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EMISSION OF THERMAL RADIATION BY MULCHED SOIL *

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A b s t r a c t. The thermal radiation emitted by wet mulched soil samples having the same composition and subjected to different treatments has been measured for soil temperatures ranging from 65°C down to 58°C. For each soil sample a treatment was characterized by the shape given to the soil surface and by the transparent film used for mulching the soil. The shape was chosen among smooth surface, surface with holes of diameter 10 mm, surface with holes of diameter 6 mm. Two surfaces with holes of different diameter were geometrically similar figures, consequently the hole depths and the distances between the nearest holes were scaled in the same ratio as the hole diameters. The film was chosen among: EVA, Patilux, Polyethylene. The emissivities corresponding to the nine treatments have been measured. For each film the emissivities of soil with holes (both of diameter 10 mm and 6 mm) are greater than the emissivity of soil having a smooth surface and the difference between the emissivities of the two samples with holes is not statistically significant. Previous experiments in Soil Solarization had shown that the temperature regimes of soil samples mulched with an EVA film and having surfaces shaped as in the present experiments were pair wise remarkably different.

K e y w o r d s: thermal radiation, mulched soil

INTRODUCTION

Experiments performed since 1957 by various authors showed that soil mulching by a transparent polyethylene film induced at various soil depths increased soil temperature with respect to the temperature measured in bare (i.e. not mulched) soil. A review of such experiments till 1960, as well as a theoretical estimation of the observed effects, was given by Waggoner *et al.* [14]. In 1976 Katan *et al.* [7] described a new soil disinfestation method for controlling soil borne pathogens and weeds, today commonly referred to as 'Soil solarization', based on a preplanting soil treatment achieved by mulching the soil with a transparent polyethylene film during the hot season.

The detailed description enabled other researches to reproduce and examine the method under their local conditions. Since then soil solarization has greatly developed and ten years later it had already been investigated in 24 countries and commercially applied in many of them [8]. In the last years international conferences have been dedicated prevalently [1] or entirely [4] to soil solarization and the comparison between this disinfestation method and other chemical or physical ones has been carefully carried out and discussed by several authors.

Pullman *et al.* [13] shoved that the effects of soil solarization are strictly related to thermal death of soil borne plant pathogens; laboratory experiments highlighted a linear relationship between logarithms of time required to kill 90 % of the tested propagules when plotted against temperature. The laboratory results accounted for the field results in soil solarization. Therefore if one find refinements of the method of soil solarization which yield a further increase

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of temperature, then advantages would be expected in several cases: e.g., in marginal climatic conditions or when it is convenient to shorten the mulching period.

Soil solarization experiments performed in summer 1987 [2] showed that the existence of holes in soil below the mulch influences the temperature regime. The effects are more relevant when using an EVA rather than a Polyethylene mulch. At the depth of 25 cm, temperatures in soil having about 1 200 holes/m^2 (hole diameter 1 cm, hole depth 9 cm) were about 3 °C for EVA mulch, and 3 °C for Polyethylene mulch, higher than the corresponding temperatures in soil having a smooth surface; in the case of a smooth surface soil temperature was almost independent on the mulching film (EVA or Polyethylene). The above results were confirmed and extended in experiments performed in summer 1988 and 1989 [5,6]. Cylindrical holes were made in soil according to the pattern of Fig. 1. Denoting the hole diameter by ∅, the hole

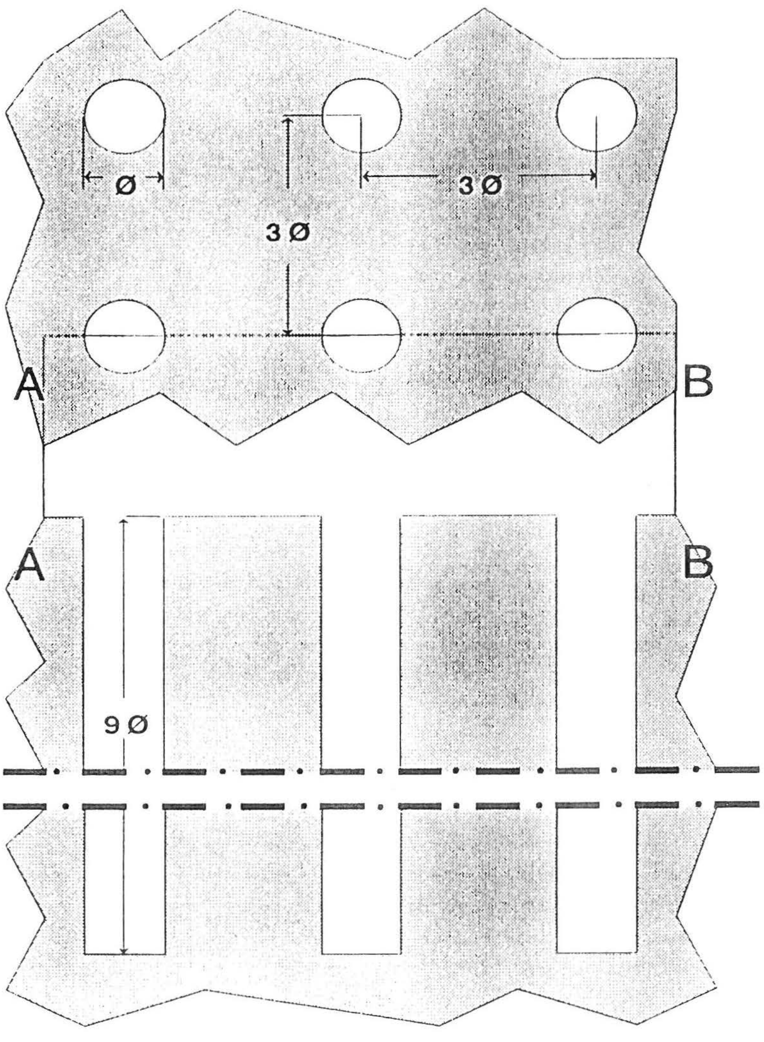

Fig. 1. Hole pattern in soil. The shaded area represents the soil. The white areas surrounded by soil represent the holes.

depth was 9 ∅ and the distance between the centers of the nearest holes was 3 ∅ for all the experiments. Various values of ∅ were chosen, so that the pierced soil surfaces in two different experiments were related to each other by a scale transformation. Minimal, maximal and mean values of soil temperatures measured on August 16th, 1989 (20 days after the mulching) at the depth of 5 cm, 15 cm and 25 cm for ∅=6 mm, ∅=10 mm, for smooth (i.e. without holes) mulched soil and for smooth unmulched soil are shown in Table 1. The fact that soil temperature is higher for a pierced soil surface than for a smooth one (keeping all the other conditions fixed) is theoretically explained [5], and has been exploited in solar collectors, while the temperature dependence on the scale of the holes, as shown by Table 1, is not explained by usual physical theory of soil solarization [5,6,11]. In reference [5] some conjectures were made concerning such a scale dependence of temperature, among them one was based on the fact that the ratio of the wavelength of the every monochromatic component of radiation absorbed or emitted to the size of the absorber or emitter will change if the absorbers or emitters are geometrically similar figures connected by a scale transformation.

The usual physical theory of soil solarization is based on an energy balance equation and on coupled differential equations for the heat and the moisture diffusion [5, 11,12]. Such a theory for sufficiently wet soil, having a smooth plane surface and mulched with a Polyethylene film (i.e., when the usual soil solarization method is carried out) gives soil temperature as a function of depth and time which are in good agreement with the observed values [11]. However, the theory, in the present form, does not account for the above mentioned temperature dependence on the scale of the holes.

T a b l e 1. Minimal, maximal and mean soil temperatures in a day of soil solarization (August 16, 1989, 20 days after the mulching) at three depths for different mulching of soil: C1-unmulched smooth soil surface, C2-mulched smooth soil surface, C3-mulched soil with holes of diameter 10 mm, C4-mulched soill with holes of diameter 6 mm

Depth (cm)	Soil temperature (^{o}C)				
	C1	C2	C3	C4	
5	48.0	50.0	54.0	59.9	Maximal
	20.5	25.3	26.0	26.2	Minimal
	31.3	35.3	37.2	39.2	Mean
15	34.3	39.9	42.6	45.2	Maximal
	27.0	29.7	30.8	31.4	Minimal
	30.5	34.5	36.3	37.6	Mean
25	31.8	36.5	38.5	40.1	Maximal
	28.2	31.1	32.4	32.9	Minimal
	30.1	33.9	35.5	36.5	Mean

The aim of the present paper is to investigate the thermal radiation emitted by soil having a smooth surface or a surface with holes according to the pattern of Fig. 1, with hole diameter of 6 mm or 10 mm, as in the experiments [5,6] in which soil temperature was measured during soil solarization (Table 1), and mulched with various transparent plastic films. In soil solarization such a radiation contributes as an outgoing flux to the energy balance of the considered soil layer, therefore the knowledge of the flux of radiation provides one of the pieces of information required for calculating the soil temperature.

MATERIALS AND METHODS

The apparatus used to measure the thermal radiation emitted by mulched soil is represented in a vertical cross section in Fig. 2. A cubic brass box D without cover, the edge of which was 20 cm long, was filled with sandy soil (sand 92.4 %, silt 4.7 %, clay 2.9 %, water content 26.3 % w/w). Soil samples were taken from soil already used in soil solarization experiments [5,6], for which temperatures had been measured (Table 1). The surface of the soil was either smooth or with holes made according to the pattern of Fig. 1; for the diameter ⌀ of holes the choices ⌀=6 mm or ⌀=10 mm were made. The brass boxes, covered with a plastic film to avoid water evaporation, were previously heated in a oven till a uniform temperature of about 70 °C was reached. Then the boxes were extracted from the oven, the plastic cover was removed, two temperature probes Pt 100 were placed on the soil surface and soil was covered (mulched) by one of the plastic films to test, which were: EVA, 45 μm thick, Patilux, 120 μm thick and Polyethylene, 65 μm thick (the films EVA and Polyethylene were made by SISAC S.r.1., Ragusa, Italy, the film Patilux was made by PATI S.p.A., Treviso, Italy).The box D so prepared was inserted in the apparatus of Fig. 2. The walls and the bottom of the box D were thermally insulated using a suitable insulating material C.

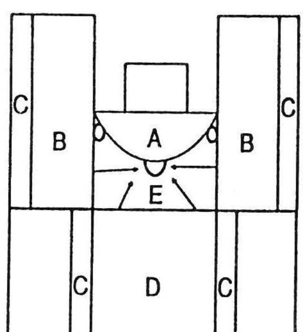

Fig. 2. Measuring apparatus. A-Pyrgeometer, B-vessel containing melting ice in equilibrium with liquid water, C-insulating material, D-brass box containing soil, E-radiation in the radiation chamber.

Over the mulched soil surface there was an Eppley precision infrared radiometer (Pyrgeometer) A, having a sensitivity of $5\,\mu$V/W m^{-2} and a response time of 2 s. Such an instrument measures the exchange of radiation E between a horizontal blackened surface (i.e. the detector) and the targets viewed, (in our case the surface of the mulched soil, and vertical brass walls, painted with black enamel paint). For the measurement of long-wave radiation and for the isolation of this flux from the short-wave radiation (when present) the glass hemisphere system has been replaced by a hemisphere of silicon. On the inner surface of this envelope is a vacuum-deposited interference filter. The composite envelope transmission exhibits a sharp transition between about 4 and 5 m, from complete opaqueness to maximum transparency, and (apart from the normal waviness associated with such interference patterns) a general transmittance of about 0.50 to 0.30-0.40 around 50 μm. A thermistor-battery-resistance circuit is incorporated to precisely compensate for the detector temperature. The calibration is referred to black body sources. The above information concerning the Pyrgeometer is taken from the data sheets supplied by the Eppley with the instrument.

Let us call 'radiation chamber' the region delimited by the Pyrgeometer on the top, the mulched soil on the bottom, four vertical painted brass walls on the sides (only two can be seen in Fig. 2). The Pyrgeometer could exchange radiation only with the inner surface of the radiation chamber. The temperature of the surface of the vertical walls facing the radiation chamber was monitored by two temperature probes Pt 100.

In B there was melting ice maintained in thermal equilibrium with liquid water. The exterior part of the vessel containing the melting ice was thermally insulated by thermal insulating material C.

The signals given by all the sensors (the Pyrgeometer, two temperature probes for the mulched soil, two temperature probes for the walls of the radiation chamber), suitably converted into digital values for the corresponding physical quantity, were loaded on a data logger every 2 s, the mean value of 30 data for each sensor (mean value of 30 values in 1 min) was recorded in a record of the form ($P_p, t_{I1}, t_{I2}, t_{J1}, t_{J2}$), where P_p is the value in W m^{-2}, with the precision of 1 W m^{-2}, given by the Pyrgeometer, t_{I1} and t_{I2} are the values in °C, with the precision of 0.1 °C, given by the temperature probes placed on the soil surface, t_{J1} and t_{J2} are the values in °C, with the precision of 0.1 °C, given by the temperature probes placed on the walls of the radiation chamber. For each record let us define t_I and t_J by:

$$t_I = \frac{t_{I1} + t_{I2}}{2}, \quad t_J = \frac{t_{J1} + t_{J2}}{2}.$$

In our experiments all the values t_J satisfied the condition 0.4 °C $\leq t_J \leq$ 0.8 °C. In each run of measurements the temperature t_I decreased as time increased. For each experiment the records we have processed are those which satisfied the condition 58 °C $\leq t_I \leq$ 65 °C. There were about 40 records in a run of measurements.

THEORY

In order to calculate the emissivity of the mulched soil in the various conditions of our experiments it is convenient to introduce the absolute temperatures:

$$T_I = t_I + 273.15$$

$$T_J = t_J + 273.15 .$$

As a result the record of experimental data to be processed are of the form: (P_p, T_I, T_J).

Let I (respectively J) be the shape factor [3] between the surface of the detector of the Pyrgeometer and the surface of the bottom (respectively of the walls) of the radiation chamber. I and J have been calculated for the geometry of our experiment. It turns out that I=0.82542, J=0.17458.

Let ε_I be the (unknown) emissivity of the mulched soil at the temperature T_I, and let ε_J be the emissivity of the walls of the radiation chamber at the temperature T_J; ε_J is known within an error from the characteristics of the used enamel paint [9].

Let us put:

$$P_I = \sigma T_I^{\ 4} \quad (1)$$

$$P_J = \sigma T_J^{\ 4} \quad (2)$$

where σ=5.6697 x 10^{-18} J m^{-2} s^{-1} K^{-4} is the Boltzmann constant. P_I (respectively P_J) is the flux of radiation emitted by a black body at the temperature T_I (respectively T_J).

In our model we assume that the detector of the Pyrgeometer is a black body, therefore:

$$P_p = \sigma T_p^{\ 4} \quad (3)$$

where T_p is the temperature of the detector expressed in K.

Let us denote by $P_{p,n}$ the flux of radiation emitted at some boundary surface element dS_o of the radiation chamber, scattered by n-1 (and no more) surface element $dS_1, dS_2, ..., dS_{n-1}$ and absorbed at a surface element dS_n of the detector.

One gets:

$$P_{p,1} = \varepsilon_I I P_I + \varepsilon_J J P_J . \quad (4)$$

If the outgoing and incoming fluxes of radiation at the surface of the detector of the Pyrgeometer are equal, then the following equation must be fulfilled:

$$P_p = \sum_{k=1}^{\infty} P_{p,k} . \quad (5)$$

The series at the right hand side of Eq. (5) converges (as it must be, if we require that our mathematical model consistently describes the physical situation) since it is term by term smaller than a geometrical series of ratio $\alpha=\max\{(1-\varepsilon_I), (1-\varepsilon_J)\}<1$, for at each surface element at which the scattering occurs the absorbed flux is at least $(1-\alpha)$ multiplied by the incident flux and the scattered flux is at α most multiplied by the incident flux.

The right hand side of Eq. (4) is unknown (since ε_I is unknown) and $P_{p,1}$ is not an experimental datum, but by substituting the mulched soil in the bottom of the radiation chamber with suitable materials having a known emissivity (within an experimental error) Eq. (4) gives an estimate of $P_{p,1}$. We have performed such calibration measurements and have found that, in the conditions of our experiments, $0.96\, P_p \leq P_{p,1} \leq 0.98\, P_p$. If we put:

$$P_{p,1} = 0.97\, P_p \tag{6}$$

then $P_{p,1}$ is determined up to an error due to the estimate of Eq. (6) not greater than 1%.

From Eq. (5) one gets:

$$\varepsilon_I = \frac{P_{p,1} - \varepsilon_J\, J P_J}{I P_I}. \tag{7}$$

For any given record (P_p, T_I, T_J) of the experimental data the right hand side of Eq. (7) is known by using Eqs (1),(2), and (6). In this way we have calculated ε_I for every record of data collected by the data logger such that $58\,^{\circ}C \leq t_I\,^{\circ}C \leq 65\,^{\circ}C$, where $t_I = T_I - 273.15$.

We add two comments to the mathematical model presented in this section. First: Eq. (5) is not expected to hold exactly for all the collected records of experimental data, since in a run of measurements P_p is a not increasing function of time which is decreasing or piecewise constant, but not constant in the whole time interval relative to a run of measurements and consequently the energy lost by the detector is greater than or equal to the energy it received. Therefore, to describe our experiments, the sign '=' in Eq. (5) must be substituted by the sign '≥'. However, it is possible to choose in a run of measurements times τ_1 and τ_2 such that: (i) $P_p(\tau_1) = P_p(\tau_2)$, (ii) in a neighbourhood of τ_1 the radiation flux P_p is constant with respect to time, (iii) in a right neighbourhood of τ_2 P_p is a decreasing function of time. By comparing $\varepsilon_I(\tau_1)$ with $\varepsilon_I(\tau_2)$ for several choices of the pair (τ_1, τ_2) satisfying the above conditions, no relevant difference was found. This means that the heat capacity of the detector, in relation with the involved radiation fluxes and time responses, is sufficiently small for Eq. (5) to be a good approximation. Second: the ε_I we calculate is the emissivity of a 'fictitious material'; $\varepsilon_I P_I$ is the flux of radiation that a plane surface of unit area bounding this material would emit if it had the temperature T_I. A horizontal cross section of unit area, bounding the radiation chamber on the bottom, emits in the upper half-space a flux of radiation which is just $\varepsilon_I P_I$ if the temperature measured on the soil surface, beneath the mulching film, is F_I . Our method cannot distinguish whether this radiation has been emitted by the bottom of a hole or by the soil surface and transmitted through the layer between the soil and the mulching film and through the mulching film, or it has been emitted from the upper surface of the mulching film, and so on. However, $\varepsilon_I P_I$ is the energy lost per unit area per unit time by the system 'mulched soil' as thermal radiation, and for this reason the knowledge of it provides a piece of information which is relevant to the energy balance of the mulched soil.

RESULTS

For soil mulched with the Polyethylene film, the radiation flux P_p detected by the Pyrgeometer is plotted against the soil temperature t_I in Fig. 3, for smooth soil surface, or soil having holes of diameter ⌀=6 or 10 mm.

P_p depends not only on the soil temperature T_T=273.15 + t_I, but also on the temperature T_J of the walls, as it can be seen from Eqs (4) and (6). However, the term ε_J $J P_J$ in Eq. (4), which is the source of the dependence of P_p on T_J, is almost constant in our conditions, e.g., for a typical fluctuation in T_J, from T_{J1}=273.55 K to T_{J2}=273.75 K, the corresponding increment in P_p would be 0.1558 W m^{-2}, which is small as compared to the involved values of P_p. One can see that the two curves relative to the conditions ∅=6 mm and ∅=10 mm for the hole diameters are almost indistinguishable, while the curve relative to smooth soil surface lies below them.

The mean values and standard deviations of the mulched soil emissivity ε_I measured in the temperature interval 58 °C ≤ t_I ≤ 65 °C of the soil surface, for each tested treatment, defined by the choice of the mulching film (EVA, Patilux, Polyethylene) and of the shape of the soil surface (smooth, with holes of diameter ∅=6 mm, with holes of diameter ∅=10 mm, positioned according to the pattern of Fig. 1) are given in Table 2. The same results are graphically represented in Fig. 4, where one can see that for any mulching film the intersection of a segment relative to soil with holes (of diameter ∅=6 mm or ∅=10 mm)

Table 2. Mean values and standard deviations of the soil emissivities for various mulching films and various shapes of the soil surface: t1-hole diameter 6 mm, t2-hole diameter 10 mm, t3-smooth soil surface

Mulching film	Soil emissivities			
	t1	t2	t3	
EVA	0.9228	0.9244	0.8999	Mean
	0.0117	0.0140	0.0051	Std. Dev.
Patilux	0.9038	0.9040	0.8990	Mean
	0.0029	0.0030	0.0009	Std. Dev.
Polyethylene	0.9053	0.9053	0.8953	Mean
	0.0011	0.0013	0.0016	Std. Dev.

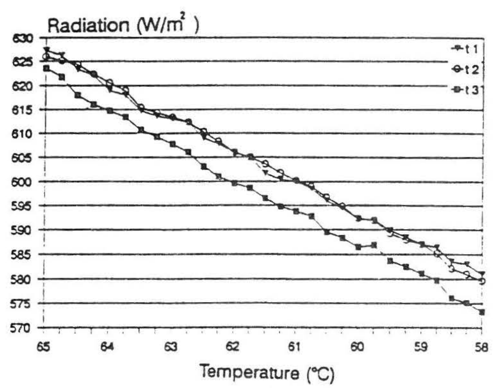

Fig. 3. Measured flux of radiation (W/m^2) for soil mulched with the Polyethylene film, versus the soil temperature. t1:soil with holes of diameter 6 mm, t2: soil with holes of diameter 10 mm, t3: soil without holes.

and the segment relative to soil without holes is void, while the intersection of the two segments relative to the soil with holes is a segment whose length is of the same order as the two intersecting segments.

For any choice of the mulching film (EVA, Patilux, Polyethylene) and for any unordered pair (A,B) or treatments of the soil surface such that A≠B and (A,B) is a subset of the set of treatments of the soil surface (smooth, with holes of diameter ∅=6 mm, with holes of diameters ∅=10 mm) the 'Null Hypothesis' δ_0: 'the experimental data relative to treatment A and those relative to treatment B belong to populations having the same normal distribution' has been tested by the statistical test F with

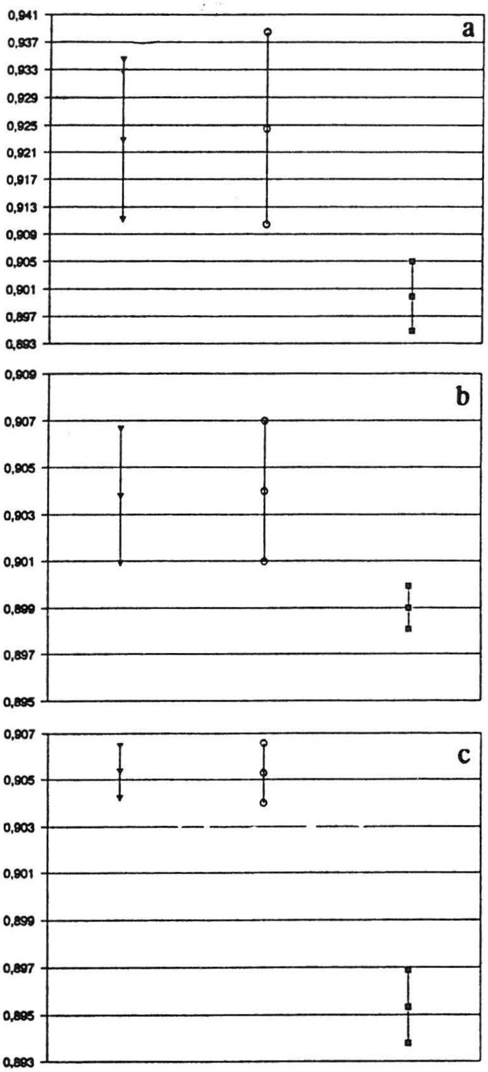

Fig. 4. Emissivities ε_I of the soil mulched with the EVA (a), Patilux (b) and Polyethylene (c) films in the range of soil temperatures [58 $^{\circ}$C, 65 $^{\circ}$C]. For each segment the middle point represents the mean value $M(\varepsilon_I)$ and the extreme points represent the values $M(\varepsilon_I) \pm s(\varepsilon_I)$, where $s(\varepsilon_I)$ is the standard deviation.

$(1, \nu_2)$ degrees of freedom [10]. The values of the function F estimated from the experiments, the values of ν_2 and the level of significance of confirmation of corresponding to the values of F tabulated in ref. [10] which are the nearest to the estimated ones, are given in Table 3.

DISCUSSION AND CONCLUSIONS

The values of emissivity of the soil mulched with the EVA film exhibit wider fluctuations than the values relative to Patilux and Polyethylene films, as the respective standard deviations show (Table 2 and Fig. 4). This is probably due to some and uncontrolled factor. For this reason we have measured more values for the EVA film than for the other ones. The difference between the emissivity of pierced and smooth soil is greater for an EVA mulch than for a Patilux or Polyethylene mulch.

For the three tested plastic films the results of the preceding section confirm that the emissivities of pierced mulched soil are greater than the emissivities of smooth mulched soil. This is an expected phenomenon, since the behaviour of a sufficiently narrow and deep hole even in a non blackened material approaches the behaviour of black body. The fact that to greater soil emissivities correspond higher soil temperatures in soil solarization (Table 1) is not surprising [5]: both the absorbed and the emitted energy increase as the emissivity increases, but the increase in the absorbed energy is greater than the increase in emitted energy, since the transmittance of the mulching film for wavelength $\lambda \in (300\ \text{nm}, 2600\ \text{nm})$, for which the energy input is about 95 % of the total is greater than the transmittance for wavelength $\lambda \in (5\ \mu\text{m}, 48\ \mu\text{m})$, for which the energy output is about 95 % of the total at soil surface temperatures typical in soil solarization (323 K).

For each of the tested film there is non significant difference between the emissivities of soil having holes of diameter $\varnothing=6$ mm and $\varnothing=10$ mm, positioned according to the pattern of Fig. 1 (Tables 2, 3 and Figs 3-6). Since in such conditions the two soil surfaces are related by a scale transformation, and in a horizontal plane bounding the soil the ratio of the area of the holes to the total area is the same in the two cases ($\varnothing=6$ mm and $\varnothing=10$ mm), our results agree with a model in which the spatial energy distribution of the radiation field does not depend

Table 3. Statistical test F

Compared treatment	ν_2	Measured F	P	Mulching film
t1, t2	400	1.197504	>>0.1	
t2, t3	400	535.367862	<<0.001	EVA
t1, t3	400	665.14834	<<0.001	
t1, t2	74	0.058684	>>0.1	
t2, t3	74	96.933692	<<0.001	Patilux
t1, t3	74	95.229240	<<0.001	
t1, t2	66	0.200978	>>0.1	
t2, t3	66	908.802175	<<0.001	Polyethylene
t1, t3	66	922.736077	<<0.001	

For explanations see Table 2.

on the wavelength [5]. At a high level of confidence the source of the remarkable differences in the temperature regimes in soil solarization between the two cases ∅=6 mm and ∅=10 mm (Table 1) is not in thermal radiation.

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