Temperature Evaluation in Solarized Soils by Fourier Analysis

J. L. Cenis

Nematologist, Dpto. Protección Vegetal, Centro Regional de Investigaciones Agrarias, La Alberca, Murcia, Spain. Present address: Dpto. Protección Vegetal, C.I.T.-I.N.I.A., Apdo. 8111, 28080 Madrid, Spain.

Part of a thesis submitted to the Universidad Politécnica de Madrid in partial fulfillment of the requirements for the Doctor degree.
I thank Dr. P. F. Martínez and A. González-Benavente for their technical assistance.
This research was supported by Project 2907/84 from the Comisión Asesora de Investigación Científica y Técnica (Spain).
Accepted for publication 25 July 1988.

ABSTRACT

Cenis, J. L. 1989. Temperature evaluation in solarized soils by Fourier analysis. Phytopathology 79:506-510.

Fourier analysis, a methodology for the mathematical treatment of periodic phenomena, was used to describe temperature variations in a solarized soil. Starting from the daily maximum and minimum temperatures at two depths in a homogeneous soil, a daily sinusoidal equation can be applied that gives the soil temperature at any hour and depth. The validity of the method was studied during a three-summer temperature-recording period. The fitted sinusoidal equations accounted for at least 93% of the variation, and the hourly mean differences between the measured soil temperatures and those derived from the equations calculated for the solarization period did not surpass 1.9 C. Soil temperature throughout the solarization period was estimated by using the data of 7 days as a sample. A sinusoidal equation from the data of the first week of solarization was calculated and used as a representative of the whole solarization period. The hourly mean differences between measured and estimated temperatures for the three solarization periods were 2.2 C at 10 cm, 1.3 C at 20 cm, and 1.4 C at 30 cm.

Additional keywords: mulching, soil heating, temperature model.

Soil solarization is a technique for the hydrothermal disinfestation of agricultural soils. Since its introduction (11), the technique has proved effective in the control of many soilborne plant pathogens (10). Additional effects such as weed control and increased growth response after treatment have also been observed (3,7,18).

The evaluation of solarization performance in a new region requires the observation of several biological and climatological components. Soil temperature is the most important, as it is the main cause of microorganism death. Therefore, some method of soil temperature monitoring is necessary in solarization trials. This can be done easily with automatic dataloggers; however, they are expensive. Consequently, determination of soil temperature is attempted in most cases by direct readings of conventional geothermometers. However, readings may be incomplete during noctural hours, and the process is cumbersome or impractical in remote plots. On the other hand, the prediction of temperature in a soil before solarization would provide a key criterion for making a decision regarding the benefit of solarizing in a particular site. A model for predicting temperature in solarized soils already exists (13–15). The model is based on the mathematical simulation of the soil-heating process, starting from the energy budget equation at the surface level. However, implementing the model requires much instrumentation and computing power.

So, the application of Fourier analysis, a methodology intended for the mathematical treatment of cyclical phenomena, can simplify measuring temperature variations in soil. Through Fourier analysis, soil temperature is described as a sinusoidal function of time that can be fitted with a variable number of thermometric observations. Applications of Fourier analysis methodology in soil science are diverse (1,6,19), including the calculation of thermal properties of soil (9) and the prediction of soil temperature and soil heat flux (4,8).

In this study, the concepts of this methodology are applied to obtain complete thermometric information for a solarized soil with minimum instrumentation and work. A sinusoidal function of time can be fitted daily at each depth with at least two thermometric readings. By taking temperatures at two depths, a single function of time and depth can be written. Such a function gives the soil temperature at any hour and depth, assuming that the thermal properties of soil are vertically homogeneous. Consequently, daily variations of temperature in the soil profile can be described starting from a reduced number of thermometric observations.

Another concept that was tested is the possibility of estimating soil temperature throughout the solarization period by sampling the soil temperature a few days before or at the start of solarization. Assuming that average soil temperature is stable over several weeks, the measurement of it during several days could yield a reliable estimation. By placing these sampling days at the beginning of the solarization period, one has time to interrupt the solarization and apply other measures if the estimated soil temperatures are considered insufficient for effective control.

The objective of this work was to test the usefulness of Fourier analysis for predicting soil temperature and to determine whether soil temperature at the beginning of solarization could be used to estimate soil temperature throughout the solarization period.

MATERIALS AND METHODS

Description of the model. The reference work on the application of Fourier analysis to soil temperature variations is that of Van Wijk and De Vries (19). A brief description follows.

Soil temperature varies according to a diurnal cycle, within an annual cycle. Like any other arbitrary periodic function of time (t) with radial frequency ω, temperature at the soil surface $T_{0,t}$ can be represented by a superposition of sinusoidal waves oscillating around an average daily temperature $\bar{T}$, and radial frequencies that are integral multiples of ω. This is known as a Fourier series, with the form:

$$T_{0,t} = \bar{T} + \sum_{k=1}^{\infty} A_{0,k} \sin (k\, \omega\, t + \phi_{0,k}) \qquad (1)$$

in which $\bar{T}$ = average daily temperature at the surface (C), $A_{0,k}$ = amplitude of the wave at the surface level for the kth harmonic (C), k = index of the harmonic in the series, $\omega = 2\pi / P$ where $P = 24$ in a daily cycle, t = time (hours), and $\phi_{0,k}$ = phase angle of the wave at the surface level for the kth harmonic (radians). The model is illustrated by Figure 1.

A Fourier series can be fitted to soil temperature oscillation at each depth. Assuming that the soil is homogeneous and that thermal properties are constant with depth, a more general equation can be obtained that expresses temperature as a function of depth (z) and time (t):

$$T_{z,t} = \bar{T} + \sum_{k=1}^{\infty} A_{0,k} \exp(-z\, k^{1/2}/D) \sin(k\, \omega\, t + \phi_{0,k} - z\, k^{1/2}/D) \quad (2)$$

in which z = depth (cm) and D = damping depth (cm). The damping depth is a parameter that depends on the thermal properties of a given soil through the equation $D = (2\delta/\omega)^{1/2}$, where δ is the coefficient of thermal diffusivity of the soil ($cm^2\ sec^{-1}$). This coefficient is the quotient of thermal conductivity and volumetric heat capacity of the soil.

The assumption of the constant value of thermal diffusivity with time and depth is critical for the validity of equation 2. As thermal properties of soil are strongly influenced by moisture content, which fluctuates with time and depth, the assumption is not valid for soils subject to evaporation. However, moisture content in a solarized soil is kept practically constant, due to the cycle of evaporation-condensation on the inner side of the plastic sheet. Therefore, δ and D can be considered constant, provided soil texture is the same at all depths. In this situation, the daily average temperature is also constant with depth.

Each one of the kth terms in equation 2 is called a harmonic of first order for $k = 1$, second order for $k = 2$, and so on. Usually, two harmonics are sufficient to describe the temperature variations in homogeneous soils (19). The equation with the first harmonic only, called the fundamental wave, is less accurate, but is also applicable for the description of soil temperature variations.

Implementation of the model. Given a solarized soil, the objective is to fit an equation like equation 2 with the least number of temperature readings. The first step is to calculate equation 1 at several depths. To fit the equation with two harmonics, at least eight daily readings are needed (9). The one-harmonic equation requires only two readings by day. The mathematical procedure for fitting equation 1 is quite simple, as described by Little and Hills (12) or Van Wijk and De Vries (19). The process is considerably shortened when readings are taken at regular intervals.

Although the use of computers is not essential, they do simplify the process. Software exists for fitting all kind of periodic curves (Wave-form Analysis, for H.P. Series 80 and 200, Hewlett-Packard Co., Palo Alto, CA). I wrote a BASIC program based on the method of Little and Hills (12), which runs in H.P. Series 80 and in PC-compatible computers and is available on request.

With equation 1 calculated at several depths, the next step for obtaining equation 2 is the calculation of the damping depth (D). Several methods exist for this, but the simplest is to compare values of wave amplitude and phase angle at two depths. When these parameters are known at two depths z_1 and z_2, D can be calculated by either of the following expressions:

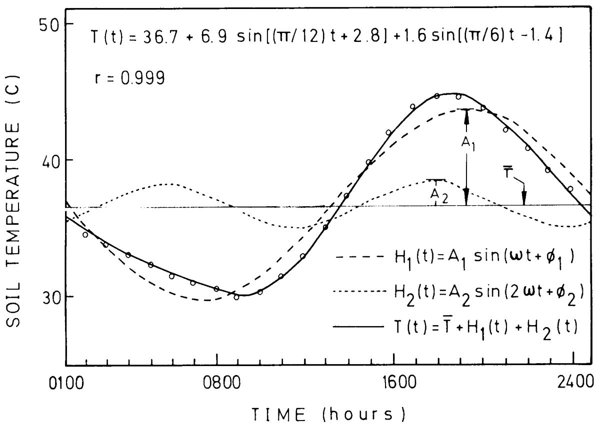

Fig. 1. Fourier series of two harmonics (H) fitted with the soil temperature (T) measured 5 August 1982 at 10 cm and representation of the two additive components of the equation. A = amplitude, t = time, ϕ = phase angle, ω = radial frequency.

$$A_{z_2} = A_{z_1} \exp(-z/D) \quad (3)$$

or:

$$\phi_{z_2} = \phi_{z_1} - z/D \quad (4)$$

in which A_{z_1}, A_{z_2}, ϕ_{z_1}, and ϕ_{z_2}, are the amplitudes and phase angles at depths z_1 and z_2, and $z = z_2 - z_1$. From equations 3 and 4 the value of amplitude and phase angle of the temperature wave can be obtained at any depth by knowing these parameters at a given depth and the value of D. If the amplitude $A_{0,k}$ and phase angle $\phi_{0,k}$ at the surface are calculated in this way, equation 2 can be established. The parameters at the surface level are better determined by extrapolation with equations 3 and 4 than by direct temperature measurement. This is because the pattern of temperature variation at the air-soil interphase is more irregular than that deeper in the soil. Therefore, the parameters at the surface are inconsistent with those obtained in depth.

As observed, to calculate the value of D, temperature readings must be taken at at least two depths. However, if it is suspected that the thermal properties of the soil are not homogeneous, readings must be taken at other depths to calculate several values of D and to verify that it is constant. The value of $\bar{T}$ in an ideally homogeneous soil would be the same at all depths, but it usually presents small differences. In equation 2, $\bar{T}$ is calculated as the average of the values at the different depths. The process described above is greatly simplified by using equation 2 with one harmonic. In this case, equation 2 becomes:

$$T_{z,t} = \bar{T} + A_0 \exp(-z/D) \sin[(\pi/12)t + \phi_0 - z/D] \quad (5)$$

The steps involved in the calculation of equation 5 are: first, determination of the daily maximum $T_{mx,i}$ and daily minimum $T_{mn,i}$ temperatures at two depths $i = 1,2$; second, calculation of daily average temperature at each depth by the expression: $\bar{T}_i = (T_{mx,i} + T_{mn,i})/2$. If T_1 and T_2 are slightly different, then $\bar{T}$ in equation 5 is the average between them. If they differ by several degrees, then the assumption of homogeneous thermal properties of the soil is not accomplished, and the model is not applicable; third, calculation of the wave amplitude A_{z_i} at each depth, through the expression: $A_{z_i} = (T_{mx,i} - T_{mn,i})/2$; fourth, calculation of the wave phase angle ϕ_{z_i} at each depth, by the expression: $\phi_{z_i} = \pi/12\ (30 - h)$, in which h is the hour at which the daily maxima occurs on a 24-hr clock; fifth, calculation of damping depth D, by equations 3 and 4; and sixth, calculation of amplitude and phase angle at the surface, from A_{z_i}, ϕ_{z_i}, and D through equations 3 and 4.

The temperatures, $T_{mx,i}$ and $T_{mn,i}$, can be obtained with conventional geothermometers, taking the readings at the hours in which they occur. They take place around sunset and sunrise, respectively, and the exact moment is determined by multiple readings. On request, some local manufacturers can make a geothermometer for maximum and minimum temperatures that requires a single reading a day.

Soil temperature estimation through sampling. Assuming a normal distribution of daily values of $\bar{T}$, A, and ϕ, the minimum number of days necessary for obtaining a reliable estimation of these parameters for the whole period, allowing an error of 1 C for a confidence interval of 95% and with a maximum standard error of 1.3, would be 6.6 days (17). The normality of the distributions of the parameters $\bar{T}$, A, and ϕ was verified by calculating the Pearson coefficients, which had values corresponding approximately to that of a normal distribution.

Experimental array for the validation of the model. During the summer months of 1982, 1983, and 1984, soil temperature was recorded with several modalities of solarization and different types of plastic materials in the region of Murcia (southeastern Spain) to assess the effectiveness of the method in the area. Complete results are reported elsewhere (2). In this article, only data on solarization with normal polyethylene mulching in the open air are used. The solarization treatment was implemented in the same way for each of the 3 yr. A 7- × 7-m plot of clay-loam textured soil, previously fallowed, was plowed and flood irrigated at field capacity. Two days later, the plot was covered with a clear polyethylene sheet 0.050 mm thick, and the edges were buried by hand. Soil temperature was taken through copper-constantan thermocouples, Type T, with cold junction compensation, and the device was connected to an automatic datalogger (model 1200 of Datron Electronics Ltd., Norwich, England) programmed to record and print temperatures at hourly intervals.

One thermocouple was buried at each of the depths of 10, 20, and 30 cm at the center of the solarized plot just before the plastic cover was laid down. The same array was made in a nonmulched plot that was the same size and also irrigated, as a control. Given the proven reliability of the thermocouples, no replications were made. Effective temperature recording started 7 days after the tarping to allow the buildup of high soil temperatures and the stabilization of the recording device. The effective recording periods were: 3–31 August 1982, 15 July to 31 August 1983, and 15 August to 10 September 1984.

The recorded temperatures were used as a database for testing the validity of the model. Soil temperature data obtained at the different depths in the solarized plot every day were fitted to one- and two-harmonic Fourier series according to the method of Little and Hills (12). For each day, temperature for each hour was considered. The average value of the series parameters for each depth and period was calculated. Starting from these parameters, an average Fourier series was obtained for the recording period of each year.

To assess the aptitude of the calculated average equations for describing the actual temperatures throughout the period, the hourly difference between the actual temperature and that obtained from the fitted Fourier series was determined according to the expression:

$$DF = 1/24 \sum_{1}^{24} | T_f - T_m | \qquad (6)$$

in which T_f is the calculated temperature and T_m the measured one. For assessing the reliability of the soil temperature estimation made from a sample of 7 days, a Fourier series was fitted with the data of the first week of effective recording (7 days after tarping). In this case, the one-harmonic series was fitted only with the maximum and minimum temperatures at 10 and 20 cm, through the simplified method described above. The two-harmonic series was fitted with eight daily readings at regular intervals. In both cases, the thermometric readings were taken from the thermometric database. The accuracy of the estimation was tested by calculating hourly differences by equation 6 as above and by calculating the cumulative number of hours above a predetermined temperature threshold. This cumulative time can be directly related to exposure time/mortality curves as calculated by Pullman et al (16) for several microorganisms.

RESULTS AND DISCUSSION

The temperatures in mulched and nonmulched soil appear in Table 1. Maximal temperatures in solarized soil are not as high as those observed in other solarization trials (7,10,11,18). However, the increase of soil temperature over the control varies from 7 to 12 C, which is within the usual rank of soil solarization performance.

Table 2 shows the average values of the coefficients of the Fourier series, fitted daily for the recording periods of the 3 yr. The value of the average daily temperature is very similar at the three depths considered. Therefore, the basic assumption for the application of the model is accomplished—that is, the homogenity of thermal properties of soil with depth. The fitting of the first harmonic accounts for at least 93%, and the first and second harmonics for 99.7%, of the total variance. Both types of series are highly significant, with small differences between them at 20 and 30 cm. In fact, the mean amplitude of the second harmonic at those depths is between 0.2 and 0.7 C and is a very small contribution to the accuracy of the fundamental wave. Therefore, the Fourier series with one harmonic, which can be fitted in a much simpler way than the two-harmonic series, was sufficient to describe accurately the daily variations of temperature in a solarized soil.

TABLE 1. Soil temperature in polyethylene-mulched and nonmulched soil, in the southeast of Spain

		Soil temperature (C)			
		Solarized		Control	
Period	Depth (cm)	Maximal (average)	Maximal (absolute)	Maximal (average)	Maximal (absolute)
3–31 August 1982	10	43.5	46.0	31.3	33.0
	20	38.1	40.3	30.0	32.2
	30	37.5	39.2	28.5	30.6
15 July–31 August 1983	10	37.9	40.6	31.0	32.9
	20	34.5	36.7	29.0	30.4
	30	33.7	35.2	28.3	29.5
15 August–10 September 1984	10	40.3	42.8	31.7	34.3
	20	35.6	37.5	27.8	29.5
	30	34.0	35.3	27.2	28.7

TABLE 2. Average and standard deviation values of the terms of the two-harmonic Fourier series fitted to hourly soil temperatures at three depths, in solarized soil during the summers of 1982, 1983, and 1984 in the southeast region of Spain

			Harmonics					
			1st			2nd		
Period	Depth (cm)	$\bar{T}$[a]	A_1[b]	ϕ_1[c]	Variance[d] (%)	A_2	ϕ_2	Variance (%)
3–31 August 1982	10	35.1 ± 1.3	5.6 ± 1.2	2.7 ± 0.1	94.0	1.5 ± 0.3	−1.5 ± 0.3	99.9
	20	34.9 ± 1.2	3.6 ± 0.8	2.4 ± 0.1	96.4	0.7 ± 0.2	−2.2 ± 0.3	99.9
	30	34.9 ± 1.0	2.4 ± 0.5	2.0 ± 0.2	96.5	0.5 ± 0.2	−2.4 ± 0.6	99.9
15 July–31 August 1983	10	33.1 ± 1.2	4.5 ± 0.8	2.6 ± 0.1	94.5	1.0 ± 0.2	−1.7 ± 0.3	99.8
	20	32.5 ± 1.1	2.3 ± 0.6	1.7 ± 0.2	96.6	0.5 ± 0.2	−2.7 ± 0.3	99.7
	30	32.9 ± 1.0	1.2 ± 0.2	0.8 ± 0.1	96.8	0.2 ± 0.2	−2.4 ± 1.0	99.9
15 August–10 September 1984	10	34.3 ± 1.3	4.7 ± 1.0	2.8 ± 0.1	93.0	1.3 ± 0.2	−1.2 ± 0.6	99.7
	20	33.8 ± 1.0	1.8 ± 0.4	1.8 ± 0.2	95.4	0.3 ± 0.2	−2.6 ± 0.3	99.8
	30	33.2 ± 0.7	1.0 ± 0.5	1.0 ± 0.2	97.5	0.2 ± 0.5	−2.6 ± 2.4	99.9

[a] Average daily temperature (C).
[b] Wave amplitude of the corresponding harmonic (C).
[c] Wave phase angle of the corresponding harmonic (radians).
[d] Percentage of the variance accounted for by the corresponding harmonic.

The two-harmonic series almost perfectly fits the curve of daily temperature variation (Fig. 1). Therefore, this variation can be expressed on an hourly basis through the specification of the five parameters ($\bar{T}$, $A_{0,1}$, $A_{0,2}$, $\phi_{0,1}$, $\phi_{0,2}$) of the fitted Fourier series instead of as a listing of the 24 temperatures by depth and day. This can be useful when working with some types of automatic dataloggers connected to computers. As was mentioned, a simple computer program can be written for fitting temperature readings to a Fourier series. The use of a series is easier and more meaningful than the use of a long listing of raw temperature data and can also be the starting point for further elaboration and plotting.

Starting from the parameters of Table 2, three generalized equations like equation 2 can be written for each recording period. These equations are:

3–31 August 1982:

$$T_{z,t} = 35\ .\ 10.1 \exp(-z/13.4) \sin((\pi/12)t + 2.7 - z/13.4) + 1.5 \exp(-z/9.5) \sin((\pi/6)t - 1.5 - z/9.5) \quad (7)$$

15 July–31 August 1983:

$$T_{z,t} = 32.8 + 9.3 \exp(-z/13.8) \sin((\pi/12)t + 2.8 - z/13.8) + 2.3 \exp(-z/9.7) \sin((\pi/6)t + 0.2 - z/9.7) \quad (8)$$

15 August–10 Sept. 1984:

$$T_{z,t} = 33.8 + 8.1 \exp(-z/14.4) \sin((\pi/12)t + 2.4 - z/14.4) + 3.4 \exp(-z/10.7) \sin((\pi/6)t + 0.4 - z/10.7) \quad (9)$$

The frequency of the sinusoidal term and the value of D change with the order of the harmonic, due to the k term in equation 2. The value of D included in the equations is the mean of the four values obtained by comparing the wave amplitude and phase angle values at 10 and 20 cm and 20 and 30 cm. $\bar{T}$ in the equations is the mean of the parameter at the three depths. The amplitudes and phase angles at the surface are calculated by substituting the corresponding values at 10 cm and D in equations 3 and 4, as mentioned in the previous section. The ability of equations 7–9 to express actual temperatures is reflected in Table 3.

The average hourly difference between measured and fitted temperatures does not surpass 1.9 C. This is within the range of accuracy obtained by other soil temperature models (8). As could be expected, differences attained with the one-harmonic equation are slightly larger than those with the two-harmonic equation. However, the difference between the two types is small in most cases. The performance of the series is similar at the three depths considered. In consequence, a Fourier series of one or two harmonics is able to synthesize and express the thermometric variations of a solarized soil throughout the soil profile during a period of time. The length of this period depends on the variability of the average soil temperature. In the area in which this experiment was conducted, the variability is low, and, consequently, a single equation is able to express the average situation of soil throughout 1 mo. In other areas with a less stable soil temperature, the calculation of several Fourier series on a week-long basis may be necessary.

Soil temperature estimation through sampling. When an average Fourier series is fitted with the data of the first week of effective solarization, differences between estimated and actual temperature are bigger than with monthly monitoring. However, the increase is of the order of 0.3 C, and the hourly difference, although with a maximum value of 2.6 C, does not surpass 2 C in most cases (Fig. 2).

The estimated curves describe correctly the pattern of temperature variations in soil, consisting of a reduction of amplitude and a displacement of peaks with increasing depth (Fig. 2). With respect to the estimation of cumulative exposure time, the result can be considered correct at 10 and 20 cm, as the deviation of actual values is small (Fig. 3).

These results show that it is possible to estimate the temperature of a solarized soil throughout at least 1 mo through the measurement of soil temperature during the first week of effective solarization. However, the estimation is very sensitive to variability of soil temperature, and the assumption of a stable value of $\bar{T}$ throughout the summer months becomes critical. Short periods of a few days of unusual cold or heat should not greatly affect the accuracy of the estimation. Given the thermal inertia of soil, the value of $\bar{T}$ changes slowly from day to day and does not react immediately to air temperature changes (2,5). But in areas with rainy summer months or week-long temperature variations, the estimation may be completely unreliable. Consequently, the variability of temperature in summer months must be examined and evaluated in each region in relation to the application of the model. On the Spanish southern Mediterranean coast, the assumption is true from mid-June to mid-September, as shown by thermometric observation (2). The risk of rain is low, as average annual precipitation is less than 300 mm, of which 15 mm corresponds to the summer months. Long temperature recordings in the south of France also show the stability of $\bar{T}$ during July and August (5).

The Fourier analysis methodology has other applications than those mentioned here. Gupta et al (8) developed a fully predictive model that predicts soil temperatures starting from the measured daily maximum and minimum air temperatures. Another possibility is to model the oscillations of $\bar{T}$ in the annual cycle, which is also sinusoidal. This can be made by fitting the monthly

TABLE 3. Average values of hourly differences (DF), and standard deviations (SD), between measured soil temperatures and temperatures calculated from Fourier series fitted to the average day of each solarization period in 1982, 1983, and 1984

Period	Type of Fourier series	DF ± SD at soil depth (cm) 10	20	30
3–31 August 1982	Two harmonics	1.3 ± 0.5	1.5 ± 0.4	1.4 ± 0.3
	One harmonic	1.7 ± 0.8	1.6 ± 0.7	1.5 ± 0.6
15 July–31 August 1983	Two harmonics	1.2 ± 0.6	0.9 ± 0.7	0.9 ± 0.4
	One harmonic	1.7 ± 0.6	1.2 ± 0.5	1.3 ± 0.7
15 August–10 September 1984	Two harmonics	1.7 ± 0.5	1.3 ± 0.4	0.9 ± 0.6
	One harmonic	1.9 ± 0.4	1.2 ± 0.6	0.9 ± 0.6

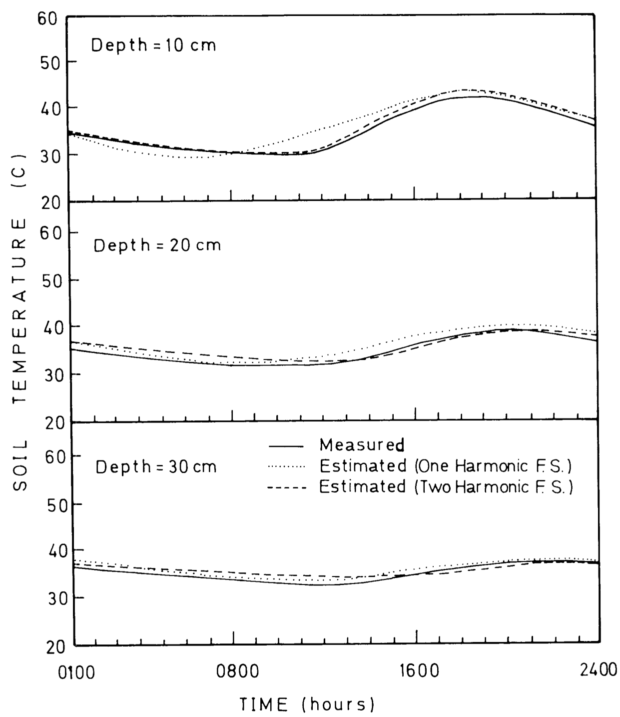

Fig. 2. Comparison of the average soil temperature at three soil depths during the period from 15 July to 31 August 1983, and the temperature estimated with one- and two-harmonic Fourier series fitted with the average data of the first week of that period, in a solarized soil.

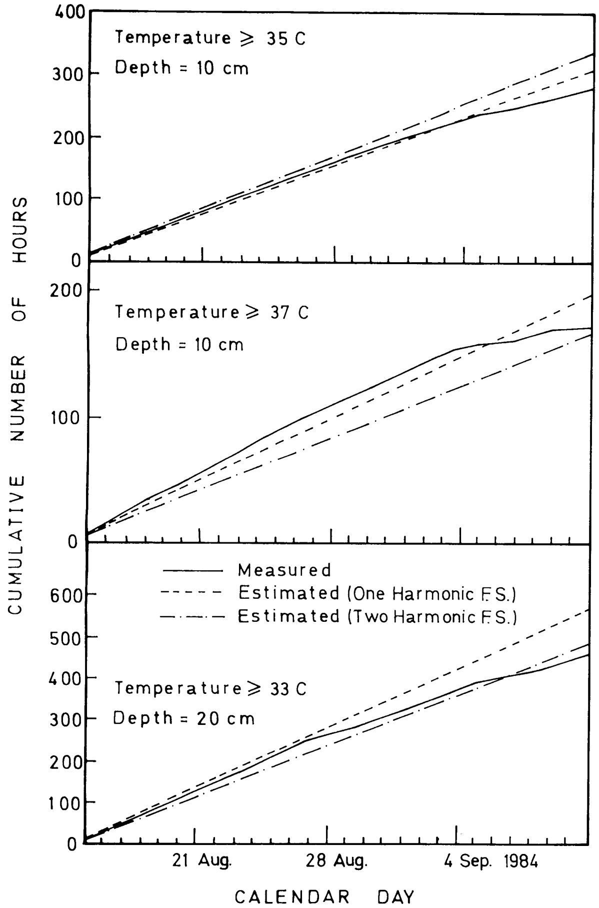

Fig. 3. Comparison of the cumulative number of hours with soil temperature equal to or above 35 and 37 C at 10 cm and 33 C at 20 cm, measured through the period from 15 August to 10 September 1984, and the cumulative hours estimated with one- and two-harmonic Fourier series fitted with the average data of the first week of that period, in a solarized soil.

average value of $\bar{T}$ to Fourier series with radial frequency $\omega = 2\pi/12$. It is then possible to express with a compounded series the annual and diurnal cycles of variation of soil temperature (19). These approaches can yield a better understanding of the thermal behavior of soil. As a consequence, an improvement in the implementation of soil solarization can be expected. They can also serve as a useful tool in ecological research on soilborne plant pathogens.

LITERATURE CITED

1. Carson, J. E. 1963. Analysis of soil and air temperature by Fourier techniques. J. Geophys. Res. 68:2217-2232.
2. Cenis, J. L. 1986. Development of a quantitative approach to soil solarization: Application to the control of *Meloidogyne javanica* (Treub) Chit. Doctoral thesis, Univ. Politécnica. Madrid. 372 pp. (In Spanish)
3. Chen, Y., and Katan, J. 1980. Effect of solar heating of soils by transparent polyethylene mulching on their chemical properties. Soil Sci. 130:271-277.
4. Cruse, R. M., Linden, D. R., Radke, J. K., Larson, W. E., and Larntz, K. 1980. A model to predict tillage effects on soil temperature. Soil Sci. Soc. Am. J. 44:378-383.
5. De Villele, O. 1975. Evolution des temperatures dans le sol dans la Region d'Avignon. Note Technique M/75/1. Centre de Recherches Agronomiques du Sud-Est, Montfavet, France. 16 pp.
6. Ghuman, B. S., and Lal, R. 1982. Temperature regime of a tropical soil in relation to surface condition and air temperature and its Fourier analysis. Soil Sci. 134:133-140.
7. Grinstein, A., Katan, J., Abdul Razik, A., Zeydan, O., and Elad, Y. 1979. Control of *Sclerotium rolfsii* and weeds in peanuts by solar heating of the soil. Plant Dis. Rep. 63:1056-1059.
8. Gupta, S. C., Larson, W. E., and Allmaras, R. R. 1984. Predicting soil temperature and soil heat flux under different tillage-surface residue conditions. Soil Sci. Soc. Am. J. 48:223-232.
9. Horton, R., Wierenga, P. J., and Nielsen, D. R. 1983. Evaluation of methods for determining the apparent thermal diffusivity of soil near the surface. Soil Sci. Soc. Am. J. 47:25-32.
10. Katan, J. 1981. Solar heating (solarization) of soil for control of soil-borne pests. Annu. Rev. Phytopathol. 19:211-236.
11. Katan, J., Greenberger, A., Alon, H., and Grinstein, A. 1976. Solar heating by polyethylene mulching for the control of diseases caused by soil-borne pathogens. Phytopathology 66:683-688.
12. Little, T. M., and Hills, F. J. 1978. Agricultural Experimentation. John Wiley & Sons, New York. 350 pp.
13. Mahrer, Y. 1979. Prediction of soil temperature of a mulched soil with transparent polyethylene. J. Appl. Meteorol. 18:1263-1267.
14. Mahrer, Y., and Katan, J. 1981. Spatial soil temperature regime under transparent polyethylene mulch: Numerical and experimental studies. Soil Sci. 131:82-87.
15. Mahrer, Y., Naot, O., Rawitz, E., and Katan, J. 1984. Temperature and moisture regimes in soils mulched with transparent polyethylene. Soil Sci. Soc. Am. J. 48:362-367.
16. Pullman, G. S., DeVay, J. E., and Garber, R. H. 1981. Soil solarization and thermal death: A logarithmic relationship between time and temperature for four soilborne plant pathogens. Phytopathology 71:959-964.
17. Snedecor, G. W., and Cochran, W. G. 1980. Statistical Methods, 7th ed. Iowa State University Press, Ames. 700 pp.
18. Stapleton, J. J., and DeVay, J. E. 1984. Thermal components of soil solarization as related to changes in soil and root microflora and increased plant growth response. Phytopathology 74:255-259.
19. Van Wijk, W. R., and De Vries, D. A. 1963. Periodic temperature variations in an homogeneous soil. Pages 102-140 in: Physics of Plant Environment. W. R. Van Wijk, ed. North Holland, Amsterdam.