Interaction Among Mycorrhizae, Soil Solarization, Metalaxyl, and Plants in the Field

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ABSTRACT

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Field trials were conducted in 1988 and 1989 to increase growth response, yield, and vesicular-arbuscular mycorrhizal (VAM) fungi colonization of cotton (*Gossypium hirsutum*), onion (*Allium cepa*), and pepper (*Capsicum annuum*) in nonfumigated soil. Treatments of fumigated and nonfumigated soil plots included soil solarization, soil solarization plus tarp coverage for 2 wk after planting, and metalaxyl application. Plants from each treatment were inoculated or not inoculated with VAM fungi. Because results were similar in both years, only those for 1989 are given. Fresh weight and boll number of cotton were highest in VAM-inoculated plants grown in nonfumigated soil after soil solarization, soil solarization plus tarp coverage, and metalaxyl application. Fresh weight of onion was highest in VAM-inoculated, nonfumigated, solarized soil, with or without tarp coverage. Fresh weight and fruit weight of VAM-inoculated pepper plants were one to two times greater in nonfumigated soil than in fumigated soil, and both were greatest in VAM-inoculated, solarized soil and in solarized soil plus tarp coverage. Fresh weight and yield of the three crops were highly correlated with percent root colonization by VAM 5 wk after planting. VAM colonization of roots of cotton, onion, and pepper was maximum (65, 59, and 63%, respectively) at 3.5–5 wk after planting in nonfumigated plots treated by soil solarization plus tarp coverage. Roots of cotton, onion, and pepper were longest (149, 51, and 94 cm, respectively) in soil solarized and tarped, whether VAM-inoculated or not. Benefit of VAM inoculation appears greatest with solarization and solarization plus tarp coverage.

Vesicular-arbuscular mycorrhizal (VAM) fungi increase nutrient uptake and growth of many plants (20,35,43,44). Most agricultural crops are grown without treating the soil with biocides to reduce or eliminate indigenous VAM fungi (9,19,29,32). However, most experiments demonstrating a beneficial effect of VAM fungi on plant growth have been conducted in sterilized or fumigated soil (2,3,19,33,44).

Growth response of plants in nonfumigated soil after treatment with VAM inoculum may be poor if soil microorganisms interfere with mycorrhizal development (3,5,17,34,45). Metalaxyl, a systemic fungicide that controls root rot and damping-off caused by oomycetes, has been reported to increase VAM colonization of plants (3,18,32,37).

Since 1976, many experiments have evaluated the potential of soil solarization for reduction of pathogen (and other pest) populations, disease control, and yield increase (1,23,26,28,42,47,49). Covering (mulching or tarping) soils with transparent polyethylene, when appropriate climate conditions prevail, is the best means for capturing solar energy to heat soil under field conditions (23,24,27,41). Long-term effects of solarization on disease control and crop yields extending through a second or even a third crop have been observed with a variety of pathogens and crops (25,42,49).

Because VAM inoculation can improve plant growth, particularly when applied with metalaxyl, and because soil solarization is also beneficial to yield, the individual and combined effects of these

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treatments were studied. The influence of these treatments on VAM colonization of roots and yield of cotton (*Gossypium hirsutum* L.), onion (*Allium cepa* L.), and pepper (*Capsicum annuum* L.) was assessed.

MATERIALS AND METHODS

Field site. An agricultural Hanford coarse sandy loam soil planted with vegetables for 5 yr on the Citrus Experiment Station, University of California, Riverside, was selected for the field plots. The soil was characterized as: saturation percentage, 27%; pH 7.7; electroconductivity, 4.0 dS/m; Ca, 23.5 meq/L; Mg, 3.8 meq/L; Na, 13.9 meq/L; sodium adsorption ratio, 3.8; exchangeable sodium percentage, 4.2%; N, 632 ppm; P, 9.5 ppm by Olsen analysis (10); K, 142 ppm; Zn, 12.8 ppm; Mn, 8.6 ppm; Fe, 6.5 ppm; Cu, 1.7 ppm; organic matter, 0.80%; clay, 8.3%; silt, 28.6%; and sand, 63.1%. One-half of the site was fumigated with 98% methyl bromide plus 2% chloropicrin equivalent to 500 kg/ha. Each half had six rows 40 m long and 30 cm wide, two rows for each crop. Plots consisted of a 1.5-m segment of a row, with a 0.5-m buffer between plots and a 4-m buffer at the beginning and end of each row.

The eight treatments were: control (no VAM inoculation), VAM inoculation, control plus soil solarization, VAM inoculation plus soil solarization, control plus soil solarization plus tarp coverage for 2 wk after planting, VAM inoculation plus soil solarization plus tarp coverage for 2 wk after planting, control plus metalaxyl, and VAM inoculation plus metalaxyl. All treatments were applied in both fumigated and nonfumigated soil. The experimental design was separately randomized blocks for fumigated and nonfumigated soil with four replicates for each treatment.

Plant material and VAM inoculum. Seeds of cotton cultivar SJ-2, onion cultivar Burpee Yellow Globe, and pepper cultivar California Wonder were surface-disinfested with 20% NaOCl for 1 min before planting. These crops were chosen because they are annuals and respond positively to VAM colonization (2,3). Plants were inoculated with the mycorrhizal fungus *Glomus intraradices* Schenck & Smith (isolate 185 collected from *Citrus* sp., Ventura, California, 1975). Inoculum consisted of mixed roots and soil from Sudan grass (*Sorghum vulgare* Pers.) that had been infected with the mycorrhizal fungus for 9 mo. Inoculum density was calculated by the most probable number method (4,13) and adjusted for similar inoculum density. Inoculum was applied by hand-spreading 170 g per meter-row for a total of 144 meter-rows, 3 cm below the depth of seeds at planting. Noninoculated plots received the same amount of soil spread at the same depth. No fertilizers were used during the experiment.

Soil populations of *Pythium ultimum*. The population of *P. ultimum* Trow was estimated 2 wk after the various treatments in fumigated and nonfumigated soil. A soil core was taken from each plot to a depth of 15 cm with a 2.5-cm-diameter Hoffer soil sampler, 10 g from each sample was diluted in 100 ml of sterilized water, and 30 ml of the suspension was poured into 30 9-cm petri dishes (1 ml per dish) containing a selective medium amended with pimaricin-vancomycin-pentachloronitrobenzene (50). Colonies were counted after 24 and 48 hr at 25 C, and the propagule number per gram of soil was calculated.

Soil solarization and tarping. Soil solarization was used on one-half of the fumigated and nonfumigated plots. Plots were irrigated for 24 hr to moisten soil and improve heat conduction (30). Soil was covered with a transparent polyethylene plastic sheet (0.1 mm) for 1 mo (22 May–22 June). Seeds were planted 24 hr after the tarp was removed. After soil solarization, two plots in each block were re-covered with a tarp to reheat the soil, and holes were opened for the growing plants. During the month the soil was tarped before planting, all-metal stem thermometers were used to measure soil temperature under and outside the tarp at depths of 0, 5, 10, 20, and 30 cm. Soil temperature was measured daily at 4:30 p.m. and was usually maximum at 4:30–5:00 p.m. During the first 20 days, the sky was cloudy and the surface temperature was 28–33 C. Maximum temperatures 0, 5, 10, 20, and 30 cm deep were 41, 41, 40, 26, and 26 C, respectively, under the tarp and 33, 32, 30, 23, and 22 C, respectively, outside the tarp. During the last 11 days, the surface temperature was much higher (45–50 C), and maximum temperatures 0, 5, 10, 20, and 30 cm deep were 54, 53, 50, 37, and 33 C, respectively, under the tarp and 50, 43, 37, 27, and 25 C, respectively, outside the tarp. Soil temperatures with and without a tarp after planting were also recorded during the first 2 wk (tarps were removed 2 wk after planting). Temperatures 0, 5, 10, 20, and 30 cm deep under a tarp were 4–5, 4–5, 3–4, 2–4, and 2–3 C higher, respectively, than those outside a tarp. All soil temperature measurements, before and after planting, were done in two replications.

Metalaxyl application. Metalayxl was applied by drenching 1 L of 700 μl/L of liquid metalaxyl (25% a.i.) per treatment (1.5 × 0.35 m) 1 hr after the planting. This amount is equivalent to 333 mg a.i. per square meter.

Harvesting. Percent colonization of cotton, onion, and pepper by VAM fungi was measured and calculated 2, 3.5, and 5 wk after planting. The roots were stained with trypan blue and the number of colonized sites per total sites × 100 was calculated (40). Total root length was measured 3.5 wk after planting using the line-intercept method (38). The final harvest was 4 mo after the planting. Fresh weight was measured for all plants. In addition, cotton bolls were counted and pepper fruit were weighed.

Correlation coefficients. Data and correlation coefficients were analyzed with the Statistical Analysis System (SAS, Cary, NC). Experiments were done in 1988 and 1989, but because results were similar, only those of the 1989 study are presented.

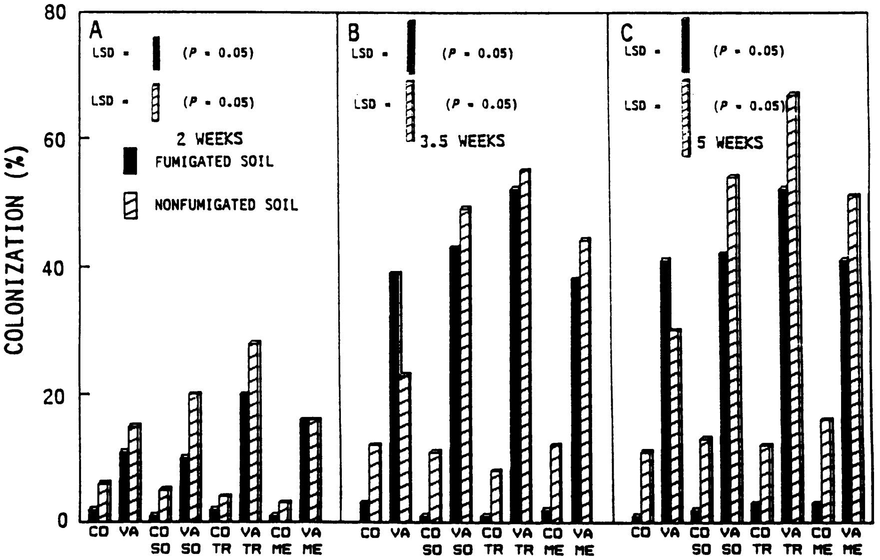

Fig. 1. Percent mycorrhizal colonization of cotton plants **(A)** 2, **(B)** 3.5, and **(C)** 5 wk after planting and one of the following treatments: noninoculated control (CO); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VA); CO + soil solarization (SO); VA + SO; CO + SO with tarp coverage for 2 wk (TR); VA + TR; CO + metalaxyl (ME); and VA + ME.

RESULTS

VAM colonization. VAM colonization of VAM-inoculated plants in soil that received only the fumigation treatment was greater than that of VAM-inoculated plants in nonfumigated soil (Fig. 1). Treatment of the soil with solarization with or without 2 wk of tarp coverage reversed this phenomenon, however, and VAM colonization of plants grown with these treatments was greater in nonfumigated soil than in fumigated soil. Colonization of VAM-inoculated cotton was maximum (>65%) at 5 wk after planting in nonfumigated soil treated with solarization plus tarp coverage (Fig. 1).

Colonization of VAM-inoculated onion after 2 and 3.5 wk was maximum in plants growing in soil treated with solarization with or without tarp coverage regardless of whether the soil was fumigated or not (Fig. 2). After 5 wk, however, colonization of VAM-inoculated onion was maximum (59%) in plants growing in nonfumigated soil treated with solarization alone, solarization plus tarp coverage, or metalaxyl.

Colonization of VAM-inoculated pepper after 2 wk was 31% greater in nonfumigated soil treated with solarization plus tarp coverage than for any other treatment (Fig. 3). After 5 wk, colonization of VAM-inoculated pepper was maximum (63%) in nonfumigated soil treated with solarization with or without tarp coverage.

Percent VAM colonization of control plants (not inoculated) was 1–3% in fumigated soil and 3–16% in nonfumigated soil at all sample dates (Figs. 1–3).

Root length. In both fumigated and nonfumigated soil, root lengths of all three crops were maximum in soil that was solarized and covered with tarp (Table 1). In fumigated soil, solarization plus tarp coverage increased cotton root growth by 57% in VAM-inoculated plants and 40% in noninoculated plants compared with VAM-inoculated and noninoculated control plants. In nonfumigated soil, solarization plus tarp coverage increased cotton root growth 126% in VAM-inoculated plants and 204% in noninoculated plants compared with VAM-inoculated and noninoculated control plants.

In fumigated soil, solarization plus tarp coverage increased onion root growth 31% in VAM-inoculated plants and 27% in noninoculated plants compared with growth of VAM-inoculated and noninoculated control plants. In nonfumigated soil, solarization plus tarp coverage increased onion root growth 155% in VAM-inoculated plants and 175% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants. Also in nonfumigated soil, solarization alone increased onion root growth 45% in VAM-inoculated plants and 125% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants. In nonfumigated soil, metalaxyl increased onion root growth 70% in VAM-inoculated plants and 93% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants.

In fumigated soil, solarization plus tarp coverage increased pepper root growth 91% in VAM-inoculated plants and 50% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants. In nonfumigated soil, solarization plus tarp coverage increased pepper root growth by 185% in VAM-inoculated plants and 104% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants. Also in nonfumigated soil, solarization alone increased pepper root growth by 90% in VAM-inoculated plants and 52% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants. In nonfumigated soil, metalaxyl increased pepper root growth by 128% in VAM-inoculated plants and 64% in noninoculated plants compared with growth in VAM-inoculated and noninoculated control plants.

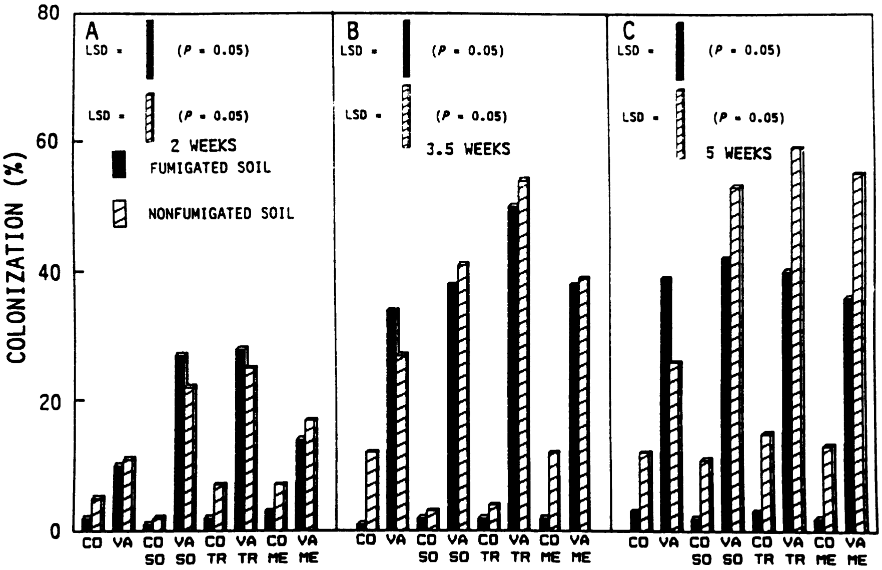

Fig. 2. Percent mycorrhizal colonization of onion plants (**A**) 2, (**B**) 3.5, and (**C**) 5 wk after planting and one of the following treatments: noninoculated control (CO); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VA); CO + soil solarization (SO); VA + SO; CO + SO with tarp coverage for 2 wk (TR); VA + TR; CO + metalaxyl (ME); and VA + ME.

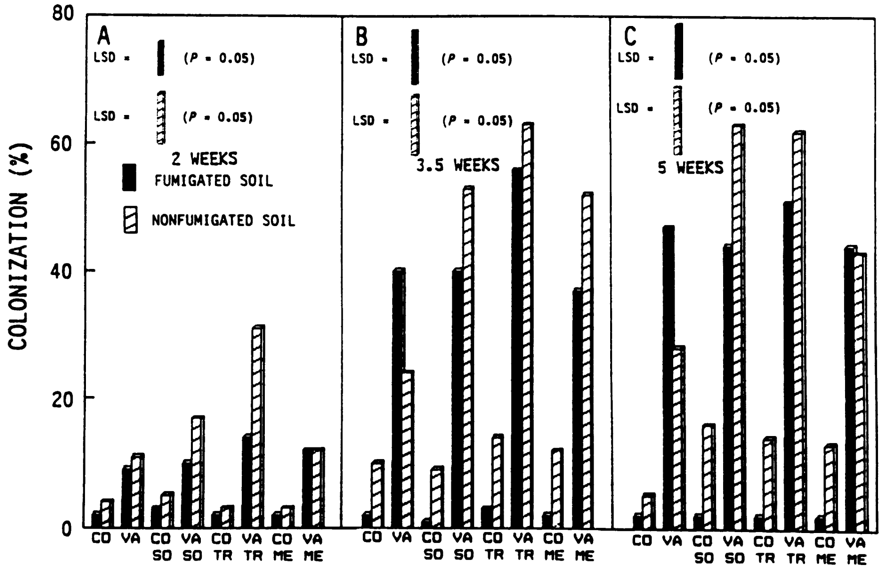

Fig. 3. Percent mycorrhizal colonization of pepper plants (**A**) 2, (**B**) 3.5, and (**C**) 5 wk after planting and one of the following treatments: noninoculated control (CO); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VA); CO + soil solarization (SO); VA + SO; CO + SO with tarp coverage for 2 wk (TR); VA + TR; CO + metalaxyl (ME); and VA + ME.

Crop yield. VAM inoculation increased the fresh weight of cotton plants by 58% in nonfumigated soil and by 345% in fumigated soil (Fig. 4). In nonfumigated soil, VAM plus solarization increased the fresh weight of cotton 81% over that of the noninoculated control and 87% over that of solarization without VAM inoculation. In nonfumigated soil, the VAM plus solarization plus tarp treatment increased the fresh weight of cotton by 118% over that of the untreated control and by 165% over that of the solarization plus tarp treatment without VAM inoculation.

In nonfumigated soil, the VAM plus metalaxyl treatment increased the fresh weight of cotton by 103% over that of the untreated control and by 58% over that of the metalaxyl treatment without VAM inoculation. In fumigated soil, the VAM plus metalaxyl treatment increased the fresh weight of cotton by 520% over that of the untreated control and by 1,100% over that of the metalaxyl treatment without VAM inoculation. In fumigated soil, fresh weight of cotton was greater by 859 and 837%, respectively, with VAM inoculation plus solarization and solarization plus tarp coverage than with the same treatments without VAM inoculation. Fresh weight of cotton plants inoculated with VAM in nonfumigated soil was more than double that of inoculated plants in fumigated soil.

In the control without VAM inoculation, fresh weight of plants in nonfumigated soil was about 10 times greater than that of control plants in fumigated soil. The best cotton yields in fumigated and nonfumigated soil were achieved with VAM and solarization, solarization plus tarp coverage, and metalaxyl treatments (Fig. 4).

The number of cotton bolls was clearly related to fresh weight of plants. The number of bolls on VAM-inoculated cotton plants in nonfumigated soil was 1.8–2.8 times higher than that in fumigated soil. Boll yields per plant were highest—78, 80, and 66, respectively—after VAM inoculation in metalaxyl, solarization plus tarp coverage, and solarization treatments.

Fresh weight of VAM-inoculated onion plants in fumigated soil was greater than that of the same treatment in nonfumigated soil. In nonfumigated soil, however, fresh weight of onion plants was greater after soil solarization, either with or without tarp coverage, than after all other treatments. In fumigated soil, no significant differences in onion fresh weight were observed among treatments. VAM inoculation increased the fresh weight of onion plants by 57% in nonfumigated soil and by 417% in fumigated soil. In nonfumigated soil, VAM plus solarization increased the fresh weight of onion by 177% over the noninoculated control and by 163% over solarization without VAM inoculation. In nonfumigated soil, the VAM plus solarization plus tarp treatment increased the fresh weight of onion by 200% over that of the untreated control and by 68% over that of the solarization plus tarp treatment without VAM inoculation.

Table 1. Total root lengths of cotton, onion, and pepper inoculated or not inoculated with the vesicular-arbuscular mycorrhizal (VAM) fungus *Glomus intraradices* 3.5 wk after planting in the field

	Root length (cm)^z		
Treatments	Cotton	Onion	Pepper
Fumigated soil			
Control (not inoculated)	94	33	55
VAM	80	29	49
Control + soil solarization	98	27	47
VAM + soil solarization	107	30	40
Control + soil solarization + tarp coverage for 2 wk	131	42	83
VAM + soil solarization + tarp coverage for 2 wk	126	38	94
Control + metalaxyl	93	34	50
VAM + metalaxyl	86	29	43
LSD (*P* = 0.05)	19	7	10
Nonfumigated soil			
Control (not inoculated)	60	16	25
VAM	49	20	21
Control + soil solarization	98	36	38
VAM + soil solarization	87	29	40
Control + soil solarization + tarp coverage for 2 wk	136	44	51
VAM + soil solarization + tarp coverage for 2 wk	149	51	60
Control + metalaxyl	99	31	41
VAM + metalaxyl	108	34	48
LSD (*P* = 0.05)	23	8	13

^{z}Each number is the average of four replicates.

In nonfumigated soil, VAM plus metalaxyl increased the fresh weight of onion by 140% over that of the untreated control and by 126% over that of metalaxyl without VAM inoculation. In fumigated soil, VAM plus metalaxyl increased the fresh weight of onion by 390% over that of the untreated control and by 550% over that of metalaxyl without VAM inoculation. In fumigated soil, onion fresh weight was greater by 716 and 626%, respectively, with VAM inoculum plus solarization and solarization plus tarp coverage than that with the same treatments without VAM inoculum (Fig. 5).

Fresh weight of VAM-inoculated pepper plants increased by 84% in nonfumigated soil and by 269% in fumigated soil. In nonfumigated soil, VAM plus solarization increased the fresh weight of pepper by 100% over that of the noninoculated control and by 76% over that of solarization without VAM inoculation. In nonfumigated soil, VAM plus solarization plus tarp coverage increased the fresh weight of pepper by 134% over that of the untreated control and by 81% over that of solarization plus tarp without VAM inoculation.

In nonfumigated soil, VAM plus metalaxyl increased the fresh weight of pepper by 96% over that of the untreated control and by 52% over that of metalaxyl without VAM inoculation. In fumigated soil, VAM plus metalaxyl increased the fresh weight of pepper by 380% over that of the untreated control and by 236% over that of metalaxyl without VAM. In fumigated soil, pepper fresh weight was greater by 258 and 400%, respectively, with VAM inoculum plus solarization and solarization plus tarp coverage than that with the same treatments without VAM inoculum (Fig. 6).

Pepper fruit weight was clearly related to fresh weight of plants. Fresh weight and fruit weight of VAM-inoculated plants were 1.5–2 and 1.3–2 times greater, respectively, in nonfumigated soil than in fumigated soil. In both fumigated and nonfumigated soil, fresh weight and fruit weight were greatest after soil solarization and soil solarization plus tarp coverage. Fresh weight and fruit weight of controls (not inoculated) were 3–5 and 2–2.8 times greater in nonfumigated soil than in fumigated soil.

Soil populations of *P. ultimum*. Fumigated soil contained one to three propagules per gram, with no significant differences among treatments. Nonfumigated soil contained 135 propagules per gram; nonfumigated solarized soil plus tarp coverage, 21 propagules; nonfumigated solarized soil, 26 propagules; and nonfumigated soil plus metalaxyl, 11 propagules. Each number is the average of four replicates; LSD

($P = 0.05$) was 7.

Correlation coefficients. No correlation was found between root lengths and percent colonization by VAM in any of the crops. However, all weights and yields of the plants were positively correlated with percent colonization by VAM at 5 wk. In fumigated soil these were: cotton plant fresh weight $r^2 = 0.898$, $P < 0.01$; cotton plant boll number $r^2 = 0.822$, $P < 0.05$; onion plant fresh weight $r^2 = 0.928$, $P < 0.01$; pepper plant fresh weight $r^2 = 0.950$, $P < 0.001$; and pepper plant fruit weight $r^2 = 0.834$, $P < 0.05$. In nonfumigated soil these were: cotton plant fresh weight $r^2 = 0.918$, $P < 0.01$; cotton plant boll number $r^2 = 0.846$, $P < 0.01$; onion plant fresh weight $r^2 = 0.900$, $P < 0.01$; pepper plant fresh weight $r^2 = 0.872$, $P < 0.01$; and pepper plant fruit weight $r^2 = 0.941$, $P < 0.001$.

DISCUSSION

To date, experiments that have been most successful in increasing percent root colonization by VAM and weight and yield of crop plants have been performed in fumigated or sterilized soil (19,33,44). In this study, we attempted to use new approaches, such as soil solarization, that can replace, or at least reduce, fumigants in the soil and allow high levels of VAM colonization of plants.

Many experiments have indicated the potential of soil solarization in the reduction of pathogen (and other pest) populations, in disease and weed control, and in yield increase (1,21,23,24,27). However, none of the studies addressed the effect of soil solarization on VAM colonization of roots or the effect of combined VAM application and soil solarization on growth response and yield of plants. Our results show that soil solarization does not damage native VAM fungi, whereas fumigation with methyl bromide does (Figs. 1–3). Other studies (9,14,29,31), as well as our study, show that indigenous VAM fungi are very important for growth response and yield of plants (Figs. 4–6). Several researchers reported that failure of plants to become colonized by VAM fungi in natural soil is due to microorganisms that compete with mycorrhizal fungi on the root and interfere with mycorrhizal development (5,34,45). Similarly, our research suggests that control or elimination of microorganisms that can compete or interfere with mycorrhizal development improves VAM colonization, growth response, and yield of crops. Our results show that VAM colonization of roots of inoculated plants 3.5 and 5 wk after planting is greater in fumigated than in nonfumigated soil (Figs. 1–3). This situation was reversed, however, and VAM colonization of plant roots was greater in nonfumigated but solarized soil than in fumigated soil, probably because solarization controlled deleterious microorganisms (Figs. 1–3).

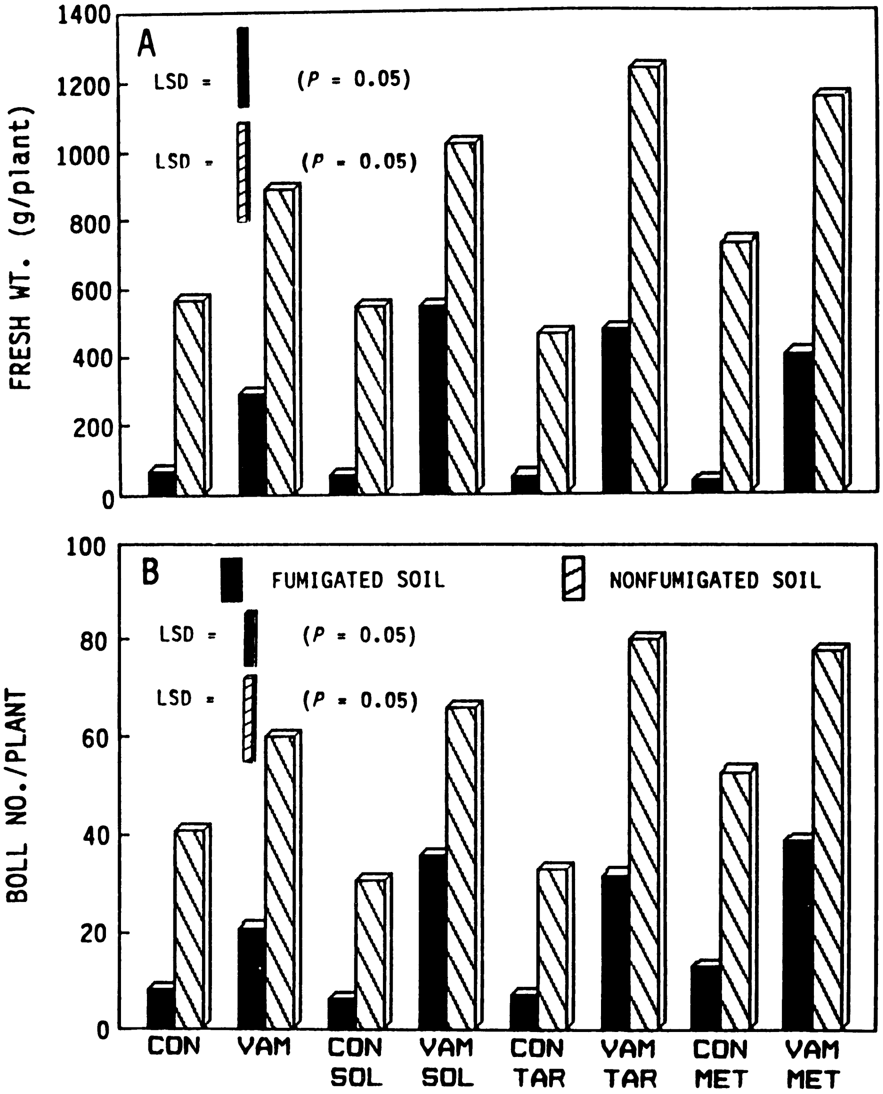

Fig. 4. (**A**) Fresh weight per plant and (**B**) number of bolls per plant of cotton harvested 4 mo after planting and one of the following treatments: noninoculated control (CON); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VAM); CON + soil solarization (SOL); VAM + SOL; CON + SOL with tarp coverage for 2 wk (TAR); VAM + TAR; CON + metalaxyl (MET); and VAM + MET.

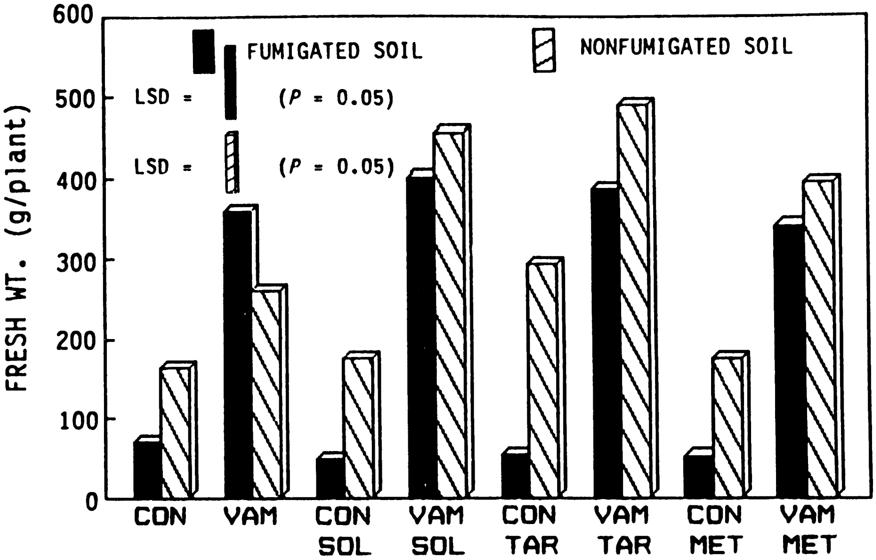

Fig. 5. Fresh weight per plant of onion harvested 4 mo after planting and one of the following treatments: noninoculated control (CON); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VAM); CON + soil solarization (SOL); VAM + SOL; CON + SOL with tarp coverage for 2 wk (TAR); VAM + TAR; CON + metalaxyl (MET); and VAM + MET.

In a previous study (3), we reported that root colonization by VAM fungi increased in nonfumigated soil treated with metalaxyl, apparently because *P. ultimum* was controlled by the fungicide. The results of our present field study are similar (Figs. 1-3). Other researchers reported that metalaxyl improved VAM colonization of roots (18,32,37) and that *Pythium* spp. reduced VAM colonization of roots (3,22). Cook et al (11) reported that soil solarization reduced the soil population of *Pythium* spp. by 80-90% and increased growth response of wheat (*Triticum aestivum* L.). Therefore, reduction of the *P. ultimium* population in solarized soil, as described in our study, may also increase VAM colonization of the plants. Our study also demonstrated that soil solarization and metalaxyl improved VAM colonization of cotton, onion, and pepper more in nonfumigated soil than in fumigated soil. This indicates that the increase in VAM colonization of plants may not result only from control of deleterious microorganisms (3,17,45) but that soil fumigation may kill beneficial microorganisms, such as bacteria and actinomycetes, that can improve colonization by VAM (6-8,12,36). Because metalaxyl acts against *P. ultimum* and not against beneficial microorganisms, VAM colonization of root crops was greater in nonfumigated soil.

Katan (24) suggested that soil solarization, in addition to controlling pathogens in the soil, may increase the number of beneficial microorganisms in the soil. Solarized soils undergo significant changes in temperature, moisture, physical structure, and the inorganic and organic composition of their solid, liquid, and gaseous phases, all of which in turn affect the biotic and abiotic components (24,39,48). Such changes may explain why in fumigated soil, where most microorganisms were already controlled, percent colonization of cotton and onion by VAM increased after soil solarization (Figs. 1 and 2). High temperature can also enhance colonization by VAM (15,16). Heating the soil, especially during the first 2 wk after planting, which is a critical period for establishment of VAM in annual crops (2,46), increased colonization by VAM in our study (Figs. 1-3). Heating the soil after planting, even by 3-4 C in the upper 20 cm, may increase colonization by VAM by enhancing root growth response, root exudation, and germination of VAM spores, all of which can improve VAM colonization of plants (15,16). Our results indicated that higher levels of root colonization by VAM fungi in the crops 5 wk after planting led to greater weight and yield 4 mo after planting (Figs. 4-6) and that these factors were clearly correlated.

This study leads to the conclusion that vesicular-arbuscular mycorrhizae combined with soil solarization can be one of the best approaches to replace, or at least reduce, the use of chemicals in agriculture. We believe that the future for mycorrhizae as a biofertilizer lies not in fumigated soil but in nonfumigated soil, especially now when growers approach a crisis because of pesticide and toxic chemicals found in food, water, and the environment.

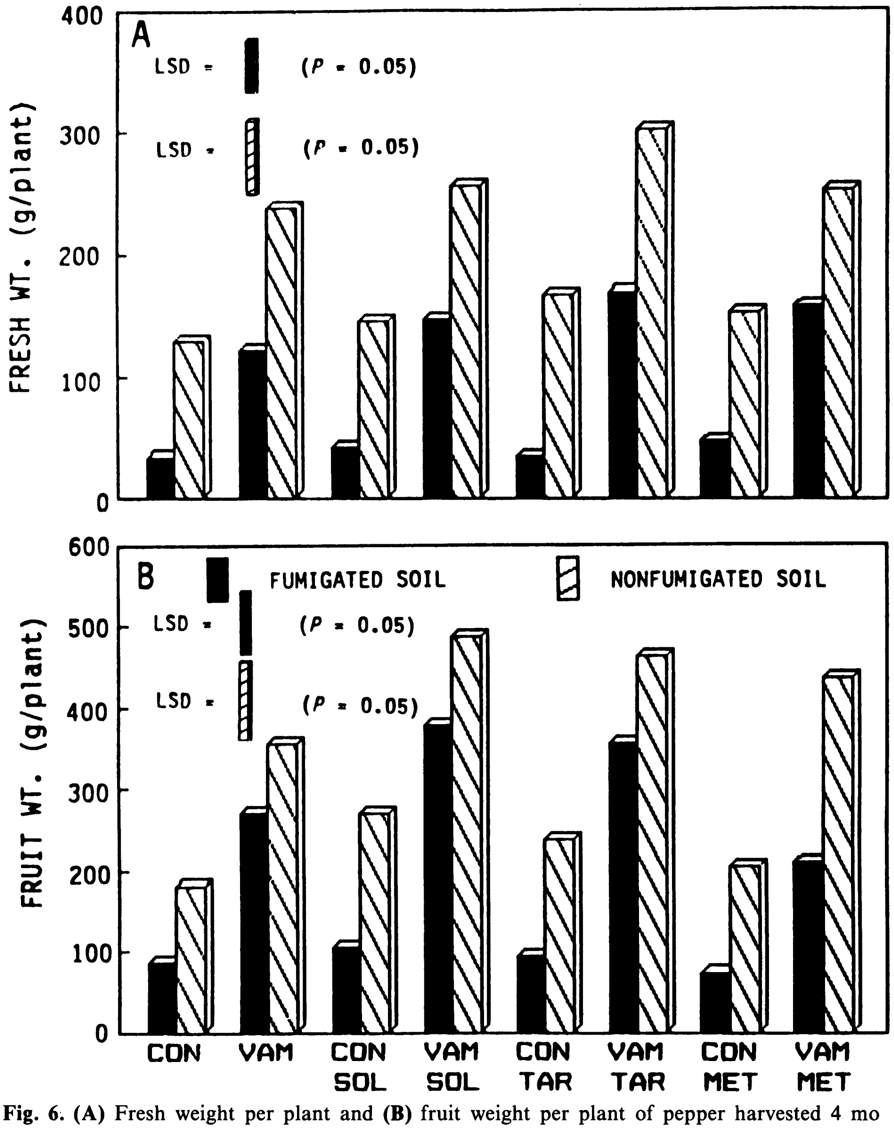

Fig. 6. (**A**) Fresh weight per plant and (**B**) fruit weight per plant of pepper harvested 4 mo after planting and one of the following treatments: noninoculated control (CON); inoculation with the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices* (VAM); CON + soil solarization (SOL); VAM + SOL; CON + SOL with tarp coverage for 2 wk (TAR); VAM + TAR; CON + metalaxyl (MET); and VAM + MET.

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