PREDICTIONS OF MONTHLY ACCUMULATED HOURS OF SOIL TEMPERATURE IN SOLARIZED SOILS

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ABSTRACT

Solarization is a soil disinfestation method that uses solar energy to achieve the control of pests, diseases, and weeds. The method consists of covering the soil with a transparent polyethylene film before planting, for a period lasting from one to two months. Solarization efficiency is dependent upon choosing an adequate season of the year when it is to be used.

A simplified numerical procedure has been developed to estimate monthly hours of accumulated temperature in solarized soils, thus allowing the selection of a suitable season for the treatment to be implemented. The proposed modeling requires the monthly means of daily solar irradiation and maximum air temperature as input data, and a daily profile of temperature variation, admitted to be sine-shaped.

The procedure was verified using observations made during the years of 1992-93 in Jaguariúna, SP. Generally, there exists good agreement between calculated and measured data. The calculated number of accumulated hours with maximum daily temperatures higher than 35°C in the solarized soil during the period from November to April differed by 20% at most from the observed number of hours. For temperatures higher than 40°C, the estimates for the period from November to March were different from the observed values by 24% at most. The evolved procedure can predict, with good precision, the monthly temperature hours in solarized soil, down to a 10 cm depth, in the region for which it was developed; for other localities, however, it must be evaluated and verified.
Keywords:Soil Disinfestation-1:Soil Pasteurization-2:Soil Pathogens-3: Numerical Modeling-4: Solarization-5

1. INTRODUCTION

Solarization is a soil disinfestation method for controlling plant pathogens, weeds, and pests, which consists of covering the soil with a transparent polyethylene film in pre-planting, preferably when it is moist, during the highest solar radiation season, for a period of one to two months. This method was developed in Israel by Katan et al. (1976), and since then it has been successfully tested and used in many countries (Katan and De Vay, 1991). In several crops, solarization has proved viable, especially for vegetables and ornamental plants, with advantages resulting from the fact that it is not a chemical method. The conventional disinfestation method consists of treatment with fumigants; however, this presents several problems with regard to residues, toxicity, and environmental contamination. The most frequently used product is methyl bromide; however, since its action destroys the ozone layer in the Earth's stratosphere, it is being banned from the market. This fact, in addition to greater pressure from society in favor of the preservation of nature, and of products that are free from agrochemical residues and risks to workers, has resulted in an increased interest in the use of solarization.

During solarization, solar energy increases soil temperature and causes a change in microbiota composition. Pathogens are eliminated, but part of the microbiota will survive and colonize the disinfested soil, making it difficult for pathogens to reinfest it, which increases the persistence of treatment. Thus, the physical and biological components involved in solarization act synergically to control soil-borne pathogens (Katan, 1996). In Brazil, control has been achieved for *Verticillium dahliae* in eggplant (Ghini et al., 1992) and tomato (Ghini et al., 1993), *Pythium* in chrysanthemum (Bettiol et al., 1994) and cucumber (Lopes et al. 2000; Ghini et al., 2002), gall nematode (*Meloidogyne javanica*) in okra (Bettiol et al., 1996), *Sclerotium cepivorum* in garlic (Nunes, 1992), *Sclerotium rolfsii* in bean (Ghini et al., 1997), and *Sclerotinia sclerotiorum* (Pereira et al., 1996b), *Rhizoctonia solani*, and *Sclerotinia minor* in lettuce (Sinigaglia et al., 2001). Weed infestation reductions have also been verified (Bettiol et al. 1994; Sinigaglia et al., 2001; Ricci et al., 2000).

The efficiency of solarization depends on solar irradiation; however, published papers generally do not show solar irradiation data for the treatment period, which makes it difficult to apply the obtained information to other regions. Predicting temperatures attained in solarized soils around the year would be very useful when selecting the most suitable seasons for treatment in each location. Simulation also allows solarization to be adapted to the cropping schedule, by choosing periods that would result in better utilization of time. In addition, it can provide information on the possible level of control to be obtained.

The use of simulation to determine temperatures in solarized soil has been studied by Mahrer (1979), Cenis (1989), Sui et al. (1992), Streck et al. (1996), and Wu et al. (1996). Even though relatively simple, the many detailed simulation procedures require temporal series of solar radiation, temperature in the environment, precipitation, and/or temperatures in the solarized soil at two different depths, and/or bare soil temperature, at hourly or daily scales. In turn, if measurements are not obtained for these series, they must be modeled, which requires a detailed knowledge on autocorrelation and cross-correlation coefficients for the generation of bi-variate or even tri-variate temporal series. The difficulty remains as these coefficients are scarcely measured or known, both spatially and temporally, in addition to the fact that they also depend on location.

In view of the situation that has been presented, the present work had the objective of developing a simplified numerical procedure for the estimation of accumulated monthly hours of solarized soil temperatures. The procedure is partly based on the methodology proposed by Cenis (1989), who used the Fourier series to model the daily soil temperature profile. The proposed modeling only requires mean monthly values of meteorological variables that can be easily found in weather stations, or are part of their routine: daily solar irradiation and their monthly means, maximum temperatures and their monthly means, and mean values for the variation amplitude of daily temperature admitted to be sine-shaped.

2. MATERIAL AND METHODS

2.1 Correlation between daily solar irradiation and solarized soil temperature

Based on solarized soil temperatures, evaluated at a 10 cm depth during January, 1989 in the city of São Manuel, SP (22°44'S, 48°34"W) by Lefevre (1990), a high correlation was obtained between daily solar irradiation and maximum daily temperature in the solarized soil (Figure 1).

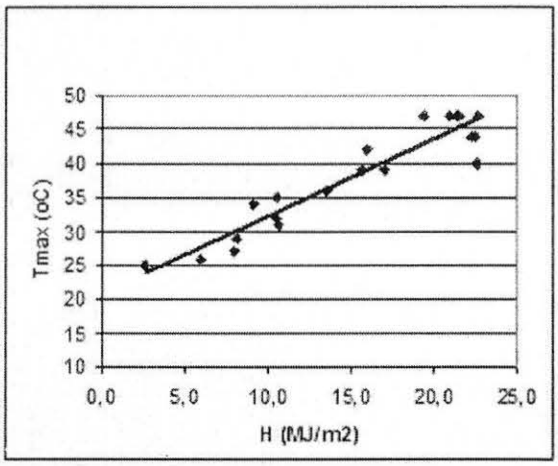

Fig. 1: Correlation between maximum daily temperature (T_{max}) of solarized soil at a 10 cm depth and daily solar irradiation (H) in the January 1989 period, in São Manuel, SP (Lefevre, 1990).

The regression equation for daily solar irradiation (H) in relation to maximum temperature (T_{max}) in the solarized soil at a 10 cm depth is:

$$T_{max}(^0C) = 1.12H + 20.89 \qquad (1)$$
$$R^2 = 0.89$$

Since this correlation was obtained for the month of January, it is necessary to make a correction in case it is used for other months. Due to the fact that long-term means of maximum temperature data do not exist for the location (São Manuel), the nearest location for which this information is available was selected (São Carlos, SP - 22°01"S, 47°53"W). Table 1 shows the mean monthly maximum temperature values contained in the 1961-1990 Weather-Normals (INMET, 1992), and the proposed corrections, considering January as a standard month. The correction is made by subtracting Δ from the value found in equation (1).

2.2 Correlation between maximum temperature and temperature amplitude in solarized soil

One of the few pieces of experimental information on temperature amplitude variation of soil submitted to solarization as a function of its maximum temperature, obtained in the region, is available from Patrício (2000). In this work, solarized soil temperature values are presented

TABLE 1: MAXIMUM TEMPERATURE CORRECTION FOR DIFFERENT MONTHS

Month	$\overline{T}_{max}$ (°C)*	Δ
January	26.8	0.0
February	27.2	-0.4
March	27.0	-0.2
April	25.7	1.1
May	23.6	3.2
June	22.7	4.1
July	22.1	4.7
August	24.3	2.5
September	25.0	1.8
October	24.7	2.1
November	25.7	1.1
December	25.2	1.6

* Weather-Normals 1961-1990 (INMET,1992)

for 8 a.m. and 3 p.m., and it is understood that these are times for minimum and maximum temperatures. Figure 2 shows the correlation between temperature amplitude and daily maximum temperature for the 10 cm depth in the city of Piracicaba, SP (22°43'S, 47°39'W), where the research was developed.

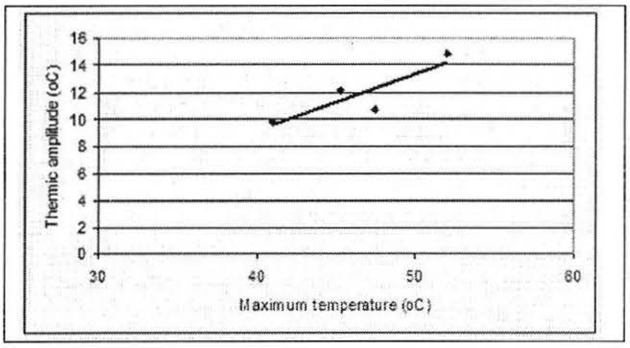

Fig. 2: Correlation between temperature amplitude and daily maximum temperature in solarized soil for the 10-cm depth in the city of Piracicaba, SP (Patrício, 2000).

The regression equation for maximum temperature in the solarized soil at a 10 cm depth in relation to daily temperature amplitude is:

$$A(^0C) = 0.42T_{max} - 7.52 \qquad (2)$$

$R^2 = 0.76$

2.3 Daily variation in temperature profile of soil submitted to solarization

According to Cenis (1989), the temperature of a soil submitted to solarization can be modeled using a Fourier series. The general expression for the Fourier series with one harmonic is given by:

$$T_1(t) = \overline{T} + A_1 \mathrm{sen}(\omega t + \phi_1) \qquad (3)$$

where T is the temporal variation of temperature at a given depth, A is the amplitude, $\omega=\pi/12$, t is time, ϕ is the phase and index 1 indicates the harmonic.

The angular phase of the ϕ wave can be calculated for each depth by means of the expression:

$$\phi_{1z} = \frac{\pi}{12}(30 - h_z) \qquad (4)$$

where h is the time at which the maximum daily temperature occurs, and z is depth.

According to a research developed by Ferraz (2000) in the region of Piracicaba, SP, the maximum temperature of the solarized soil at a 10 cm depth occurs around 5 p.m.; therefore, the phase angle calculated by equation (4) results in 3.4. The minimum temperature value in that research work occurred at 8 a.m.

The generation of hourly temperature data for the solarized soil will be done using the formula:

$$T(h) = T_{max\,imumdaily} - Af \qquad (5)$$

where T(h) is the temperature at a given time, A is amplitude (given by equation 2), and f is the amplitude fraction corresponding to that time in a sine model.

The daily amplitude is the difference between the daily maximum and minimum values; the percentage values (f) corresponding to each time are given in Table 2.

2.4 Generation of daily solar irradiation series

Experimental information on daily solar irradiation is very rare in Brazil and in the world. Only little information is available, both temporally (when available, series are relatively short) and spatially (few seasons when measurements were done). One alternative to this situation is the synthetic generation of temporal series (Aguiar, 1988; Graham, 1988). The generated series reproduce the statistical properties of actual series, and are therefore suitable for numeric simulation purposes.

TABLE 2: VALUES OF F (TEMPERATURE AMPLITUDE FRACTION) TO CALCULATE HOURLY TEMPERATURE

Hour	f (%)	Hour	f (%)
1:00	0.75	13:00	0.25
2:00	0.85	14:00	0.15
3:00	0.93	15:00	0.07
4:00	0.98	16:00	0.02
5:00	1.00	17:00	0.00
6:00	0.98	18:00	0.02
7:00	0.93	19:00	0.07
8:00	0.85	20:00	0.15
9:00	0.75	21:00	0.25
10:00	0.63	22:00	0.37
11:00	0.50	23:00	0.50
12:00	0.37	24:00	0.63

The "Atlas Solarimétrico do Brasil" CD-ROM title (Solarimetric Atlas of Brazil) (Tiba et al., 2003) has been recently released; the program has a calculation tool that allows temporal series to be generated using Markov's Transition Matrix Method (Aguiar, 1988). The synthetic series generator only requires the local geographical coordinate values and the mean monthly solar irradiation value. These data are also provided by the Atlas.

2.5 Calculation procedure

The steps involved in the estimation of solarized soil monthly temperature accumulated hours, at a given depth and threshold are:

a) Generation of solar irradiation daily series using, for example, the calculation tool provided in the Atlas Solarimétrico do Brasil CD-ROM (Tiba et al., 2003);

b) Calculating, for each month, by means of a correlation between daily solar irradiation and solarized soil temperature, the maximum daily temperature achieved in the soil, according to equation (1);

c) Correcting the maximum daily temperature calculated in the previous item, using the correction factor presented in Table 1, provided it was obtained at 26.8 °C;

d) Using the maximum daily temperature calculated in the previous item, to determine the daily amplitude by means of the correlation between temperature amplitude and daily maximum temperature for the 10 cm depth in the city of Piracicaba, according to equation (2);

e) Knowing the daily temperature and amplitude, and admitting that the temperature profile is given by a Fourier series containing a single harmonic, to calculate the distribution of hourly temperatures, according to equation (3) and Table 2, and finally,

f) Estimating the temperatures for all other days in the month and calculating the hours accumulated at certain thresholds (temperature ranges).

3. RESULTS AND DISCUSSION

The solarization assays conducted by Ghini et al. (1994) at Embrapa Meio Ambiente in Jaguariúna, SP (22°42'S, 46°59'W), during the period from July 1992 to June 1993 were used to evaluate the method presented for estimating accumulated solarization hours. Due to the scarcity of local information for obtaining the several correlations previously mentioned, it was admitted that, from a climatological and pedological standpoint, the various locations (São Manuel, Piracicaba, Jaguariúna, and São Carlos) are homogeneous.

A sufficient number of series were generated for each month so that the final result would be 10 daily irradiation series (monthly means), each with a deviation lower than 10% in relation to the long-term mean monthly value (input data). The characteristics of series generated for November 1992 and January 1993 for Jaguariúna, for example, shows that it is necessary to generate less than 20 series to ultimately produce 10 series, each containing a deviation from the mean monthly value smaller than 10% in relation to the input value.

Based on the daily solar irradiation series synthesized for each month for Jaguariúna, and using equations (1) and (2), the maximum daily temperatures were calculated for each month of the year. It is worth noting that the maximum temperatures calculated by the mentioned equations are only good for S. Manuel and S. Carlos; however, because the region is being considered homogeneous from a pedological and climatic point of view, the results are also valid for Jaguariúna. Finally, using equation (5) and Table 2, the daily temperature profiles were determined using a filter, such as the one available in the Excel program (Microsoft Corporation, 1997); this allows the number of hours with temperatures above a certain threshold to be determined. The mean values resulting from the ten series of each month are presented in Table 3. For comparison purposes, the values measured in the experimental assays by Ghini et al. (1994) are also presented in the same table.

For the solarization period from November to March in Jaguariúna, SP, the calculation procedure produced results that were close to the experimental data, by estimating monthly temperature hours higher than 35°C with deviations smaller than 20% in relation to values measured by Ghini et al. (1994). Considering the more central period that goes from November to February, when a better sampling of accumulated hours in the experimental assay could be obtained, the deviation was then less than 14%.

For the temperature range above 40°C in the period from November to February, the deviation between the calculation and the experimental assay was less than 24%, when the month of February is disregarded, since the values obtained by Ghini et al. (1994) for that period were atypical. In other words, it can be seen that solarized soil temperatures in March were higher than those in February, which demonstrates some alteration in the result, in addition to the fact that February has a fewer number of days. The experimental values measured presented other inconsistencies; for example, temperatures for the months of October and January were different, in spite of their similarity from a solar irradiation and precipitation point of view. In this case, the model anticipates closer results. These variations are due to the fact that only a one-year period was evaluated, while the model uses mean values obtained during 30 years.

Generally, the procedure described above provides estimates, for agricultural engineering purposes (solarization project), of the number of monthly solarization hours for the region of the State of S. Paulo from which the data were obtained. Validation of such modeling must be done more extensively with other experimental data. The correlations used in modeling (such as daily solar irradiation as a function of daily maximum temperature and daily amplitude) must be reviewed for other locations. Extending the modeling to other regions of the country that are completely different from the State of S. Paulo is also recommended.

Another aspect to be considered is that, in order to calculate the daily maximum soil temperatures, the long-term mean air temperatures used were for the city of S. Carlos, and were obtained from the 1961-1990 Weather Normals. Ghini's assays (1994) were conducted specifically in the second semester of 1992 and the first semester of 1993; thus, air temperatures (monthly means) in the experimental assays are certainly different from the model's, due to monthly interannual variabilities. The introduction of monthly mean maximum temperature interannual variabilities could improve modeling, especially in the highest temperature threshold region.

The procedure described in the present work, even though still requiring broader validation at a nationwide level, is an important tool for solarization project purposes, since it allows the number of experimental assays to be reduced, thus making the solarization process more economical, and allowing this technique to be used in new regions.

8. ACKNOWLEDGEMENTS

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TABLE 3: COMPARISON BETWEEN MONTHLY ACCUMULATED TEMPERATURE (T) HOURS IN SOLARIZED SOILS (10 CM DEPTH) AT VARIOUS EXPERIMENTAL THRESHOLDS, CALCULATED FOR JAGUARIÚNA, SP

Month	Precipitation (mm/mês)	Solar irradiation (H) (MJ/m^2/mês)			Number of accumulated hours with T > 35 °C			Number of accumulated hours with T > 40°C		
		Obs.[a]	Calc.[b]	Dif. (%)	Obs.[a]	Calc.[b]	Dif. (%)	Obs.[a]	Calc.[b]	Dif. (%)
Sept	105.8	358.8	358.8±21.3	0.0	62	97±28	-56.3	6	11±11	-86.7
Oct	288.6	483.8	492.4±20.7	-1.8	159	220±27	-38.2	22	74±24	-235.0
Nov	239.8	493.3	492.2±31.0	0.2	250	272±50	-8.6	85	105±39	-23.9
Dec	149.6	555.8	577.6±21.9	-3.9	398	351±35	11.9	166	156±40	6.2
Jan	250.4	483.9	481.6±23.9	0.5	284	273±26	4.0	129	114±21	11.6
Feb	336.8	358.1	358.4±19.9	-0.1	199	173±38	13.3	33	64±25	-93.6
Mar	107.8	451.0	448.3±28.0	0.6	303	244±36	19.4	99	93±32	6.0
Apr	67.4	378.2	383.8±16.2	-1.5	126	123±31	2.1	0	19±13	-

[a] Observed Ghini et al. (1994).

[b] Values calculated considering maximum (air) temperatures, monthly means (Tmax), for the city of S. Carlos, SP, whose values are presented in INMET's (1992) 1961-1990 Weather Normals.

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