Notas Científicas

Numerical procedure for estimating temperature in solarized soils

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Abstract – The objective of this work was to develop a simplified numerical procedure for the estimation of accumulated monthly hours of solarized soil temperatures. The proposed model requires monthly means of daily solar radiation and maximum air temperature as input data, and a daily pattern of temperature variation assumed to be sine-shaped. The procedure was verified using observations made during the years 1992 and 1993 in Jaguariúna, SP. The proposed procedure can predict monthly temperature hours at 10 cm depth in the solarized soil, with acceptable accuracy, in the region for which it was developed.

Index terms: soil disinfestation, physical control, soil pathogens, alternative methods, solar energy, numerical modelling.

Procedimento numérico para estimar temperaturas de solos solarizados

Resumo – O objetivo deste trabalho foi desenvolver um procedimento numérico simplificado para estimar as horas mensais acumuladas de temperaturas de solo solarizado. A modelagem proposta requer como dados de entrada as médias mensais de densidade de fluxo de radiação solar diária e temperatura máxima diária do ar, e um perfil diário de variação de temperatura, admitida como senoidal. O procedimento proposto foi verificado usando-se observações realizadas durante 1992 e 1993, em Jaguariúna, SP. A modelagem desenvolvida prediz as horas mensais de temperatura de solo solarizado, a 10 cm de profundidade, para a região em que foi desenvolvida.

Termos para indexação: desinfestação do solo, controle físico, patógenos de solo, métodos alternativos, energia solar, modelagem numérica.

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 season in which the solar radiation is high, for one to two months period. Predicting temperatures in solarized soils along 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 cropping schedule, by choosing periods that would result in better use of time. The use of a simulation model 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). The detailed simulation procedures require temporal series of solar radiation, air temperature, precipitation, and temperatures in the solarized soil at two different depths, and bare soil temperature, at an hourly or daily basis. Moreover, if measurements of weather variables are not available for these series, they must be estimated, which requires detailed knowledge of auto-correlation and cross-correlation coefficients for the generation of bi-variate or even tri-variate temporal series. The difficulty remains since these coefficients are scarcely measured or known, both spatially and temporally, moreover they also depend on location.

Therefore, the present work had the objective of developing a simplified numerical procedure for the estimation of accumulated monthly hours of solarized soil temperatures.

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

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

T_{max} (ºC) = 1.12H + 20.89 (R^2 = 0.89) (1)

Since this correlation was obtained for January, it is necessary to adjust it to 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°1'S, 47°53'W). Table 1 shows the mean values for monthly maximum air temperature contained in the 1961–1990 Weather-Normals (Brasil, 1992), and the proposed corrections, considering January as a standard month. The correction is made by subtracting Δ from the value obtained in equation 1.

This proposed correction is based on the fact that solarized soil temperature, at 10 cm of depth, is determined by the soil energy exchange between the soil, the polyethylene and surrounding air. In the interface between polyethylene film and atmosphere, heat fluxes occur by convection and radiation. The net flux of convective heat is proportional to the difference of temperature between atmospheric air temperature and the temperature of the polyethylene surface. The radioactive flux is proportional to the difference between the fourth power of the sky temperature and the fourth power of the polyethylene surface temperature. The sky temperature can be considered proportional to 1.5 power of the ambient temperature (Swinbank, 1963). Thus, T_{max} of solarized soil depends on the ambient temperature.

Based on temperature amplitude variation of solarized soil measured by Patrício (2000), in Piracicaba, SP (22°43'S, 47°39'W), a correlation between temperature amplitude and daily maximum temperature for the 10 cm depth was obtained (Figure 1 B).

The regression equation for daily temperature amplitude, as a function of maximum temperature in the solarized soil at 10 cm depth, is:

A(ºC) = 0.42T_{max} - 7.52 (R^2 = 0.76) (2)

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

$$T_1(t) = \overline{T} + A_1 \,\text{sen}(\omega t + \phi_1) \quad (3)$$

where T is the temporal variation of temperature at a given depth; $\overline{T}$ is the mean temperature; 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:

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

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

According to Ferraz et al. (2003), the maximum temperature of the solarized soil at 10 cm depth, in Piracicaba, SP, occurs around 17h; therefore, the phase angle calculated by equation (4) results in 3.4. The minimum temperature value in that research work occurred at 8h.

Hourly temperature data for the solarized soil is calculated by:

$T(h) = T_{maximum\ daily}$ - Af (5)

where: T(h) is the temperature at a given time; $T_{maximum\ daily}$ is daily maximum temperature; A is ampli-

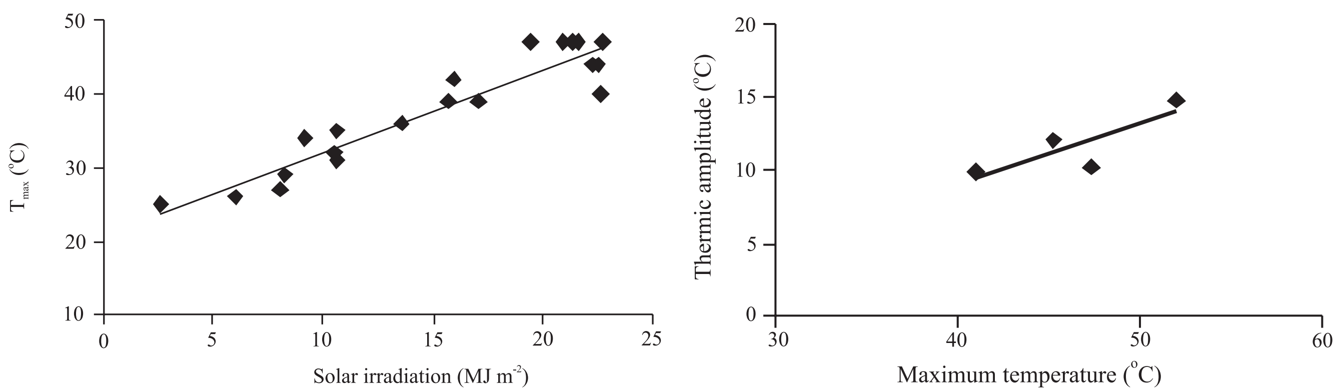

Figure 1. Correlation between daily maximum temperature (T_{max}) of solarized soil, at 10 cm depth, and daily incoming solar irradiation (H) in January 1989 period, in São Manuel, SP (Lefèvre, 1990); and correlation between temperature amplitude and daily maximum temperature, in solarized soil for 10-cm depth, in Piracicaba, SP (Patrício, 2000).

tude (given by equation 2); and f is the temperature amplitude fraction at this given time in a sine model. The daily amplitude is the difference between the daily maximum and minimum values. The temperature amplitude fraction (f), for each time are: 1h: 0.75, 2h: 0.85, 3h: 0.93, 4h: 0.98, 5h: 1.00, 6h: 0.98, 7h: 0.93, 8h: 0.85, 9h: 0.75, 10h: 0.63, 11h: 0.50, 12h: 0.37, 13h: 0.25, 14h: 0.15, 15h: 0.07, 16h: 0.02, 17h: 0.00, 18h: 0.02, 19h: 0.07, 20h: 0.15, 21h: 0.25, 22h: 0.37, 23h: 0.50, and 24h: 0.63.

As experimental information on daily incoming solar irradiation is not promptly available for many locations in Brazil, one alternative to overcome this situation is to generate synthetic temporal series (Aguiar et al., 1988; Graham et al., 1988). The generated series reproduce the statistical properties of actual series, and are therefore suitable for numeric simulation purposes.

The Solarimetric Atlas of Brazil (Tiba et al., 2003) has a calculation tool that allows temporal series to be generated using Markov's Transition Matrix Method (Aguiar et al., 1988). The synthetic series generator requires the local geographical coordinates and the mean monthly incoming solar irradiation value. These data are also provided by the Atlas.

The steps for estimating monthly temperature accumulated hours of solarized soil, at a given depth and threshold, are: a) generation of incoming solar radiation daily series using, for example, the calculation tool provided by Tiba et al. (2003); b) calculating, for each month, the maximum daily temperature in the solarized soil, using a correlation between daily solar irradiation and solarized soil temperature, according to equation (1); c) correcting the maximum daily temperature, calculated in the previous item, using the correction factor presented in Table 1; d) using the maximum daily temperature, calculated in the previous item, to determine the daily amplitude, using a correlation between temperature amplitude and daily maximum temperature at 10 cm depth, according to equation (2); e) knowing the daily temperature and amplitude, and assuming that the temperature wave is given by a Fourier series containing a single harmonic, to calculate the distribution of hourly temperatures, according to equation (5) and values of f (temperature amplitude fraction); f) estimating the temperatures for all other days of the month, and calculating the accumulated hours that temperature is above a given threshold.

The solarization experiment conducted by Ghini et al. (1994), at Embrapa Meio Ambiente, in Jaguariúna, SP (22º42'S, 46º59'W), during the period from July 1992 to June 1993, evaluated the method proposed for estimating accumulated solarization hours. Due to the lack of local information, for obtaining the several correlations previously mentioned, it was assumed that, from a climatological and pedological standpoint, the various locations (São Manuel, Piracicaba, Jaguariúna, and São Carlos) are homogeneous.

A sufficient number of series was generated for each month, so that the final result would be 10 daily radiation 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, show 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% of the input value (Table 2).

Based on synthetic daily incoming solar irradiation series, for each month for Jaguariúna, and using equations (1) and (2), the maximum daily temperatures were calculated for each month of the year. Finally, using equation (5) and values of f (temperature amplitude fraction), the daily temperature waves were determined using a filter, such as the one available in Excel spreadsheet; this filter 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 were compared to those measured in the experiment by Ghini et al. (1994) (Table 3).

From November to March, in Jaguariúna, SP, the results were close to the experimental data. The estimated monthly temperature hours higher than 35°C had deviations smaller than 20%, in relation to values measured by Ghini et al. (1994). Considering the period from November to February, when a improved sampling of accumulated hours in the experimental assay could be obtained, the deviation was then less than 14%.

For temperature above 40°C, from November to February, the deviation between calculated and measured

Table 1. Correction factor (Δ) for maximum temperature, for different months.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
$\overline{T}_{max}$(°C)[1]	26.8	27.2	27.0	25.7	23.6	22.7	22.1	24.3	25.0	24.7	25.7	25.2
Correction	0.0	-0.4	-0.2	1.1	3.2	4.1	4.7	2.5	1.8	2.1	1.1	1.6

[1]Climatological normals 1961–1990 (Brasil, 1992).

data 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. 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 fewer days. The measured values presented other inconsistencies; for example, temperatures for the months October and January were different, in spite of their similarity in solar irradiation and precipitation. In this case, the model anticipates closer results. These variations were due to the fact that only a one-year period was evaluated, while the model uses mean values obtained over 30 years.

The model departs from measured data by 41%, for the month of January, for temperatures higher than 45°C. The comparison for the month of December resulted in a deviation of 120%; however, it must be noted that a certain inconsistency exists in the experimental data, as December, with approximately one half of the precipitation relative to January and about 19% more solar irradiation, resulted in a practically identical number of accumulated hours at a temperature higher than 45°C. Also, for the months of November and January, the

Table 2. Synthetic daily incoming solar irradiation series (H), for the months of November 1992 and January 1993. Jaguariúna, SP.

Month/year	Series	H (synthetic) (MJ m^{-2} per month)	Error (%)
Nov. 1992	Series 1	460.2	6.7
	Series 3	464.7	5.8
	Series 5	530.7	-7.6
	Series 6	491.3	0.4
	Series 7	464.9	5.8
	Series 10	474.8	3.8
	Series 11	493.4	0.0
	Series 13	518.7	-5.1
	Series 14	531.4	-7.7
	Series 15	540.6	-9.6
	Mean	497.1	0.2
	Value observed(1)	493.3	
Jan. 1993	Series 1	509.7	-5.3
	Series 2	460.2	4.9
	Series 4	486.6	-0.6
	Series 5	436.1	9.9
	Series 7	476.9	1.4
	Series 8	485.4	-0.3
	Series 9	477.7	1.3
	Series 10	490.5	-1.4
	Series 11	510.9	-5.6
	Series 14	452.1	6.6
	Mean	478.6	0.5
	Value observed(1)	483.9	

(1)Ghini et al. (1994).

Table 3. Comparison between calculated and measured monthly accumulated temperature (T) hours, in solarized soils (10-cm depth), at various experimental thresholds. Jaguariúna, SP.

Month	Precipitation (mm per month)	Solar irradiation (H) (MJ m^{-2} per month)			Accumulated hours with T>35°C			Accumulated hours with T>40°C			Accumulated hours with T>45°C		
		Observed(1)	Calculated(2)	Difference (%)	Observed	Calculated	Difference (%)	Observed	Calculated	Difference (%)	Observed	Calculated	Difference (%)
Sep.	105.8	358.8	358.8±21.3	0.0	62	97±28	-56.3	6	11±11	-86.7	0	0	-
Oct.	288.6	483.8	492.4±20.7	-1.8	159	220±27	-38.2	22	74±24	-235.0	0	13±15	-
Nov.	239.8	493.3	492.2±31.0	0.2	250	272±50	-8.6	85	105±39	-23.9	6	24±21	291.7
Dec.	149.6	555.8	577.6±21.9	-3.9	398	351±35	11.9	166	156±40	6.2	23	51±28	-119.6
Jan.	250.4	483.9	481.6±23.9	0.5	284	273±26	4.0	129	114±21	11.6	22	31±17	-40.9
Feb.	336.8	358.1	358.4±19.9	-0.1	199	173±38	13.3	33	64±25	-93.6	0	13±11	-
Mar.	107.8	451.0	448.3±28.0	0.6	303	244±36	19.4	99	93±32	6.0	0	24±21	-
Apr.	67.4	378.2	383.8±16.2	-1.5	126	123±31	2.1	0	19±13	-	0	0	-

(1)Ghini et al. (1994). (2)Values calculated considering maximum air temperatures, monthly means (T_{max}), for São Carlos, SP, with values presented in Brasil (1992) 1961–1990 climatological normals.

experimental precipitation and solar irradiation conditions were quite similar; therefore, if these dimensions are the driving forces of the process, they should have resulted in very close numbers of accumulated hours, as anticipated by the calculations, which did not happen.

Monthly accumulated hours for temperatures higher than 45°C had a very small experimental sampling. A number of monthly hours less than 10 hours could be observed on a single day, or numbers less than 30 hours could occur in three or four days, at most. From the standpoint of solar radiation modelling, i.e., the synthetic generation of daily solar irradiation, the mean, auto-correlation coefficient, and other statistical parameters can be surely reproduced; however, reproduction of the exact sequence and daily experimental values for a single year cannot be guaranteed. Therefore, it would be quite common to generate a sequence of days, whose daily irradiations would be below the threshold that results in higher temperatures, and thus it would also be common to easily introduce or remove fluctuations of one to two days, therefore being of 10 to 15 monthly hours.

In order to calculate daily maximum soil temperatures, the long-term mean air temperatures used were from São Carlos, and were obtained from the 1961–1990 Weather Normals. Ghini et al. (1994) conducted the assay, specifically in the second half of 1992 and the first half 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 provides estimates of the number of monthly solarization hours, for the region of the State of São 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) have to be reviewed for other locations.

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