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Soil nutrient and plant responses to solarization in an agroecosystem utilizing an organic nutrient source

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Abstract

Soil solarization is used to manage nematodes, pathogens and weeds, but relatively few studies have examined solarization effects on soil mineral nutrients, soil properties and plant tissue nutrients. This study was designed to optimize the duration of solarization treatment for the management of soil and plant nutrients and crop biomass in an agroecosystem utilizing an organic nutrient source. The experiment was a split-plot with treatment duration as the main effect and solarization as the sub-effect. Solarization treatments of 2-, 4- and 6-week durations began on sequential dates and concluded in mid-August. Immediately post-treatment, okra (*Hibiscus esculentus* L.) seedlings were transplanted into subplots for tissue nutrient analysis. Freshly chopped cowpea [*Vigna unguiculata* (L.) Walp.] hay was applied to the soil surface directly around the okra seedlings as an organic nutrient source. Immediately following solarization treatment, concentrations of soil K and Mn were higher, while Cu and Zn concentrations were lower in solarized soils than in non-solarized soils. Soil pH was slightly lower in solarized plots. Concentrations of K, N, Mg and Mn in okra leaf tissue were higher in solarized plots than in non-solarized plots, but concentrations of P and Zn were lower in plants grown in solarized soil. Okra biomass was three and four times higher in the 4- and 6-week solarization treatments than in non-solarized treatments. Based on data from this experiment, 4- and 6-week durations of solarization were optimal for increasing crop biomass. The data indicate that solarization has significant effects on soil and plant nutrients. Results of the nutrient analyses suggest that the availability of nutrients from an organic source was not limited by solarization.

Key words: nutrient availability, organic agriculture, soil fertility, soil solarization, sustainable agriculture

Introduction

Soil solarization is the passive solar heating of soil under clear plastic mulch to reach high temperatures lethal to soil-borne pests[1]. Soil solarization has been used to successfully manage soil-borne pests including fungal and bacterial pathogens, nematodes and weeds[2–5]. Use of solarization has increased crop yields at sites with various pest problems[1–4]. Solarization may cause an increased growth response in plants not only due to reductions in soil pathogens but also due to changes in chemical or physical properties of the soil[6,7], including increased availability of mineral nutrients[1,8]. However, in one recent study, no differences were found in macronutrient concentrations between solarized and non-solarized soil[9].

Studies on solarization effects on soil properties and soil mineral nutrients have shown mixed results. In one study, concentrations of Ca, K, Na and Mg, and soil electrical conductivity increased consistently after solarization, while pH and P concentration remained the same or changed inconsistently[6]. In this same study, large increases in the concentrations of NO_3^- and NH_4^+ occurred, which may have been the result of increased mineralization of organic matter in the soil[6]. A follow-up study found twice as much mineralized organic matter in solarized soils as in untreated soils[10]. Stapleton et al.[7] found similar increases in NO_3^-, NH_4^+, Ca and Mg concentrations with solarization in four soil types in California[7]. Contrary to the findings of Chen and Katan[6], Stapleton et al.[7] found an increase in P concentration, no change in K concentration and inconsistent results with electrical conductivity. A more recent study[8] confirmed the previously published increases in soil concentrations of K, Ca and Mg, and also found lower pH in solarized soil. Discrepancies among studies are possibly due to differences in soil types, sampling depth and assay procedures[7].

Studies examining the effects of solarization on soil chemistry and physical properties have included an examination of these effects on plant nutrition. Tomato (*Lycopersicon esculentum* Mill.) seedlings grown in solutions from solarized and non-solarized soils and in pure water increased in height, leaf length and whole plant dry weight when grown in solution from solarized soil[6]. In another study, a 33% increase in fresh weights of Chinese cabbage (*Brassica rapa* L. 'Lei Choi') was observed in solarized versus untreated soil, with a further increase of 28% if solarized treatments were fertilized[7]. The authors concluded that the increases in plant growth may be attributed to a combination of pathogen reduction, increases in available soil nutrients and other ecological factors caused by solarization[7]. Another study found an increase in the concentrations of N and Cu in leaf tissue of tomato plants grown in solarized soil and a positive correlation between leaf dry weight and leaf concentrations of N, K and Cu[8]. Stapleton et al.[7] also included plant tissue analysis but there were no consistent differences in leaf tissue nutrient concentrations among treatments. This inconsistency could be a classical example of yield increases without changes in mineral nutrient concentration, a phenomenon that occurs because, as mineral nutrients become available from the mineralization of soil organic matter, nutrient concentrations are diluted within the increased plant biomass.

The objective of our research was to examine solarization effects on soil mineral nutrients, properties and crop health. It was also designed to include an examination of solarization effects on plant tissue nutrients. An additional objective was to determine the effects of solarization on plant nutrition in a system that utilized an organic nutrient source.

Materials and Methods

The experimental site was located at the University of Florida Plant Science Research and Education Unit (PSREU) near Citra, Florida, and the study was conducted during summer of 2003. The soil at the study site was a hyperthermic, uncoated typic Quartzipsamments of the Candler series with a 0–5% slope[11]. Measured soil texture was 95% sand, 2% silt and 3% clay. Measured soil pH prior to the experiment ranged from 5.5 to 6.0 with an average of 5.9. The field was prepared with a crimson clover (*Trifolium incarnatum* L. 'Dixie') cover crop during the winter season and disked 2 days before raised beds were constructed.

The experiment was a split-plot design in which the main effect was duration of treatment and the sub-effect was solarization. Five replicates were arranged in a randomized complete block design on the main effect. Each experimental plot was a raised bed 6 m long, 1 m wide and 20 cm high. The bed soil was moistened by overhead irrigation if it was not sufficiently moist before plastic application. The solarization treatment was installed using a single layer of clear, 25-μm-thick, UV-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC). Solarization treatments and non-solarization control (without plastic) treatments of 2, 4 and 6 week durations were conducted during July and August. The treatments began on sequential dates and concluded on 12 August 2003.

Soil sampling and analysis

Six soil cores, 2.5 cm in diameter and 15 cm deep, were collected from each plot immediately after the conclusion of solarization treatment (0 days post-treatment). The samples were air-dried and sieved through a 2-mm stainless steel screen. Nitrogen concentration was determined from soil samples using a modified micro-Kjeldahl procedure[12] and further modified by treating a 2-g soil sample using a 380°C digestion in a mixture of concentrated H_2SO_4, H_2O_2 and $K_2SO_4 : CuSO_4$ salt-catalyst mixture[13,14]. Soil nutrients were extracted by the double-acid procedure[15]. Soil Ca, Mg, Cu, Fe, Mn and Zn were determined by atomic absorption spectrometry, soil K by atomic emission spectrometry and soil P by colorimetry. Soil pH was measured at a 2 : 1 water to soil ratio using a glass electrode[16]. Mechanical analysis was used to determine percent sand, silt and clay using a soil hydrometer method[17,18]. Organic matter content ($g\,kg^{-1}$) was determined using the Walkley–Black method[19,20]. Cation exchange capacity (CEC) was determined by the summation method of relevant cations[21,22].

Crop management and nutrient analysis

Okra (*Hibiscus esculentus* L. 'Clemson spineless') seeds were planted and germinated in a growth room, then moved to a greenhouse for maturation. Seedlings were watered and fertilized with a 20 : 20 : 20 ($N : P_2O_5 : K_2O$) mix as needed for 5 weeks. One week after the conclusion of solarization treatments, 5-week-old okra seedlings were planted in the experimental plots. An organic fertilizer consisting of green cowpea [*Vigna unguiculata* (L.) Walp. 'Iron Clay'] hay was applied on the soil surface to the area immediately around the okra seedlings at a rate of $3.5\,kg\,m^{-2}$. The hay was obtained from a cowpea cover crop grown in an adjacent field, which was cut at the early bloom stage, and immediately applied to the plots. The cowpea tissue was analyzed for nutrient concentration from samples collected at the time of application. The okra plants were harvested 6 weeks after planting, at early flowering. Dry whole plant biomass was measured, and the youngest, fully expanded okra leaves were collected for nutrient analysis.

For the nutrient analysis of both okra (youngest, fully expanded leaves to make 0.5 g dried) and cowpea (chopped green hay), plant material was weighed, dried, reweighed and ground to pass a 2-mm stainless steel screen using a Wiley mill. Plant material was ashed in a muffle furnace at

Table 1. Extractable soil mineral nutrient concentrations from 2003 summer solarization experiment (0 days post-treatment).

	Soil nutrient concentrations (mg kg^{-1})											
Time[1]	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**
		-------------N-------------			-------------P-------------			-------------K-------------			----------Mg----------	
2 weeks	406	340 B[2]*	373	38.9	38.1	38.5	21.4 C	22.7	22.1	10.8	13.0	11.9
4 weeks	385	408 A	397	38.6	46.5	42.6	37.0 A	21.4*	24.2	11.8	9.0	10.4
6 weeks	381	406 A	394	40.3	47.6	44.0	30.6 B	26.9	28.8	14.5	15.8	15.2
Mean	391	385		39.3	44.1		26.4	23.7		12.4	12.6	
		----------Zn-------------			------------Cu-----------			-----------Mn-----------				
2 weeks	1.2	1.4	1.3	0.25	0.27 B*	0.26	2.1	2.0	2.0			
4 weeks	1.4	1.4	1.4	0.26	0.29 AB*	0.28	2.2	2.0	2.1			
6 weeks	1.3	1.5	1.4	0.24	0.31 A*	0.28	2.4	1.7	2.1			
Mean	1.3	1.5**		0.25	0.29		2.2	1.9*				

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.

[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter in a column indicates no significant differences.

* and ** indicate significant differences between solarized and non-solarized at $P < 0.05$ and 0.01, respectively. No symbol indicates no significant difference.

480°C for a minimum of 4 h and treated with HCl in preparation for nutrient analysis[13,14]. Nitrogen was determined using a method similar to that used for the soil samples, except that a 100-mg sample was used and boiling beads were added to the samples before being placed on the aluminum block digester[12–14]. Leaf tissue concentrations of Ca, Mg, Cu, Fe, Mn and Zn were determined by atomic absorption spectrometry, K by atomic emission spectrometry and P by colorimetry.

Statistical analysis

Okra biomass, okra leaf nutrient concentration and extractable soil nutrient data were compared among durations and between solarized and non-solarized treatments using analysis of variance (ANOVA). If significant differences were detected among duration treatments, means were separated using a least significant difference (LSD) test at the $\alpha = 0.05$ level. All data were analyzed using MSTAT-C software (Michigan State University, East Lansing, MI; 1989).

Results

Soil mineral nutrients

The concentrations of several soil mineral nutrients and soil properties responded to solarization treatment. However, no significant differences were found among any treatments for concentrations of P and Mg in soil (Table 1). Calcium and Fe were also monitored but were not affected by treatment either in soil or in plant tissue (data not shown). Across all plots, the concentration of soil Ca averaged 110.8 and Fe averaged 10.6. A significantly higher concentration of Mn was found in the soil of solarized treatments ($P < 0.05$, Table 1). Zinc concentration and organic matter (g kg^{-1}) were lower in solarized treatments, although not significantly ($P < 0.10$; Tables 1 and 2).

Significant interactions of solarization treatment × duration occurred with N, K, Cu and pH (Tables 1 and 2). Nitrogen was 19% higher in the 2-week solarized treatment compared to the 2-week non-solarized treatment and about 16% lower in the 2-week non-solarized compared to the 4- and the 6-week non-solarized treatments ($P < 0.05$). Potassium was 73% higher in the 4-week solarized treatment compared to the 4-week non-solarized treatment ($P < 0.05$). Among the treatments involving durations of solarization, K was highest in the 4-week treatment and lowest in the 2-week treatment ($P < 0.05$). Copper was lower ($P < 0.05$) in solarized treatments compared to non-solarized treatments regardless of duration, and Cu was higher in the 6-week non-solarized treatment than in the 2-week non-solarized treatment ($P < 0.05$). We found slightly lower pH in solarized plots of 2- and 6-week durations compared to non-solarized plots (Table 2). Soil pH was highest in the 6-week non-solarized treatment compared to the 2- and 4-week non-solarized treatments ($P < 0.05$). With the exception of K (Table 1), no mineral nutrients or soil properties were affected by the duration of solarization treatment.

Okra leaf tissue nutrients

Several okra leaf tissue nutrient concentrations (N, P, K, Mg, Na, Zn and Mn) changed with solarization treatment. Foliar N concentration was also higher in solarized treatments than in non-solarized ($P < 0.05$) and concentration decreased as duration of treatment increased ($P < 0.01$). The concentration of K in okra leaf tissue was 40% higher in solarized treatments compared to non-solarized treatments ($P < 0.01$; Table 3).

Table 2. Soil properties from 2003 summer solarization experiment (0 days post-treatment).

	Soil pH			**CEC (cmol kg^{-1})**			**Organic matter (g kg^{-1})**		
Time[1]	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**
2 weeks	5.2	5.3 B[2]*	5.3	2.7	2.5	2.6	10.5	11.0	0.7
4 weeks	5.3	5.3 B	5.3	2.6	2.6	2.6	10.6	12.2	11.4
6 weeks	5.3	5.6 A*	5.4	2.9	2.7	2.8	11.5	12.0	11.8
Mean	5.3	5.4		2.7	2.6*		10.9	11.7 +	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter indicates no significant difference.
+ and * indicate significant differences between solarized and non-solarized at $P < 0.10$ and < 0.05. No symbol indicates no significant difference.
CEC, cation exchange capacity.

Table 3. Okra leaf tissue nutrient concentrations at conclusion of 2003 summer solarization experiment (59 days post-treatment).

	Okra leaf nutrient concentrations								
Time[1]	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**	**Sol**	**Non**	**Mean**
	-------------N (g kg^{-1})-------------			------------P (g kg^{-1})-------------			---------K (g kg^{-1})-------------		
2 weeks	41.2	38.6	39.9 A[2]	4.3 AB	4.4 B	4.3	33.4	28.2	30.8
4 weeks	37.3	29.2	33.3 B	4.9 A	4.9 B	4.9	38.1	22.2	30.2
6 weeks	30.1	29.2	29.7 B	4.0 B	5.6 A*	4.8	33.4	24.3	28.9
Mean	36.2	32.3*		4.4	5.0		35.0	24.9**	
	---------Mg (g kg^{-1})---------			------------Zn (mg kg^{-1})-----------			----------Mn (mg kg^{-1})----------		
2 weeks	7.0	8.4	7.7	102	102	102	442	327	385
4 weeks	7.6	7.3	7.4	123	129	126	515	440	478
6 weeks	6.1	8.7*	7.4	99	139*	119	518	373	445
Mean	6.9	8.1		108	123		492	380*	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test. No letter indicates no significant difference.
* and ** indicate significant differences between solarized and non-solarized at $P < 0.05$ and 0.001, respectively. No symbol indicates no significant difference.

There were significant interactions between solarization duration and treatment for several foliar nutrients (Table 3). Phosphorus concentration was 29% lower in the 6-week solarized treatment compared to the 6-week non-solarized treatment. Among non-solarized treatment durations, the 6-week treatment was higher than the 2- and 4-week treatments ($P < 0.05$). Among solarized treatments, P was higher in the 4-week treatment than in the 6-week treatment ($P < 0.05$). Magnesium was 30% lower in 6-week solarized treatments compared to 6-week non-solarized treatments ($P < 0.05$).

Of the micronutrients that showed significant changes in leaf tissue, the concentration of Zn showed a similar pattern to P and Mg and was 29% lower in the 6-week solarized treatment than in the 6-week non-solarized treatment ($P < 0.05$). The concentration of Mn in leaf tissue was 29% higher in solarized treatments than non-solarized treatments ($P < 0.05$). Further analysis indicated that soil Mn concentration and leaf tissue Mn concentration were highly correlated ($r = 0.587$, $P < 0.01$).

Okra biomass

Dry whole plant biomass of the okra crop was more than three times higher in the 4-week solarized treatment and four times higher in the 6-week solarized treatment compared to the non-solarized treatments of the same duration ($P < 0.01$; Table 4). Okra biomass was 67% lower in the 6-week non-solarized compared to the 2-week non-solarized treatment ($P < 0.05$).

Discussion

Solarization affected the chemistry and properties of the soil in treatment areas. Extractable N was higher in 2-week solarized soil. The concentration of K was higher in the 4-week solarized soil compared to non-solarized soil. The occurrence of a maximum level of K in 4-week solarized soil among the three solarization treatment durations was interesting and somewhat unexpected. Activity of many soil micro-organisms increases with temperature[23], so we

Table 4. Dry okra biomass at conclusion of summer solarization experiment (56 days post-treatment).

	Dry weight of okra biomass (g plot^{-1})		
Time[1]	Sol	Non	Mean
2 weeks	181.0	161.8 A[2]	171.4
4 weeks	247.4	81.6 AB**	164.5
6 weeks	221.1	54.1 B***	137.6
Mean	216.5	99.2	

[1] Time = duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.

[2] Means in columns followed by the same letter do not differ at $P < 0.05$ according to the LSD test; no letter in a column indicates no differences at $P < 0.05$.

** and *** indicate significant differences between solarized and non-solarized at $P < 0.01$ and 0.001, respectively.

may expect more decomposition of the cowpea hay and therefore more release of K as the duration of solarization increases. Therefore the lowest level of K in 2-week solarized soil would be expected, but the decrease in 6-week solarized soil was not. Potassium is a highly leachable nutrient[24], and therefore would be subject to loss once it is mineralized from the organic hay. Because the 6-week solarization was started 2 weeks earlier than the 4-week solarization (in order to synchronize the okra planting date), the substantial amounts of K mineralized during the initial several weeks of solarization would have occurred 2 weeks earlier in the 6-week solarization treatment. If a significant rainfall event occurred during this time, it is possible that some of the mineralized K was leached. Leaching may be limited because the beds were covered with clear plastic; however, the soil beneath may become saturated during a heavy rainfall event, which may allow for some leaching to occur. Manganese concentration was higher in solarized soil in general. We also saw a lower concentration of Cu with solarization treatment, a finding that is consistent with earlier research[7]. Zinc decreased with solarization as well. We found consistently lower pH in solarized soils compared to non-solarized soils, which confirms earlier research[8]. These differences in soil pH between treatments were small however (maximum difference was only 0.3; Table 2), and may not be biologically important.

Some prior solarization research examining plant tissue found no significant differences in nutrient concentrations, which was likely due to a mineral dilution effect[7], while others found an increase in K, N, Ca and Mg[8]. In the current experiment, K concentration in leaf tissue increased with solarization treatment. This increase likely reflected the quick mineralization of soil organic matter and luxury consumption of K above that required for plant growth[25]. Leaf tissue concentrations of N and Mn increased in solarized treatments, while Mg, P and Zn decreased. Because the sum of the total cations (K, Ca and Mg especially) on an equivalent basis tends to remain constant in plant leaf concentration, an increase in plant absorption of K will result in a decrease in Mg even when sufficient soil Mg is available[26,27].

The increase in N and Mn in leaf tissue may reflect the increase of these nutrients in solarized soil from the cowpea hay, and may also be considered an indication of overall plant health. Solarization affects a wide range of organisms in the soil[1] and an increase in amino acid synthesis following solarization, which may suggest an increase in microbial activity, has been observed[10]. Data from the current study suggest that solarization did not harm organisms involved in nutrient cycling sufficiently to impair nutrient release and uptake from an organic nutrient source.

Okra biomass tripled in the 4-week solarized treatment and quadrupled in the 6-week solarization treatment compared to the non-solarized treatments of the same duration. The increase in okra biomass in 4- and 6-week solarized treatments is in part due to a decrease in weed competition by solarization[28] and a reflection of overall plant health. The higher concentrations of N and K in leaf tissue indicate that solarization increases the uptake of these essential nutrients in biomass production, even in agroecosystems utilizing an organic nutrient source. Since crop yield of okra is closely related to plant biomass[29], solarization treatments would increase okra yield if the plants had been maintained through harvest. The data suggest that solarization durations of 4 and 6 weeks are equally effective and significantly better in increasing crop biomass than the 2-week solarization treatment.

Conclusions

In general, the changes in soil mineral nutrients were reflected in changes in leaf tissue nutrients, particularly N, K, Mn and Zn. Overall, concentrations of some essential nutrients, including N, K and Mn, were higher with solarization treatment. This increase in nutrients was reflected in the leaf tissue analysis and increased biomass that indicated an improvement in crop health due to solarization. The increase in okra biomass in solarization treatments of 4- and 6-week durations indicates that okra plants utilized the increased nutrients available and that solarization did not limit the nutrient availability from an organic nutrient source. This study also indicates an increased growth response that may involve changing soil chemical and physical properties, which adds to the benefits of using solarization for soil-borne pest management.

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