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Soil solarization, a non-chemical technique for controlling *Orobanche crenata* and improving yield of faba bean

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Abstract – *Orobanche crenata* Forsk. is a widespread holoparasite weed that inflicts severe damage (yield reduction can reach up to 100%) on legume crops in the Mediterranean and West Asian regions. In Italy and Spain, faba bean crop (*Vicia faba* L.) area has drastically decreased in the last four decades mainly due to *O. crenata* infection. The effectiveness of soil solarization for controlling *O. crenata* in heavily and naturally infested fields of faba bean in Sicily (south Italy) was studied during two growing seasons. Ploughed, leveled and moistened soil was mulched with transparent polyethylene sheets for about 50 days from the end of July to early September. The residual effect of solarization was also investigated the next year in season one and two, respectively. Mulching increased mean daily maximum temperatures of the soil by 8.9 °C and 10.7 °C at 5 cm depth and 11.5 °C and 11.3 °C at 15 cm depth. Solarization achieved a total control of *O. crenata*, since no shoots emerged from the treated soil. In contrast, in non-solarized plots shoots of *O. crenata* emerged and were present at high intensity (from 13 to 44 shoots per faba bean plant), impeding the faba bean plants from producing flowers, pods and seeds. Soil solarization improved faba bean growth and consequently grain yield compared with non-solarized soil. The almost complete control of *O. crenata* and improvement of growth and grain yield of faba bean were also maintained the next year.

soil solarization / crenate broomrape emergence / *Vicia faba* growth / soil temperature / residual effect

Résumé – La solarisation du sol, une technique non chimique pour contrôler *Orobanche crenata* et améliorer le rendement de la féve. *Orobanche crenata* Forsk. est une adventice holo-parasite, très répandue, qui inflige de sévères dommages aux cultures légumineuses (la réduction du rendement peut parvenir à 100 % dans les régions de la Méditerranée et de l’Asie occidentale). En Italie et en Espagne, les cultures commerciales de féves (*Vicia faba* L.) ont subi une forte réduction dans les 40 dernières années, principalement à cause de l’infestation par *O. crenata*. Durant deux saisons on a conduit des essais de plein champ en Sicile (sud de l’Italie) pour étudier l’efficacité de la solarisation dans la lutte contre *O. crenata*. Le sol, travaillé précédemment, nivelé et arrosé, a été couvert d’un paillage plastique en polyéthylène transparent de 20 µm d’épaisseur durant environ 50 jours à partir de la fin juillet jusqu’à début septembre. De plus, l’année suivante, on a évalué les effets résiduels de la solarisation. Le paillage a augmenté respectivement la température moyenne journalière maximale du sol de 8,7 °C et 10,7 °C à une profondeur de 5 cm et de 11,5 °C et 11,3 °C à une profondeur de 15 cm. La solarisation a permis un contrôle total d’*O. crenata*, étant donné qu’aucun bourgeon d’orobanche n’a émergé du sol traité. Par contre, dans les champs non traités avec la solarisation, les bourgeons d’*O. crenata* ont été nombreux à émerger.

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(de 13 à 44 bourgeons par plant de fève), empêchant la production des fleurs, des gousses et des graines. La solarisation a amélioré la croissance de la fève et, par conséquent, le rendement en graines, qui fut 3 à 4 fois supérieur au rendement que les statistiques officielles donnent pour le sud de l’Italie. Le contrôle presque complet d’Orobanche crenata et l’amélioration de la croissance et du rendement de la culture de fèves se sont reproduits l’année suivante.

solarisation du sol / Orobanche crenata / Vicia faba / croissance / température du sol / effets résiduels

1. INTRODUCTION

Production of faba bean (Vicia faba L.), pea (Pisum sativum L.), lentil (Lens esculenta Medik.) and chickpea (Cicer arietinum L.) in the Mediterranean and West Asian countries is greatly constrained by the holoparasitic weed crenate broomrape (Orobanche crenata Forsk.). In fact, in these areas yield reductions can reach up to 100% with mean values around 35% [21]. In Italy and Spain, areas of faba bean crop have drastically decreased in the last four decades mainly due to high crenate broomrape infection [7, 16]. Seeds of this parasite are extremely small (our own results show that the 1000-seed weight was 6.1±0.5 mg) and survive in the soil for up to 20 years [6]. A single plant can produce up to 500 000 seeds [5]. In this way a large seed bank can accumulate in arable soils [22]. The control of this parasitic weed is difficult because of its large seed production, the relatively long dormancy of the seed and the fact that seeds only germinate when exposed to germination stimulants [19]. Several methods have been developed to reduce the Orobanche attacks, but none of these are as yet fully satisfactory. The methods include hand weeding, trap crops, later sowing, flooding, crop rotation, biological control by insects and fungi, nitrogen fertilization, selective herbicides, soil fumigation, soil solarization, integrated control strategy by a combination of various methods, as well as breeding for genetic resistance.

Among the control methods, soil solarization is a relatively new non-chemical approach to controlling soil-borne pests and weeds [23]. It is based on covering wet soil with transparent polyethylene sheets during the hot season of the year [9]. This mulching captures the solar radiation and thus heats the soil to a level which is lethal for various soil pests and weeds. Soil solarization should be employed in areas where climatic, soil and economical conditions are favorable for its application [24]. In the Mediterranean region, which includes areas where, in summer months, the sunshine is intense enough and there is little cropping activity, solarization would appear to provide a good opportunity for control of crenata broomrape. The present study has also been prompted by our previous research which demonstrated that the exposure of seeds to increased temperature (from 20 °C to 44 °C) caused a significant progressive reduction of O. crenata germination and, from 38 °C to 75–80 °C, a significant linear decrease of seed viability [13].

Moreover, yield reductions are dependent on the number of parasite attachments per host plant and the time of infestation. While infestation of 3-7 shoots/plant can cause 50% seed yield loss [15], heavier infestations of 10–12 shoots/plant are common in Mediterranean areas [11] where faba bean is an established crop. The purpose of this study was to evaluate the effectiveness of soil solarization for controlling O. crenata in heavily and naturally infested fields in southern Italy and improving the yield of faba bean. In addition, the residual effect of solarization was also examined during the next year.

2. MATERIALS AND METHODS

2.1. Site climate and soil

Field experiments were conducted during the 1998–1999 and 1999–2000 seasons along the coastal plain area south of Siracusa, south Italy (37°03′ N, 15°18′ E, 10 m a.s.l.) in a soil naturally infested with crenate broomrape. In fact, faba beans grown in that field during the previous years were severely attacked by crenate broomrape.

The soil type is calcixerallic xerochrepts (USDA Soil Taxonomy), moderately deep, with a loam-clay texture.

The climate in this area is semiarid-Mediterranean with mild winters and hot rainless summers. During the summer season the mean maximum temperature averages over 30 years from 1959–1988 were 29.6 °C (June), 32.5 °C (July), 31.6 °C (August) and 27.3 °C (September).

2.2. Experimental design and soil solarization

In both years, the experiment included two treatments, solarized and non-solarized soil, arranged in a randomized design with four replications. The plot size was 3 × 10 m in the first year and 3 × 15 m in the second year.

During the late spring the soil was ploughed several times to provide a uniform surface and then leveled. One day before mulching the soil was irrigated up to its field
capacity since solarization is more effective in moist soil [10, 11] owing to the increased thermal sensitivity of resting structures and improved heat conduction. Solarized plots were covered with 20 µm thick transparent polyethylene plastic with 89% total visible transmittance and 20% IR absorption. Special care was taken to minimize the distance between the polyethylene sheets and soil to prevent air pockets that retard the soil heating process. Plastic sheets were laid on bare soil, stretched close to the soil surface and then anchored.

Soil solarization was conducted from July 23 to September 8 in 1998 and July 16 to September 5 in 1999. After solarization, the sheets were removed carefully to avoid soil disturbance. Uncovered soil (control) underwent the same program as the covered plots.

2.3. Plant material and management practices

Faba bean, *Vicia faba* L. subsp. *major*, “Leonfortese”, a locally well adapted cultivar was used. This cultivar is grown for dry seed, with indeterminate growth and has a 1000-seed weight ranging from 2200 to 2700 g. It was chosen because previous work [3] has shown that it is more susceptible to crenate broomrape attack. This is in agreement with the study by Miccolis and Bianco [17] which demonstrated that the subsp. *major* is more susceptible to broomrape attack than subspp. *equina* and *minor*. In both years sowings were done in early November because it has been demonstrated that broomrape infection is more intense in early than late sowings [16]. Seeds were planted by hand to a depth of 4 cm. Distance between rows was 75 cm and between plants within a row was 33 cm. The faba bean crop was uniformly fertilized with 50 kg ha⁻¹ of P₂O₅ and 20 kg ha⁻¹ of N. Weeds were controlled by hand when necessary.

2.4. Temperature measurements

Soil temperatures were measured continuously at depths of 5 and 15 cm, using thermoistors buried in the centre of the plots (solarized and non-solarized) and connected to a portable digital microprocessor HI 9284C (Hanna Instruments, Padova, Italy). Air temperature was measured at a height of 50 cm above the ground in a meteorological shelter.

2.5. Collection of biological and productive data

*O. crenata*

The intensity of parasite infestation was evaluated by counting the number of broomrape shoots per faba bean plant that had emerged above the soil surface, two times: at 155 (pod set) and 190 (pod ripened) days after sowing. In addition, during the 1999–2000 season, a sample of broomrape shoots for each plot was collected by hand at crop harvest, dried at 105 °C and weighed.

2.6. Data analysis

Biological and productive parameters were submitted to analysis of variance when opportune and means separated with the Student’s *t*-test. In some cases to overcome the problem of non-homogeneity of variances the data were transformed into logarithms.

3. RESULTS

3.1. Soil temperature

In all cases, temperatures under polyethylene cover were consistently higher than in uncovered soil (Fig. 1). In fact, at 5 and 15 cm depth under polyethylene sheet, it reached a maximum absolute of 58.7 °C and 48.9 °C respectively, against 49.7 °C and 36.8 °C of bare soil during 1998 and 57.0 °C and 44.1 °C, against 50.6 °C and 38.0 °C during 1999. For the mean daily maximum temperatures, the differences between mulched and non-mulched soil were smaller at 5 cm depth (8.9 °C in 1998 and 10.5 °C in 1999), than at 15 cm depth (11.0 °C and 11.3 °C) (Tab. I). The number of days when maximum soil temperature equalled or exceeded 42, 50, 55 and 60 °C at 5 and 15 cm depth is shown in Table II. In particular, a temperature of 42 °C at 15 cm depth was recorded for 52 days (1998) and 41 days (1999) in covered soil and for 0 days in uncovered soil. Moreover, in both years, at 5 cm depth a temperature of 50 °C was reached almost daily under covered soil, whereas it was recorded on only 1 day in uncovered soil. The typical diurnal soil temperature fluctuations on a clear day are illustrated in Figure 2.
3.2. Broomrape control

In both years, broomrape was completely controlled by soil solarization, which never allowed the emergence of any shoot. Instead, shoots of broomrape emerged and were present at high levels in non-solarized soil, where 155 days after faba bean sowing they had reached the considerable number of 24 and 10.5 per faba bean plant.
Soil solarization for controlling *O. crenata* in the 1998–1999 and 1999–2000 growing season, respectively. The number of broomrape shoots in non-solarized soil then greatly increased to reach 44 and 15.5 per faba bean plant at crop harvest (Tab. III). In 1999–2000 dry weight of emerged shoots in non-solarized plots reached 12.4 and 50.3 g per faba bean plant at the two successive samplings (Tab. III).

The effect of soil solarization was also excellent in the next season. In fact, the number of the broomrape shoots emerged for each faba bean plant was only 0.05 corresponding to 0.1 g d.w. in the solarized plot the previous year, against 12.8 corresponding to 37.7 g d.w. in the non-solarized plot (Tab. IV).

### 3.3. Faba bean growth

The growth of faba bean plants, as shown in Tables V and VI, was consistently and significantly better on solarized soil than on non-solarized soil. In fact, the increase of plant height, leaf surface and dry weight, 190 days after sowing, due to soil solarization was consistent and ranged between 37 and 876% (Tab. VI).
Moreover, plants grown on non-solarized soil reached the senescence stage before those grown in solarized soil, as demonstrated by the percentage of dry matter which, in both samples and years, was consistently much higher than in solarized soil (on average, at the same age, 31.2 against 13.7%) (Tabs. V and VI).

Residual effects of the solarization applied in 1998 were still more evident in the second faba bean crop grown during the 1999–2000 season. In fact, plant height at the end of the cycle and leaf area 150 days after sowing were 20% and 72% higher in solarized than in non-solarized plots (Tab. VII).

### 3.4. Faba bean yield

In both years, plants grown in non-solarized plots did not produce flowers nor consequently, pods or seeds (Tab. VIII). In contrast, flowering, pod set and grain yield in solarized plots were excellent and seed quality was very good. In fact, grain yield which reached 50 and 46.2 g plant\(^{-1}\) corresponding to 6.0 and 5.6 t ha\(^{-1}\) for 1998–1999 and 1999–2000, respectively, was about 3–4 times above the average official yield for the south of Italy (ISTAT, 1999 and 2000). The field trial on residual effects of solarization has shown that the yield in

### Table III. Effect of soil solarization on crenata broomrape infestation.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Broomrape shoots/Faba bean plant (means ± s.e.)</th>
<th>155 DAS (^\text{A})</th>
<th>190 DAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Dry weight (g)</td>
<td>Number</td>
</tr>
<tr>
<td>Solarized soil</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>24±5.2</td>
<td>44±8.0</td>
<td>0</td>
</tr>
<tr>
<td>Solarized soil</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>10.5±3.1</td>
<td>15.5±3.4</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^\text{A}\)DAS = Days after sowing.

### Table IV. Residual effect of soil solarization done in 1998 on crenata broomrape infestation in faba bean grown in 1999–2000.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Broomrape shoots/Faba bean plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
</tr>
<tr>
<td>Solarized soil</td>
<td>0.05</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Significance *** P < 0.001.

Moreover, plants grown on non-solarized soil reached the senescence stage before those grown in solarized soil, as demonstrated by the percentage of dry matter which, in both samples and years, was consistently much higher than in solarized soil (on average, at the same age, 31.2 against 13.7%) (Tabs. V and VI).

### Table V. Effect of soil solarization on the height, leaf area, dry weight and percentage of dry matter of faba bean plant 150 days after sowing.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height (cm)</th>
<th>Leaf area (cm(^2) plant(^{-1}))</th>
<th>Dry weight (g plant(^{-1}))</th>
<th>Dry matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solarized soil</td>
<td>137</td>
<td>2160</td>
<td>79.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>60</td>
<td>625</td>
<td>9.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Solarized soil</td>
<td>153</td>
<td>3953</td>
<td>56.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>106</td>
<td>743</td>
<td>20</td>
<td>22.7</td>
</tr>
<tr>
<td>Significance</td>
<td>**</td>
<td>***</td>
<td>**</td>
<td>***</td>
</tr>
</tbody>
</table>

** P < 0.01; *** P < 0.001.
Soil solarization for controlling O. crenata

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Soil solarization for controlling O. crenata non-solarized plots was zero whereas it reached 49 g plant\(^{-1}\) in solarized plots (Tab. VII). This value was not significantly different from that of the first year crop grown in the solarized plot.

### 4. DISCUSSION

Solarization of wet soil for about 50 days from the end of July to early September under the Mediterranean conditions of southern Italy, in a field very heavily infested by O. crenata, proved to be an excellent method to control this parasite and consistently improve faba bean yield. The results obtained on O. crenata control are in agreement with those observed in O. aegyptiaca, O. ramosa and O. cernua [1, 8].

In the non-solarized plot, the crenate broomrape attacks were so intense (from 13 to 44 shoots per faba bean plant) as to totally impede grain production. In fact, according to other research conducted in southern Spain, faba bean dry weight decreased as the level of parasite infection increased and seed yield was reduced by half when the number of broomrape per faba bean plant ranged from 2.9 to 7.0 and averaged around 4.0 [15, 16].

In our research, the Orobanche infestation was so severe that in non-solarized plots, faba bean plants were unable to produce flowers nor consequently, pods or seeds. The high degree of O. crenata infestation found in non-solarized plots was zero whereas it reached 49 g plant\(^{-1}\) in solarized plots (Tab. VII). This value was not significantly different from that of the first year crop grown in the solarized plot.

### Table VI. Effect of soil solarization on the height, leaf area, dry weight and percentage of dry matter of faba bean plant 190 days after sowing.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height (cm)</th>
<th>Leaf area (cm(^2) plant(^{-1}))</th>
<th>Dry weight (g plant(^{-1}))</th>
<th>Dry matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solarized soil</td>
<td>139</td>
<td>3038</td>
<td>59.9</td>
<td>15.3</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>60</td>
<td>340</td>
<td>11.6</td>
<td>36.5</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solarized soil</td>
<td>151</td>
<td>2820</td>
<td>60.2</td>
<td>16.6</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>110</td>
<td>289</td>
<td>8.5</td>
<td>42.5</td>
</tr>
<tr>
<td>Significance</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

** P < 0.01; ***P < 0.001.

### Table VII. Residual effect of soil solarization done in 1998 in the second faba bean crop grown during the 1999–2000 season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height(^A) (cm)</th>
<th>Leaf area(^B) (cm(^2) plant(^{-1}))</th>
<th>Grain yield(^A) (g plant(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solarized soil</td>
<td>131</td>
<td>2056</td>
<td>49.0±11(^C)</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>109</td>
<td>1192</td>
<td>0</td>
</tr>
<tr>
<td>Significance</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

\(^A\) At end of cycle.  
\(^B\) At 150 days after sowing.  
\(^C\) s.e.  
*** P < 0.001.

### Table VIII. Effect of soil solarization on yield and its components of faba bean crop. Data are means ± s.e.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain yield (g plant(^{-1}))</th>
<th>Flowers (n main-stem(^{-1}))</th>
<th>Pods (n plant(^{-1}))</th>
<th>Seeds (n pod(^{-1}))</th>
<th>1000-seed weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solarized soil</td>
<td>50±5</td>
<td>42±10</td>
<td>8±2</td>
<td>2.5±0.1</td>
<td>2500±220</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Solarized soil</td>
<td>46.2±7</td>
<td>45±9</td>
<td>8.5±2</td>
<td>2.5±0.1</td>
<td>2200±250</td>
</tr>
<tr>
<td>Non-solarized soil</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Solarization provides total control of crenate broomrape since zero shoots emerged from the treated soil. This effect was due to the high soil temperature reached under polyethylene mulching. A maximum absolute temperature of 58.7 °C (1998) and 57.0 °C (1999) may have hindered the germination of *O. crenata* seeds, mainly by two mechanisms: induction of seed secondary dormancy and reduction of seed viability. In fact, our laboratory studies [14] showed that after exposure to 42 °C and 44 °C, seed germination of *O. crenata* was cancelled mainly due to secondary dormancy. With increasing temperature seed exposure, the germination process was also prevented by the reduction of seed viability, which reached the threshold of 50% at about 57 °C on the basis of the linear equation deduced from the results of Mauromicale et al. [14]. As the top 5 cm of soil mulched with polyethylene sheets reached a maximum temperature of 58.7 °C and 57.0 °C, it is reasonable to suppose that at this depth more than 50% of *O. crenata* seeds were dead. This result is very important because it indicates that the content of *O. crenata* seeds in the soil may be reduced after every solarization, and thus it may be hypothesized that following a certain number of solarizations, the seeds of the parasite within the soil may be kept at a level compatible with normal development of faba bean crop.

Solarization improved faba bean growth and consequently yield. This latter was, furthermore, 3–4 times above the average official yield for the south of Italy [13], where almost all the faba bean crop is concentrated. This remarkable yield improvement is probably not only due to the control of *O. crenata* but may also be explained by a control of soil-borne diseases and other factors, such as increased release and uptake of macro- and micro-nutrients, release of plant growth regulators, development of mycorrhiza and increase of nodulation [2, 4, 12, 18, 23].

The control of *O. crenata* and improvement of growth and yield of faba bean by solarization were also maintained the next year, confirming the good residual effect observed by Sauerborn et al. [20].

On the basis of these results, we believe that solarization may be taken into consideration in areas where the infestation of *O. crenata* is high, not only to contain it but also substantially reduce the seed pool in the soil in time, acting in this way as a real and proper positive reclamation. Another advantage of solarization is that it is a plant protection method which avoids site contamination and is suited to organic farming.

In the light of the above favorable results observed over two consecutive crops, the application of polyethylene mulch can be economically justified. In addition, efficient film laying machinery can reduce the cost of application.

Future research is necessary to precisely establish the quantity of *O. crenata* seeds killed at each solarization, the acceptable threshold of residual seeds rendering solarization useful and economically viable, and methodologies to reduce the cost of making the technique practicable.

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**REFERENCES**


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