tons-per-acre treatment is seen not to follow the pattern of a generally increasing coefficient of the exponential term and a decreasing argument of the exponential term. By using only the data taken on the dates after the
Figure 4. Plant height versus time for the mulch rate experiment
Table 9. Equations of the relation of plant height \( H \) to time \( t \) for the mulch rate experiment

<table>
<thead>
<tr>
<th>T/A of mulch</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( H = 2.409 \exp(0.06692) )</td>
</tr>
<tr>
<td>1</td>
<td>( H = 2.514 \exp(0.06530) )</td>
</tr>
<tr>
<td>2</td>
<td>( H = 2.470 \exp(0.06404) )</td>
</tr>
<tr>
<td>4</td>
<td>( H = 2.628 \exp(0.06023) )</td>
</tr>
<tr>
<td>8</td>
<td>( H = 2.104 \exp(0.06213) )</td>
</tr>
</tbody>
</table>

Mulch was put back in the rows on the 8-tons-per-acre treatment, the following equation was found: \( H = 2.831 \exp(0.0566) \). This equation fits the pattern of the others.

Analysis of the data (Kempthorne, 1952, p. 47) shows, omitting the data for the 8-tons-per-acre treatment, that four separate values for \( b \) are necessary; one value will not serve for all the treatments. Use of the technique of Rao (1958) shows also that the differences between growth rates were, statistically, highly significant. In using the Rao technique, the data for the 8-tons-per-acre treatment were not omitted.

Figure 5 shows the effect of mulch rate on the \( b \) values. Physically, the parameter \( b \) is the rate of growth per unit of growth, in this case cm. day\(^{-1} \) cm\(^{-1} \). The value of the parameter \( b \) should depend on the treatments. It is seen
Figure 5. Calculated values of growth rate per unit height as affected by mulch rate
b, GROWTH RATE PER UNIT HEIGHT (cm./day/cm.) x 10^3
from Figure 5 that the rate of mulch has a large effect on b and hence on the early growth of the corn plant.

Another measure of growth is the amount of dry matter produced by the plant. Figure 6 shows the effect of mulch rate on dry matter production from planting until June 19. The graph of Figure 6 is similar to that of Figure 5. Both show that an increase in the amount of mulch gives a decrease in growth.

The samples taken for dry matter determinations were analyzed for nitrogen, phosphorus and potassium content. Table 10 shows the percent nitrogen, phosphorus and potassium in the whole plant. None of the treatment differences for phosphorus or potassium in Table 10 are statistically significant. Differences in percent nitrogen, significant at the 0.01 level, are small between the 0 and 1-ton-per-acre treatments increase with increasing rate of mulch application.

The 0 and 1-ton-per-acre treatments were 75% silked on July 22, 2-ton-per-acre on July 24, 4-ton-per-acre on July 27 and 8-ton-per-acre on August 1. Comparison of the treatments with the 0-ton-per-acre treatment shows that the 2-, 4- and 8-ton-per-acre treatments were significantly later in silking. The differences of five and ten days, respectively, for the last two treatments can be considered to have practical significance. A delay of five days in
Figure 6. Dry matter production as affected by mulch rate
Table 10. Percentage nitrogen, phosphorus and potassium in whole plant samples taken on June 19

<table>
<thead>
<tr>
<th>Treatment (mulch rate, tons per acre)</th>
<th>Nitrogen %</th>
<th>Phosphorus %</th>
<th>Potassium %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.42</td>
<td>0.44</td>
<td>4.38</td>
</tr>
<tr>
<td>1</td>
<td>3.52</td>
<td>0.46</td>
<td>4.47</td>
</tr>
<tr>
<td>2</td>
<td>3.22</td>
<td>0.48</td>
<td>4.62</td>
</tr>
<tr>
<td>4</td>
<td>2.86</td>
<td>0.44</td>
<td>4.62</td>
</tr>
<tr>
<td>8</td>
<td>2.68</td>
<td>0.47</td>
<td>4.69</td>
</tr>
</tbody>
</table>

Harvest may mean a 50% decrease in yield from lodging due to the weight of an early snow storm.

Leaf samples taken at silking time were analyzed for nitrogen, phosphorus and potassium content, but the differences were less than for the whole plant samples shown in Table 10 and even nitrogen percent did not show significant treatment effects. The nutrient contents of the leaves bore no apparent relation to either growth or yield.

Soil moisture samples were taken on July 18 at the 0-6, 6-12, 12-24, 24-36, 36-48 and 48-60 inch depths. In general, as the rate of mulch application increased, soil moisture also increased. This relationship was most striking in the top two feet of soil. Moisture contents in the top two feet of soil were 14.8%, 15.9%, 16.0%, 18.0% and 19.5% for the
0-, 1-, 2-, 4- and 8-tons-per-acre treatments, respectively. The largest differences occurred in the surface six inches where the effect of mulch applications was quite evident. There was a maximum 1.9% difference in soil moisture in the 0-6 inch layer for the 0-, 1- and 2-tons-per-acre treatments, but from 4% to 6% difference between these three treatments and the 4- and 8-tons-per-acre treatments. In the latter two treatments, the mulch completely covered the soil surface, reducing evaporation, while in the low-rate treatments the mulch did not cover all of the soil surface, so that evaporation could proceed with little difficulty. The moisture values referred to in this paragraph were obtained by compositing four samples for each treatment.

Corn grain yields were taken; however, it was not expected that they would be of interest for two reasons. The plot size was extremely small and the yield estimates could not be considered really to represent a true picture. As with the heating cable experiment, there was no control over the moisture status of the soil, so that yield estimates must reflect the effect of an uncontrolled variable. The variability among plots treated alike was large and therefore the only significant yield difference was between the yield on the 8-tons-per-acre treatment of 95 bushels per acre, and the yield on the 0-tons-per-acre treatment of 114 bushels per acre. The average yield for the experiment was 113.5
Soil temperature observations were taken at three depths, 0.25, 2 and 4 inches, at each of two locations in each plot. One objective of the experiment was to attempt to determine the number of sites necessary to obtain a reliable estimate of the soil temperature for use with growth data of the type tabulated in this paper and elsewhere. The largest temperature differences occur on clear days when the solar radiation is high. On such a day, one would expect differences in soil conditions to produce the largest effects on temperature, that is, the differences between sites in plots treated alike would be the largest. June 20 and 21 were selected as having the desired characteristics of few clouds and no rainfall. These two days were early enough in the growing season so that the plants did not shade much of the soil surface. The 0.25 inch depth was selected to be analyzed, since the effects of water or wind erosion after the thermocouples were installed could be assessed. The erosion problem was severe enough that it was necessary to adjust the positions of the 0.25 inch depth thermocouples several times during the course of the experiment. Techniques of analysis of variance were used to obtain estimates of the experimental error and the sampling error for temperatures at the 0.25 inch soil depth taken at 4 p.m. June 20 (time of occurrence of the maximum), at 10 p.m. June 20
(time of occurrence of the mean), at 5 a.m. June 21 (time of occurrence of the minimum) and for the 24-hour average. Table 11 shows the estimates of experimental error, sampling error and the standard error of a treatment mean for these times. The values of the experimental errors at the time of the maximum (4 p.m.) and at the time of the minimum (5 a.m.) are less than the values of the sampling errors. This means that the differences between samples taken at these times are greater than the differences due to chance or random errors in the experiment. Therefore, the data for these times do
not permit an estimate of the number of samples that should be taken. The most useful temperature for many purposes is the daily average, called the 24-hour average here. If one makes the assumption that the components of variance remain the same for similar days and conditions, then taking four samples rather than two would give an increase of 32% relative efficiency; however, the use of three samples and three blocks would give a decrease of about 3% in relative efficiency. It would ordinarily be satisfactory if one could estimate the daily average temperature to the nearest degree. It is seen that the standard error of a treatment mean for the 24-hour average, using two samples, is 0.85°F, which is not sufficient reliability. If greater reliability is desired, it should be obvious that an increase in the number of replicates or samples is necessary.

Figure 7 is a plot of the diurnal course of soil temperature at 0.25-inch in all the treatments on June 20 and 21. The solid-line curves are the observed temperatures and the dashed-line curves are the temperatures calculated from the Fourier series, to be discussed later. The average temperatures are shown as horizontal lines, with the value written at the right side of the graph. One notes that at 1200 hours June 21 there is a dip in the curves due to clouds cutting off the solar radiation. The damping effect of mulch is seen by comparing the magnitude of the effect of this
Figure 7. Diurnal course of soil temperature at 0.25 inch depth on June 20, 21 (solid-line curves) and the Fourier series representation of the diurnal course (dashed-line curves); a separate set of curves is given for each of the five treatments, 0-, 1-, 2-, 4- and 8-tons-per-acre of mulch, in the mulch rate experiment; the average daily temperature is represented as a horizontal line for each set of curves and the value of the average is written at the right end of this horizontal line.
JUNE 20-21, 1957
0.25 INCH DEPTH

TIME OF DAY

SOIL TEMPERATURE (°F)

0 - T/A MULCH

1 - T/A MULCH

2 - T/A MULCH

4 - T/A MULCH

8 - T/A MULCH

65 70 75 80 85 90

16 18 20 22 24 02 04 06 08 10 12 14 16

77.1

77.5

75.4

71.8

69.2
short-period variation with varying rates of mulch. With 8 tons of mulch per acre short period variations are completely damped out. The variation noted has a period of two hours, making a circle frequency of $8.73 \times 10^{-4} \text{ sec}^{-1}$. The thermal conductivity of air-dry mulch was measured to be about $4 \times 10^{-4} \text{ cal. cm}^{-1} \text{ sec}^{-1}$ and the volumetric heat capacity estimated to be $0.04 \text{ cal. cm}^{-3} \text{ O}^\circ\text{C}^{-1}$. Use of these values gives a value for the damping depth for the two-hour period of 4.8 cm. The thickness of the mulch layer on the 8-ton-per-acre treatment was about 6 inches or 15 cm. According to the simple or "classical" theory, at a depth of three times the damping depth, the amplitude of temperature variations is less than 5% of the amplitude at the surface. That this is at least a good approximation is seen in Figure 7 for the two-hour variation now under discussion at noon June 21. There are other things affecting the variation in Figure 7, such as the fact that the temperatures are for the 0.25 inch depth, so that 0.25 inch of soil adds slightly to the damping effect.

Figure 8 shows the temperature curves for the 0- and 8-ton-per-acre treatments at the 0.25, 2 and 4 inch depths. Notice the two curves for the 0.25 inch depth. There is a difference of about 17$^\circ$ F. at the maximum between the bare soil and 8-ton-per-acre treatments, but at the minimum there is no difference. This leads to a difference between
Figure 8. The diurnal course of temperature at 0.25, 2 and 4 inch soil depth in the 0- and 8-tons-per-acre treatments of the mulch rate experiment on June 20, 21.
the average temperatures for the two treatments of about
8° F. As noted in the review of literature, some investi-
gators have said that temperature is a minor factor in the
study of tillage problems. The curves show the probable
reason for this conclusion in that the difference between the
average temperatures for the two treatments is about one-half
that between the maximum temperatures for the two treatments.
Thus by taking average values the large temperature differ­
ences at the maximum are not detected. These large temper­
ature differences at the maximum, when they occur, are be­
lieved to be important since these differences occur when
the plant is actively photosynthesizing, whereas any differ­
ence in minimum temperatures takes place at or shortly after
the time when no light is available for photosynthesis. The
growth processes are certainly more affected by maximum soil
temperature than minimum soil temperature within certain
limits and thus the practice of some workers of observing
the soil temperature at 4 p.m. each day would seem to be
sound.

Bliss (1958) gives a method for calculating the Fourier
series for temperature observation which is much the same as
that used in this study. Three harmonics were used which
exhausted the amount of information that may be gotten from
the 24 hourly observations. The form of the Fourier series
calculated first was
\[ T(z,t) = a_0/2 + a_1\cos(\omega t) + a_2\cos(2\omega t) + a_3\cos(3\omega t) \]
\[ + b_1\sin(\omega t) + b_2\sin(2\omega t) + b_3\sin(3\omega t), \]
\[ (13) \]

and from the coefficients \(a_1\) and \(b_1\) the final form was calculated as

\[ T(z,t) = T_{av} + A_1\sin(\omega t + \phi_1) + A_2\sin(2\omega t + \phi_2) \]
\[ + A_3\sin(3\omega t + \phi_3) \]
\[ (14) \]

where \(T_{av} = a_0/2\)

\[ A_1 = (a_1^2 + b_1^2)^{1/2} \quad \phi_1 = \tan^{-1}(a_1/b_1) \]
\[ A_2 = (a_2^2 + b_2^2)^{1/2} \quad \phi_2 = \tan^{-1}(a_2/b_2) \]
\[ A_3 = (a_3^2 + b_3^2)^{1/2} \quad \phi_3 = \tan^{-1}(a_3/b_3) \]

The parameter \(\omega\) is the circle frequency used previously. It should be noted that the first sine term estimates variations in temperature of the full period length, the second sine term estimates variations with period one-half the full period, and the third sine term estimates variations with period one-third the full period. If, as is the case here, the full period is 24 hours, then equation (14) takes account of temperature fluctuations with periods of 24, 12 and 8 hours.

Fourier series were calculated for each of the diurnal temperature curves, for the average diurnal curve for each week and for each month. For each of the three depths measured then, there are 28 daily curves, 17 weekly curves
and five monthly curves. Figure 7 shows the Fourier series curves as dashed lines. The differences between the calculated curve and the observed curve for the 8-tons-per-acre treatment were 0.2°F. or less and could not be shown in the figure. One notes, in Figure 7, that the temperature fluctuation discussed previously, with period of about two hours, does not show as a fluctuation in the calculated curves but the fluctuation is evident from the way the calculated function behaves with respect to the observed curve. From 0800 to 1500 hours the calculated curve is a sort of average of the fluctuation in the observed curve during that time. Because of this smoothing out of short-period fluctuations, the Fourier curve may be more useful than the observed curve for, while retaining the general properties of the actual temperature curve and the differences between curves, the Fourier curve does not show the peculiarities of a specific day.

In order to use the results of the "classical" theory to predict the ratio of the amplitudes of mulched to unmulched soil, as in equation (9), the following variables must be known: the circle frequency, the thermal conductivities of the mulch and of the soil, the (volumetric) heat capacities of the mulch and of the soil and the depth of the mulch on the soil; the damping depth also needed in the equation may be calculated from equation (4) using the above-noted quan-
tities. The limitations of the "classical" theory are immediately obvious when attempts are made to calculate the amplitude ratio of equation (9). No accurate measurements of thermal conductivity or heat capacity are available and thus approximations and approximate measurements must be used. The values for these thermal constants quoted in van Wijk et al. (1959) were obtained as a part of this study. Use of these estimates in this thesis resulted in ridiculous results, such as the result that the amplitude at the mulch-soil interface was greater than that at the surface of the bare soil. Another way to approach the problem is as follows. The variation of \( \left( \frac{A_m}{A_u} \right) \left( \frac{\lambda_1 C_1}{\lambda_2 C_2} \right)^{1/2} \) with \( d/D_1 \) may be plotted for various values of the parameter \( r \). By use of observed values of \( A_m/A_u \) one may then obtain estimates of the ratio \( \left( \frac{\lambda_2 C_2}{\lambda_1 C_1} \right)^{1/2} \). For example, for an average day in June the amplitude ratios are 0.93, 0.90, 0.80 and 0.45 with 1, 2, 4 and 8 tons of mulch per acre, respectively. These amplitude ratio values lead, for constant \( r = -0.7 \), to values of the ratios, \( \left( \frac{\lambda_2 C_2}{\lambda_1 C_1} \right)^{1/2} \), for the four mulch treatments, 3.10, 1.64, 1.05 and 0.43. These values should theoretically be constant since \( \lambda_1 C_1 \) refers to mulch, regardless of how thick it is and \( \lambda_2 C_2 \) refers to the same soil in each case. One reason why constant values are not obtained is that the thermal conductivity and heat capacity of the soil are functions of the soil moisture content,
which is in turn a function of the amount of mulch of the soil. The parameter \( r \) is thus not constant; however, in the range of moisture content encountered, the variation in thermal conductivity and heat capacity (see van Duin, 1956, Figures 11 and 12, pp. 18 and 20) is not large enough to account for the variation in the results. Another reason for some of the variation is that the actual ratios of thermal constants vary because different thicknesses of mulch decompose, etc. differently, changing the thermal constants. This would help explain the large variation in results.

In pointing out these lacks, in the last paragraph, of experimental checks with the "classical" theory, the author does not mean to imply that the "classical" theory is not useful. In those cases where a limited amount of data are available, for example, the case when only the maximum and minimum temperatures at two or more depths are available, then the "classical" theory may be used to extend the scope of the data and obtain some general relationships. If carried to extremes, however, one may confuse rather than enlighten, in the same way as an investigator may confuse rather than enlighten when he speaks of two thermal diffusivities, the one calculated from the phase shift and the other from the decrement in amplitudes, when there is actually only one.

Figures 9 through 20 are 12 sets of graphs of soil
Figure 9. The course of temperature at the 0.25 inch soil depth in the five treatments of the mulch rate experiment on an "average day" in May
Figure 10. Same as Figure 9 except the depth is 2 inches.
2 INCH DEPTH, MAY

TEMPERATURE

TIME

BARE SOIL 8.6
1 T/A 8.2
2 T/A 7.5
4 T/A 4.8
8 T/A 3.0
Figure 11. Same as Figure 9 except the depth is 4 inches
4 INCH DEPTH, MAY

Temperature vs. Time for different treatments and bare soil conditions.
Figure 12. Same as Figure 9 except the month is June.
Figure 13. Same as Figure 9 except the month is June and the depth is 2 inches.
2.00 INCH DEPTH, JUNE
Figure 14. Same as Figure 9 except the month is June and the depth is 4 inches.
Figure 15. Same as Figure 9 except the month is July
0.25 INCH DEPTH, JULY

Temperature vs. Time graph for different water depths:

- **0 T/A**: Temperature peaks at 81.0
- **1 T/A**: Temperature peaks at 80.4
- **2 T/A**: Temperature peaks at 79.7
- **4 T/A**: Temperature peaks at 78.1
- **8 T/A**: Temperature peaks at 75.7
Figure 16. Same as Figure 9 except the month is July and the depth is 2 inches
96

2 INCH DEPTH, JULY

85
80
75
70
85
80
75
70
85
80
75
70
85
80
75
70
85
80
75
70

TEMPERATURE

TIME

16 18 20 22 24 02 04 06 08 10 12 14 16

0 T/A

79.8

1 T/A

79.0

2 T/A

78.9

4 T/A

77.8

8 T/A

75.1
Figure 17. Same as Figure 9 except the month is July and the depth is 4 inches.
4 INCH DEPTH, JULY

TEMPERATURE

TIME
Figure 18. Same as Figure 9 except the month is August
0.25 INCH DEPTH, AUG.

TEMPERATURE

TIME

- 0 T/A
- 1 T/A
- 2 T/A
- 4 T/A
- 8 T/A

65 70 75 80

16 18 20 22 24 02 04 06 08 10 12 14 16
Figure 19. Same as Figure 9 except the month is August and the depth is 2 inches.
Figure 20. Same as Figure 9 except the month is August and the depth is 4 inches.
4 INCH DEPTH, AUG.

- 0 T/A: 73.3
- 1 T/A: 72.9
- 2 T/A: 72.6
- 4 T/A: 72.3
- 8 T/A: 71.4

TEMPERATURE

TIME
temperature variation for three depths for an "average day" of May, of June, of July and of August, the depths being 0.25, 2 and 4 inches below the soil surface, with each set of graphs covering the five mulch rate treatments. Each point used to plot the graphs is an average of observations from four replicates, two sites per plot and eight to ten days. The deviations of the temperatures calculated with the Fourier series from the observed temperatures were about 0.2° F. in most cases, which is too small to show on the graphical scale used. For each curve the average temperature is drawn as a straight, horizontal line with the value written at the right side. Each figure has the 0-tons-per-acre curve at the top and the 1-, 2-, 4- and 8-tons-per-acre treatments in the order below it.

Comparing the figures for the 0.25-inch depth over the months, that is, Figures 9, 12, 15 and 18, one sees that in July, when the days are long, the maximum temperature is reached later than in the other months. As the season progressed, the average temperature increased from May to July and decreased in August. Looking at the 0.25-inch curves for the 8-tons-per-acre treatment and the 4-inch curves for the bare soil treatment, one sees that the temperature variation during the day was about the same for the two treatments, but the mulch was more effective in reducing the temperature than four inches of soil. The difference between the average
temperatures of the bare and mulched treatments is about one-half the difference between the maximum temperatures. There is little if any difference between minimum temperatures in bare and mulched soil. Once again it may be said that if only one soil temperature observation is to be made each day in an experiment, the time of occurrence of the maximum temperature is the best time to detect differences caused by treatments.

Table 12 shows the values of the various parameters of equation (14) for June 20, 21. The graphs of the equations for the 0-tons-per-acre treatment are shown in Figure 7 as dashed lines. One sees in Table 12 the properties exhibited by the Fourier series applied to soil temperature data. There is a rapid decrease in the value of the amplitudes from the first harmonic to the third harmonic. This means that the fluctuation in soil temperature on this day was very nearly sinusoidal in form. Since the 24-hour period from 4 p.m. June 20 to 4 p.m. June 21 was almost clear, with only one cloud formation passing over, it is to be expected that the temperature fluctuation would be very nearly sinusoidal.

One sees further in Table 12 the effect of depth on the average temperature and on the amplitudes of the various harmonics. The amplitudes have almost a logarithmic decrement with depth. That the decrement is not purely logarithmic is due to the inhomogeneity of the soil, mainly with
Table 12. Values of the parameters of the Fourier series for the variation in temperature at the three soil depths, 0.25, 2 and 4 inches in each of the five treatments, 0-, 1-, 2-, 4- and 8-tons-per-acre of mulch, in the mulch rate experiment on June 20, 21, 1959

<table>
<thead>
<tr>
<th>Mulch rate (tons per acre)</th>
<th>Depth (inches)</th>
<th>$T_{av}$ ($^\circ$F.)</th>
<th>$A_1$ ($^\circ$F.)</th>
<th>$\phi_1$ (rad.)</th>
<th>$A_2$ ($^\circ$F.)</th>
<th>$\phi_2$ (rad.)</th>
<th>$A_3$ ($^\circ$F.)</th>
<th>$\phi_3$ (rad.)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0.25</td>
<td>77.1</td>
<td>12.4</td>
<td>-1.34</td>
<td>2.7</td>
<td>-0.46</td>
<td>1.4</td>
<td>0.09</td>
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<td></td>
<td>2</td>
<td>76.5</td>
<td>8.4</td>
<td>1.44</td>
<td>1.4</td>
<td>-1.01</td>
<td>0.7</td>
<td>-0.37</td>
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<td></td>
<td>4</td>
<td>75.2</td>
<td>5.5</td>
<td>1.08</td>
<td>0.8</td>
<td>-1.40</td>
<td>0.4</td>
<td>-1.32</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
<td>77.5</td>
<td>12.7</td>
<td>-1.27</td>
<td>2.8</td>
<td>-0.36</td>
<td>1.6</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>75.1</td>
<td>7.3</td>
<td>1.45</td>
<td>1.4</td>
<td>-0.95</td>
<td>0.5</td>
<td>-0.41</td>
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<td></td>
<td>4</td>
<td>73.8</td>
<td>4.8</td>
<td>1.11</td>
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<td>0.2</td>
<td>-1.22</td>
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<td>10.7</td>
<td>-1.35</td>
<td>3.0</td>
<td>-0.44</td>
<td>0.4</td>
<td>-0.46</td>
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<tr>
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<td>2</td>
<td>73.6</td>
<td>6.8</td>
<td>1.47</td>
<td>1.7</td>
<td>-0.81</td>
<td>0.2</td>
<td>0.90</td>
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<tr>
<td></td>
<td>4</td>
<td>72.4</td>
<td>4.3</td>
<td>1.10</td>
<td>0.8</td>
<td>-1.21</td>
<td>0.3</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>71.8</td>
<td>7.2</td>
<td>-1.33</td>
<td>2.3</td>
<td>-0.43</td>
<td>0.0(4)$^a$-1.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>71.4</td>
<td>5.5</td>
<td>1.55</td>
<td>1.4</td>
<td>-0.79</td>
<td>0.2</td>
<td>0.14</td>
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<tr>
<td></td>
<td>4</td>
<td>70.3</td>
<td>3.4</td>
<td>1.15</td>
<td>0.7</td>
<td>-1.28</td>
<td>0.2</td>
<td>-0.01</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>69.2</td>
<td>4.2</td>
<td>-1.34</td>
<td>1.6</td>
<td>-0.48</td>
<td>0.2</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>68.4</td>
<td>2.7</td>
<td>1.50</td>
<td>0.8</td>
<td>-0.92</td>
<td>0.1</td>
<td>-0.55</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>67.9</td>
<td>1.8</td>
<td>1.16</td>
<td>0.4</td>
<td>-1.27</td>
<td>0.1</td>
<td>-0.59</td>
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</tbody>
</table>

$^a$The entry, if rounded, would be 0.0, the value is 0.04.

respect to soil moisture. The amplitudes of the higher harmonics are small when there is no mulch on the soil; however, with mulch the amplitudes of the higher harmonics are near zero.

The damping depth $D$ of the soil may be calculated using
the amplitude of the first harmonic. The first harmonic is used rather than the second or third because, as may be seen by looking at the amplitudes of the third harmonic for the 4- and 8-tons-per-acre treatments, the magnitude of the higher harmonics is such that the amount of variation with depth is small and the decrement is not even near logarithmic. Damping depths calculated from the values of Table 12 are 4.6, 4.8, 4.4, 4.2 and 5.0 inches for the 0-, 1-, 2-, 4- and 8-tons-per-acre treatments, respectively. Thus at these soil depths the amplitude of the first harmonic is \( \frac{1}{e} = \frac{1}{2.78} \) or about 1/3 of the amplitude of the first harmonic at the soil surface (the mulch-soil interface). At a soil depth of 3D, about 95% of the amplitude is damped out; thus at about 15 inches depth the amplitudes of the first harmonics of the temperature wave would be 0.6, 0.6, 0.5, 0.4 and 0.2°F for the five treatments. The higher harmonics would be damped out more quickly because the frequency of the higher harmonics is greater. As an example, the damping depth for the second harmonic for the 0-tons-per-acre treatment is 3.6 inches. At about 11 inches the amplitude of the second harmonic would thus be about 0.5°F and at 15 inches about 0.1°F.

If the soil is homogeneous, the damping depth calculated from the first harmonic should be 2 times the damping
depth calculated from the second harmonic, since the fre-
quency of the first harmonic is one-half that of the second
harmonic. The average ratio of the damping depth for the
first harmonic to the damping depth of the second harmonic
for the data listed in Table 12 is 1.48 (compare with $\rho =
1.41$).

If the data had been taken for at least three equidis-
tant observational levels, then the procedure of Lettau
(1954) could have been used. It is of interest to note some
of Lettau's conclusions. One conclusion is that high-order
harmonics of the soil temperature curve can be produced by
intrinsic conditions of the soil and are not necessarily
determined by extrinsic or boundary conditions.

Another conclusion is that an exhaustive analysis
of heat diffusion in natural soil cannot be based
solely on a depth-time frame of temperature ob-
servations, especially when one wants to under-
stand the complexities of heat transfer during
individual days, which is imperative in view of
present-day detailed and accurate observational
data, such as the Seabrook data. Supplementary
observations, for example, the direct measure-
ment of the heat flux $B$ in a complete depth-time
frame, are a necessity.
SUMMARY AND CONCLUSIONS

The agronomic practice of mulch tillage is desirable since it results in the conservation of soil and water. The dispersing action of rainfall is lessened by a mulch cover, runoff water is slowed by mulch so that more water enters the soil and the insulating properties of the mulch slow down evaporation. Practically, however, mulch tillage has not gained widespread acceptance among corn growers in the Corn Belt, because the seedlings look weak and are smaller than where plowing tillage is used, and the grain yield is less. The application of nitrogenous fertilizer has not completely alleviated these deficiencies.

Soil temperature is known to be one of the most important factors affecting plant growth, and it is also known that soil temperature is lower where crop residues are on the soil surface, as in mulch tillage. Of the various factors affecting soil temperature, only soil moisture and soil cover are subject to control, without the creation of undesirable conditions in the soil. It was not possible to control soil moisture in the experiments described in this thesis; therefore, there is always some degree of uncertainty in the interpretation of some of the results. By controlling the soil cover, however, some of the relationships of soil temperature and plant growth have been ob-
served and evaluated. Further, by controlling the amount of mulch forming the soil cover, some of the effects of rate of mulching on soil temperature have been evaluated and thus some of the interrelations of mulch, soil temperature and plant growth have been deduced.

One field experiment was carried out with a double objective. The first objective was to see if unfavorable soil temperature conditions could be alleviated by artificial heating, and the second to see if any beneficial effects derived from heating were due to heating during all of the growing season or just during the early part of the growing season. In this experiment, seven treatments were used which were various combinations of bare and mulched soil, heated and unheated, and heated early only or all season. Two degrees of heating were also used with some combinations. Heating the soil decreased the time from planting until emergence and until silking, in both mulched and unmulched plots. Nitrogen uptake by the plants was affected by mulching but not by heating, and phosphorus and potassium uptake were not affected by the treatments. Plant growth, as measured by height and dry matter production, was greater the higher the average soil temperature. Yields of corn grain did not follow the soil temperature as did the growth data, but followed soil moisture patterns. The experiment was not irrigated so that the yield data were not as useful for
assessing the soil temperature-plant-growth relationships as were the growth data. There was no evident benefit from heating the soil all season as compared with heating only during the early part of the season.

Another experiment was conducted in which the treatments consisted of mulch applied at five different rates, 0, 1, 2, 4 and 8 tons per acre. In this experiment more comprehensive data were taken than in the heating cable experiment. The time required from planting to emergence and from planting to silking followed the mulching rate, that is, more time was required the higher the mulch rate. Plant heights, growth rates and dry matter production were decreased by increasing rates of mulch application. Average soil temperature was decreased by mulch and was decreased more the thicker the layer of mulch. Nutrient uptake was not affected except in the case of nitrogen uptake early in the season, which was decreased more the higher the mulch rate. As with the heating cable experiment, the yields were affected by soil moisture to an extent that the soil temperature effects were nearly obscured.

The soil temperature data taken in the mulch rate experiment were analyzed by the use of Fourier series or harmonic analysis. It was shown, by the use of the techniques of heat flow theory, that soil temperature data alone, even when harmonic analysis is employed, is not sufficient to
obtain an accurate estimate of soil thermal diffusivity, but that qualitative explanations of some of the soil temperature-mulch relationships can be made.

The following conclusions are drawn from the experimental results. The presence of a mulch of crop residues on the soil surface lowers the soil temperature at all shallow depths. This lowered soil temperature is apparently the cause of increased emergence time, less growth as well as lower growth rates and later maturity in corn. The deleterious effect of mulching on the corn plant may be alleviated by fertilization and heating, although the latter is certainly not economical. It is in the early part of the growing season that the temperature of the soil, and thus the practice of mulching, has the greatest effect on corn growth and maturity. It appears from the data that if the soil temperature is about 70°F at the 4-inch depth for about the first month and one-half after planting, mulch has little effect on the growth of the corn plant. The results show that if soil moisture is not critical, soil temperature effects on the growth of the corn plant can be large enough to merit the use of practices which will increase the soil temperature. In the planning of a tillage or management system, soil temperature should be considered as one of the main factors to be optimized.


. 1956. Microbial and nutritional effects of "trash cover" in western Canada's grey wooded, black earth, and brown prairie soils. 6th Int. Cong. Soil Sci. 6(C): 213-223.


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