ECOLOGICAL EFFECTS OF SOLARIZATION DURATION ON WEEDS, MICROARTHROPODS, NEMATODES, AND SOIL AND PLANT NUTRIENTS

By

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This manuscript is dedicated to Maya R. Seman-Varner, whose presence in my life has reinforced the necessity of working for a sustainable future.

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Soil solarization is an alternative to environmentally harmful soil fumigants. This study was designed to optimize the duration of solarization treatment for the management of various species and crop nutrients in an agroecosystem utilizing an organic nutrient source in North Florida. Field studies were conducted during July and August of 2003 and 2004. The experiment was designed as a split-plot with duration as the main effect and solarization as the subeffect. Five replicates were arranged in a randomized complete block design on the main effect. Solarization treatments of 2-, 4-, and 6-week durations began on sequential dates and concluded in mid August both years. Immediately post-treatment, okra seedlings were transplanted into a 2-m^2 subplot for tissue nutrient analysis at final harvest. Freshly chopped cowpea hay was applied to the soil surface directly around the okra seedlings.

The effects of solarization on several groups of organisms were studied. Nematodes and soil microarthropods were collected from composited soil samples from a 2-m^2

subplot. Nematodes were extracted from soil using a modified sieving and centrifugation technique. Mesofauna were extracted using a modified Berlese funnel. Weed cover, density, and individual weed density were determined from 1-m^2 subplots. Weed biomass was measured from 0.25-m^2 subplots within 1-m^2 subplots at final harvest. Soil nutrients and properties, and okra leaf tissue nutrients were determined using standard laboratory methods. Okra biomass was measured at the conclusion of the experiment.

Although the population of nematodes was relatively low at the beginning of the experiment, solarization delayed nematode recolonization. Collembola and mites were reduced by solarization and the rate of recolonization was also reduced, up to 2 months after treatment. Weed cover and density were reduced by solarization, but density of particular species responded differently to treatment. Weed biomass was reduced by 90% in solarized treatments at final harvest compared to non-solarized treatments. Concentrations of soil Mn and K increased with solarization, which may have caused the increase in leaf tissue Mn and K concentration. Overall, there were stronger relationships between soil nutrients and leaf tissue nutrients in solarized treatments than in non-solarized treatments.

Based on data from this experiment, 4- and 6- week durations of solarization were optimal for managing weed density and increasing crop biomass. Availability of nutrients from an organic source was not limited by decreases in soil fauna due to solarization, which may suggest the importance and recovery of fungal and bacterial detritivores. With continued research, solarization can be optimized to manage a variety of specific organisms or plant nutrients and applied as an effective, environmentally-sound alternative to soil fumigants.

CHAPTER 1
INTRODUCTION TO SOIL SOLARIZATION

Environmental concerns have led to recent restrictions on soil fumigants including methyl bromide. Although fumigants like methyl bromide effectively control soil-borne pests with low initial costs, the cost of ozone depletion caused by these fumigants is much higher than the investment in alternative methods (Thomas, 1996). Restrictions on fumigants and environmental concerns have increased research emphasis on non-chemical methods of soil disinfestation. Modern soil solarization, a non-chemical disinfestation technique, developed in the 1970s and expanded to 38 countries by 1990 (Katan and DeVay, 1991). Within the last quarter century, soil solarization has been one of the most researched non-chemical methods of soil-borne pest management and has been used in the successful management of fungal and bacterial pathogens (Katan, 1987; Davis, 1991; Shlevin et al., 2004), nematodes (Stapleton and Heald, 1991; McSorley, 1998), insects (Ghini et al., 1993), and weeds (Standifer et al., 1984; Elmore, 1991; Patterson 1998).

Soil solarization involves the application of thin (25-30μm), clear polyethylene or polyvinyl chloride plastic that transmits solar radiation to heat the underlying soil that subsequently kills soil-borne pests (Katan, 1981; Katan and DeVay, 1991; McGovern and McSorley, 1997). During solarization treatments, the upper 30 cm of the soil is heated to temperatures usually within the range of 30 to 60°C, depending on soil type, soil moisture, climate, and treatment enhancements (Katan, 1981). Over the course of treatment, generally 4 to 8 weeks, the soil is diurnally heated with temperatures highest at

shallower depths and peaking in the afternoon. The cyclical heating of the soil results in lethal temperatures sustained long enough to manage a variety of pests.

Specific methods to increase the effectiveness of solarization have been defined (Stapleton, 2000). Orienting solarization beds in a north-south direction may increase effectiveness of solarization by increasing intensity of heating in the bed shoulders (McGovern et al., 2004). A double layer of solarization plastic has been used to increase control of certain pest organisms, such as grasses, fungal pathogens such as *Rhizoctonia* spp. and *Pythium* spp., and some root-knot nematodes (*Meloidogyne* spp.) (Ben-Yephet et al., 1987; McGovern et al., 2002). Increased soil moisture before plastic application has increased the conduction of heat and the sensitivity of pest organisms (Katan, 1981). Amendments including compost, crop residues, and animal manures may also increase the effects of solarization (Gamiel and Stapleton, 1993; McSorley and McGovern, 2000; Coelho, 2001). Once the plastic is removed, the soil is disinfested and ready for planting.

Some of the earliest solarization research examined several species of fungal and bacterial pathogens. *Verticillium dahliae* Kleb., a fungal pathogen, was controlled by solarization even at lower temperatures (< 37°C) and greater soil depths (up to 70 to 120 cm; Pullman et al., 1981; Ashworth and Gaona, 1982; Davis and Sorensen, 1986). Common scab, (*Streptomyces scabies* (Thaxter) Lambert and Loria)) a bacterial pathogen, was also suppressed by solarization (Davis and Sorensen, 1986). Extensive empirical evidence found solarization effectively controlled many other pathogens including *Fusarium* spp., *Sclerotium* spp., *Phytophthora cinnamomi* Rands, *Pythium ultimum* Trow, *Agrobacterium tumefaciens* (Smith and Townsend) Conn (Katan, 1987; Davis, 1991).

Phytoparasitic nematodes are among the most studied organisms in solarization research. The management of many nematode genera by solarization has been successful, while some genera have proven more difficult to manage (Stapleton and Heald, 1991). Long-term control of nematodes by solarization has proven inconclusive, while short-term control has been successful in increasing crop yields, even under sub-optimal conditions (Overman, 1985). Several studies have incorporated additional management techniques with solarization that have increased the success of nematode management such as cover cropping, planting resistant cultivars, and using a double-layer of solarization plastic (Chellemi et al., 1993; McSorley, 1998; McSorley et al., 1999; McGovern et al., 2002).

Soil-borne arthropods have not been a focus of solarization research, but they warrant study because of their role in nutrient cycling and in the regulation of populations of other soil organisms. Ghini et al. (1993) found that solarization reduced microarthropods in plots solarized for 30 and 50 days. Studies on lethal temperatures in insects and mites have found that species are generally unable to complete their lifecycle if temperatures are elevated between 35 and 55ºC (Fields, 1992). A delicate balance exists between populations of soil microarthropods, which include nutrient-cyclers, phytoparasites, predators, and fungivores. Information on solarization and temperature effects on individual species can be applied when considering solarization effects on the ecology of the soil.

Weeds are often a major pest problem in areas where solarization is applicable, due to the optimal climate for both. Several studies have found suppressive effects of solarization on a variety of weed species including winter annuals (e.g. *Senecio* spp.,

Lamium amplexicaule L., *Poa annua* L.), summer annuals (e.g. *Cyperus* spp., *Eleusine indica* L. (Gaertn.), *Amaranthus* spp., *Chenopodium album* L.), and perennials (e.g. *Cynodon dactylon* (L.) Pers., *Convolvulus* spp., *Sorghum halepense* L. (Pers.); Elmore, 1991). Several mechanisms of weed control by solarization have been proposed. These mechanisms include direct thermal damage to seeds, germinating seeds, and shoots; morphological changes in shoots and other plant organs; breaking of dormancy and germination at greater depths; an imbalance of gases in soil; and indirect effects on soil microorganisms that might be seed pathogens (Rubin and Benjamin, 1984; Elmore, 1991; Chase et al., 1998).

Research has proven solarization to be an effective method for the management of a variety of pest species. Because solarization requires relatively clear skies, high temperatures, and a 4 to 8 week treatment period to be most effective, there are limitations on the regions where the method can be applied. Recent work has focused on the development of recyclable, reusable, or biodegradable plastics, which would minimize waste products of solarization (Stevens et al., 1991). Even with these limitations, solarization remains an effective and environmentally sound alternative to soil fumigants.

Solarization is of particular interest as an alternative to methyl bromide in organic agricultural production. However, many organic production systems utilize nutrients from organic sources such as green manures, plant residues, and compost, which may cause concern about the effects of solarization on nutrient cycling in this type of system. Nutrient release from organic sources requires decomposition of the material, primarily by bacteria and fungi, and subsequent mineralization for nutrient uptake by plants

(Powers and McSorley, 2000). Furthermore, the soil fauna is essential to accelerate the decomposition of organic matter. Mesofauna, which includes nematodes, collembolans, mites, and others, balance nutrients in the soil either directly through the decomposition of organic matter or indirectly by regulating populations of fungi, bacteria or other soil fauna (Coleman and Crossley, 1996; Larink, 1997). If solarization functions to sterilize the soil and damage populations of organisms responsible for decomposition and nutrient cycling, it is possible that the release of nutrients from an organic source could slow or stop.

This project was designed to answer several questions regarding the use and effects of solarization. The main objective was to examine the ecological effects of three durations of solarization treatment on populations of weeds, populations of soil fauna, soil chemistry, and crop nutrition. Additionally, the project was designed to test solarization effects on individual groups of arthropods, nematodes, and weeds, with the intention of recommending an optimal duration of treatment for specific target organisms. Finally, the experiment examined the effect of solarization on the availability of nutrients from an organic fertilizer source, for application in organic production systems.

CHAPTER 2
SOLARIZATION EFFECTS ON SOIL FAUNA IN AN AGROECOSYSTEM UTILIZING AN ORGANIC FERTILIZER SOURCE

Introduction

Soil solarization has been a successful, well-studied technique for the control of soil-borne pests (Katan, 1981; Davis, 1991; Elmore, 1991; Stapleton and Heald, 1991; McGovern and McSorley, 1997). Solarization has been shown to successfully manage bacterial and fungal pathogens (Hartz et al., 1993; Shlevin et al., 2004), weeds (Standifer et al., 1984; Patterson 1998), and nematodes (Chellemi et al., 1993; McSorley et al., 1999; McGovern et al., 2002). Some studies have defined specific methods that increase the effectiveness of solarization (Stapleton, 2000), including bed orientation (McGovern et al., 2004), solarization plastic structure (Ben-Yephet et al., 1987; McGovern et al., 2002), soil moisture, and amendments (Gamiel and Stapleton, 1993; McSorley and McGovern, 2000; Coelho, 2001).

Phytoparasitic nematodes are among the most studied organisms in solarization research. The management of many nematode genera by solarization has been successful, while some genera have proven more difficult to manage (Stapleton and Heald, 1991). Some ectoparasitic nematodes have been shown to move to greater soil depths but still were effectively controlled by solarization (Stapleton and DeVay, 1983; Stapleton and Heald, 1991). Long-term control of nematodes by solarization has proven inconclusive, while short-term control has been successful in increasing crop yields, even under sub-optimal conditions (Overman, 1985). Several studies have incorporated solarization with

other management techniques that have increased the success of nematode management such as cover cropping, resistant cultivars, and double-layer solarization (Chellemi et al., 1993; McSorley et al., 1999; McGovern et al., 2002).

Arthropods are not often a focus of solarization research, but warrant inclusion because of their role in nutrient cycling and in the regulation of populations of other soil organisms. Ghini and others (1993) found that solarization reduced microarthropods in plots solarized for 30 and 50 days. Bruchids (*Callosobruchus maculates* and *C. subinnotatus*) exposed to 45 and 50ºC for 2 to 6 hours laid fewer eggs and fewer adults emerged than those exposed to 40ºC (Lale and Vidal, 2003). Another study on lethal temperatures in insects and mites of stored products found that species are generally unable to complete their lifecycle if temperatures are elevated between 35 and 55ºC (Fields, 1992). Oribatid and tetranychid mites show a change in respiration and reproduction above 29ºC and are killed at temperatures above 35ºC (Stamou et al., 1995; Bounfour and Tanigoshi, 2001). Information on solarization and other heat effects on pest species can be applied when considering solarization effects on beneficial species.

Although few studies have included the effects of solarization on beneficial organisms, beneficials play a fundamental role in managing soil pest populations and in nutrient cycling. Important arthropod groups including Collembola, oribatid mites, and non-oribatid mites (Astigmata, Mesostigmata and Prostigmata) are directly involved in the breakdown of plant residue or indirectly involved by influencing populations of fungi, bacteria, and other organisms that cycle nutrients directly (Larink, 1997; Maraun et al., 1998). The effects of solarization on beneficials are important to consider under any

circumstance, but especially when working in a system that uses an organic fertilizer source.

This study was designed to add to our understanding of solarization effects on soil fauna. The main objectives were to measure the effects of solarization at varying durations on pest organisms (nematodes and macro-arthropod pests) and beneficial organisms (especially Collembola, oribatid mites and non-oribatid mites). Our specific hypotheses were that solarization would decrease plant-parasitic nematodes, pest insects, and beneficial soil fauna, and therefore affect the availability of an organic fertilizer. Further, we hypothesized that the greater the duration of solarization, the greater the delay in recolonization by soil fauna.

Methods

The experiment was conducted at the University of Florida Plant Science Research and Education Unit near Citra, Florida during the summers of 2003 and 2004. The soil type was a hyperthermic, uncoated, typic Quartzipsamments of the Candler series with a 0 to 5% slope (Thomas et al., 1979). Average soil pH measured at the study site was 5.9. The measured soil texture was 95% sand, with 3% clay and 2% silt. The field was prepared with a crimson clover (*Trifolium incarnatum* L. 'Dixie') cover crop during the winter season and disked two days before the first plots were constructed.

The experiment was conducted in a split-plot design with duration of treatment as the main effect and solarization as the sub effect. Five replicates were arranged in a randomized complete block on the main effect. Each experimental plot was a raised bed 6 m long, 1 m wide, and 20 cm high. The soil was moistened by overhead irrigation if it was not sufficiently moist before the application of solarization plastic. The solarization plastic was 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 treatments of 2, 4, and 6 week durations were applied during July and August of 2003 and 2004. The treatments began on sequential dates and concluded in mid-August both years.

Following solarization treatment, okra (*Hibiscus esculentus* L. 'Clemson Spineless') seedlings were transplanted into the experimental plots as a bioassay. Okra was used because it is well-known to be susceptible to root-knot nematodes (*Meloidogyne* spp.) (McSorley and Pohronezny, 1981). An organic fertilizer of chopped green cowpea (*Vigna unguiculata* (L.) Walp. 'Iron Clay') hay, freshly cut at the early bloom stage, was applied on the soil surface to the area immediately around the okra seedlings at a rate of 3.5 kg m^{-2}.

Six soil cores 2.5 cm in diameter and 15 cm deep were collected from the rhizosphere of the okra plants in each plot. The soil cores were composited and samples were removed for arthropod and nematode extraction. Samples for nematode extraction were collected on 2 to 3 dates from 0 to 65 days post-treatment. Nematodes were extracted from a 100 cm^3 subsample using a modified sieving and centrifugation method (Jenkins, 1964). The samples were then examined, and nematode genera identified and counted. Samples for arthropod extraction were collected on 3 to 4 dates from 0 to 65 days post-treatment. Arthropod extraction was accomplished using a modified Berlese-Tullgren funnel method (Edwards, 1991; McSorley and Walter, 1991). A subsample of 200 cm^3 of soil was removed and placed on a fine mesh screen in a Berlese-Tullgren funnel. The soil samples were exposed to a 60-watt light bulb on the funnel for 24 to 36 hours, and the extracted arthropods were collected in a 70% ethanol solution. The

samples were then analyzed for total arthropods, Collembola, oribatid mites (suborder Oribatei), non-oribatid mites (which included suborders Prostigmata, Mesostigmata, and Astigmata), microarthropods (which included all mites and Collembola) and macroarthropods (which included all insect larvae, adults, and occasionally hatching insect eggs and spiders).

During the year of the second field trial (2004) there were several factors that may have altered conditions at the field site. Three hurricanes in summer 2004 increased the total rainfall during the experiment [94 cm (37 in)] to more than twice that of 2003 [38 cm (15 in)] (Florida Automated Weather Network, 2005). This may have affected the soil fauna populations. There was also an accidental application of herbicide to some of the plots. This was immediately recognized as an error and the area was rinsed with water.

Soil fauna data were compared among durations and between solarized and non-solarized treatments using analysis of variance. If significant differences were detected among duration treatments, means were separated using a Least Significant Difference test at the $\alpha = 0.05$ level. All data were analyzed using MSTAT-C software (Michigan State University, East Lansing, MI).

Results

Nematodes

Nematodes recovered included ring (*Mesocriconema* spp.), stubby-root (*Paratrichodorus* spp.), lesion (*Pratylenchus* spp.), and root-knot (*Meloidogyne* spp). On the last sampling date (43 days post-treatment) in 2003, there was a significant reduction of nematodes due to solarization ($p < 0.05$; Table 2-1). Ring nematodes were the dominant genus in 2003 (Table 2-3). In 2004, ring and stubby-root were the dominant genera, while lesion and root-knot were also present by the conclusion of the study. By

the final sampling date (65 days post-treatment) in 2004, solarization reduced total nematode numbers by 75% and ring nematodes by almost 90% ($p < 0.05$; Tables 2-2 and 2-4). At the conclusion of the experiment, there were no significant effects of solarization treatment and no consistent duration effects on stubby-root, root-knot, or lesion nematodes. The average population numbers of lesion, stubby-root, and root-knot nematodes were 1.8, 4.0, and 10.9 per 100 cm^3 soil, respectively.

Total Arthropods

During the first field trail (2003), solarization significantly reduced total arthropod counts immediately post-treatment (0 days) in 2-week and 6-week durations ($p < 0.10$; Table 2-5). By 21 days post-treatment, solarization continued to suppress arthropod populations ($p < 0.1$). The final arthropod population (43 days post-treatment) showed a significant interaction; the 2-week solarized plots had significantly lower arthropod counts than the non-solarized of the same duration and the 2-week non-solarized plots had significantly higher population counts than either the 4- or 6-week duration non-solarized plots ($p < 0.05$).

During the second field season (2004), solarization significantly reduced arthropod populations immediately following treatment ($p < 0.01$; 5 days post-treatment; Table 2-6). By 23 days post-treatment, a significant interaction developed, with no difference between solarized and non-solarized treatments at the 2-week duration. The 4-week solarization treatment reduced total arthropod populations 10-fold compared to the 4-week non-solarized treatment ($p < 0.05$). The 6-week solarization treatment reduced the total arthropod count by more than 90% ($p < 0.1$). Of the non-solarized treatments, the 6-week duration resulted in significantly higher arthropod counts than either the 2- or 4-week treatments ($p < 0.05$). At 43 days post-treatment, there were no differences in

solarization treatments or among durations of treatment in 2004. At the final sampling date (65 days post-treatment), there was a reduction in total arthropod population in solarized treatments compared to non-solarized treatments ($p < 0.05$). There was also an increase in the total arthropod counts as duration of treatment increased ($p < 0.1$).

Macroarthropods

Macroarthropods extracted from soil samples included wireworms (hatching and larval Elateridae), adult Coleoptera (Scarabidae, Staphylinidae, Carabidae, Elateridae), Diptera, Hymenoptera, Hemiptera, Dermaptera, and spiders. Although macroarthropod population levels were relatively low at all sampling dates, there was a significant reduction in solarized plots compared to non-solarized plots at 21 and 43 days post-treatment ($p < 0.05$) during 2003 (Table 2-7). In 2004, macroarthropods were significantly lower in solarized plots following treatment (5 days post-treatment, $p < 0.1$), while at 43 days post-treatment, solarized plots had significantly more macroarthropods than non-solarized treatments ($p < 0.1$; Table 2-8).

Microarthropods

At 0 and 21 days post treatment during the first field season, microarthropods were significantly reduced in solarized treatments ($p < 0.1$; Table 2-9). At 43 days post-treatment, the 2-week treatment duration significantly lowered microarthropod populations in solarized plots compared to non-solarized ($p < 0.05$).

In 2004, microarthropods were reduced by 93% in solarization treatments at 5 days post-treatment (Table 2-10). At 23 days post-treatment, microarthropod counts were significantly lower in 4- and 6-week solarized treatments than in non-solarized treatments of the same durations ($p < 0.1$). Microarthropod populations in the 6-week non-solarized treatment were more than 5 times higher than those in the 4-week and nearly 16 times

higher than those in the 2-week non-solarized treatment, at 23 days post-treatment ($p < 0.05$). At 65 days post-treatment, microarthropod counts in solarized plots were nearly half of those in non-solarized plots. The 6-week duration had the greatest micro-arthropod population level, while the number of microarthropods in the 2-week treatment was less than half that of the 6-week treatment and the lowest of the three durations ($p < 0.05$).

Collembola

Collembola populations were virtually eliminated by solarization in all treatment durations during the first field trial (2003; Table 2-11). Immediately after treatment, there was a significant difference between Collembola populations in the solarized and non-solarized plots in the 2-week treatment, with the 2-week non-solarized treatment resulting in significantly higher Collembola counts than the 4- or 6-week non-solarized plots ($p < 0.05$). At 21 days post-treatment, the Collembola populations were significantly reduced in solarized treatments ($p < 0.1$). By the final sampling date (43 days post-treatment) solarization reduced Collembola populations by 76% ($p < 0.01$). Numbers in the 2-week treatments were significantly higher than those in both the 4- and the 6-week treatments ($p < 0.1$).

In 2004, Collembola counts were reduced by 94% in the 6-week solarized treatment when compared to the 6-week non-solarized at 23 days post-treatment ($p < 0.1$; Table 2-12). The 6-week non-solarized treatment had higher numbers of Collembola than either the 2 or the 4-week non-solarized treatments ($p < 0.05$). There were no differences in solarization or duration effects for the remaining two sampling dates in 2004.

Mites

During the 2003 experiment, mites (total consisting primarily of non-Oribatid mites) had a significantly higher population level in the 2-week non-solarized treatment when compared to both the 2-week solarized and the 4- and 6-week non-solarized treatments ($p < 0.05$), at 43 days post-treatment (Table 2-13). In the second field trial (2004), mites decreased in numbers in solarized plots at 5 and 21 days post-treatment ($p < 0.1$; Table 2-14). By the final collection date (65 days post-treatment), mites were reduced by 55% in solarized treatments compared to non-solarized treatments and by 50% or more in the 2- and 4-week treatments compared to 6-week treatments ($p < 0.1$). Oribatid mites were not found in sufficient numbers in either year to permit separate tabulation or analysis of variance.

Discussion

During both field trials, nematode populations were not immediately affected by solarization treatments, which may have been due to the relatively low density of nematode populations in the field site. Pre-treatment nematode counts indicated that ring nematodes (*Mesocriconema* spp.) were present, but in relatively low numbers (average of 23 nematodes 100 cm^{-3} of soil in 2003 and 7 nematodes 100 cm^{-3} in 2004), with stubby-root (*Paratrichodorus* spp.), lesion (*Pratylenchus* spp.), root-knot (*Meloidogyne* spp.), dagger (*Xiphinema* spp.), and spiral (*Helicotylenchus* spp.) also appearing occasionally (Seman-Varner, unpublished data). It is also possible that the methods used failed to distinguish between live nematodes and those recently killed, in the samples collected immediately after solarization (McSorley and Parrado, 1984). However, by the final sampling date, there were significantly fewer nematodes in solarized plots than in non-solarized plots, demonstrating that the non-solarized plots were recolonized at a faster

rate. The differences in recolonization rates may be due to the higher density of weed species in non-solarized plots (Seman-Varner, Chapter 3). Although the okra plants were compromised because of weed competition in non-solarized plots, nematodes had a higher density and variety of alternative hosts in those plots. Some of the weed species present were particularly good hosts for root-knot galling and egg development including pigweed (*Amaranthus* sp.), purslane (*Portulaca oleracea*), and clover (*Trifolium* sp.; Noling and Gilreath, 2003). Bermudagrass (*Cynodon dactylon*), one of the most abundant weed species at the site, is a host for ring nematode in Georgia, USA (Powell, 2001). These data suggest that solarization is an effective treatment for nematode management not only because of the direct affect of lethal temperatures on the organism, but also because of the indirect effects on the soil ecosystem and the interactions between plant hosts, alternative hosts, and phytoparasitic nematodes.

Initially following treatment, total arthropods were reduced significantly in solarized plots during 2003. In the final sampling of the 2-week treatment in 2003, arthropods were more than three times higher in non-solarized plots than in solarized and almost twice that of any other treatment. Collembola and non-oribatid mites comprised the majority of the total arthropods in the 2-week non-solarized plots. The cause of the increase in populations of Collembola and non-oribatid mites is unclear; the opposite pattern was found in 2004 where the 6-week non-solarized treatments had the highest arthropod density.

Following the initial reduction of total arthropods in solarized treatments immediately post-treatment (5 days) in 2004, arthropod populations in the solarized plots of the 4- and the 6-week durations were also reduced with a greater difference between

solarized and non-solarized treatments (23 days post-treatment). The third sampling date occurred within three weeks of two hurricanes, and there were no significant differences among any of the treatments. The dramatic increase in precipitation during the experimental period (more than twice that of 2003; Florida Automated Weather Network, 2005) would have influenced both the establishing populations and further recolonization of the site by arthropods. However at 65 days post-treatment, which was 2 weeks after the final hurricane, we saw a significant recovery of arthropod populations in the non-solarized treatments. Duration of treatment also significantly influenced recolonization, with the highest population in the 6-week treatment and the lowest in the 2-week treatment.

Although macroarthropods were found in lower numbers in solarized treatments, many of them were highly-mobile. The macroarthropod species extracted from the soil included larvae of Elateridae and Hemiptera that could be pests to many crop species, but no signs of plant disturbance from insect pests were observed. Further study is required to make any conclusion about the influences of solarization on macroarthropods. Microarthropods followed trends similar to those of Collembola because Collembola comprised the majority of this category.

Collembola populations were reduced by solarization treatments up to 75%. By the final sampling in 2003, Collembola also showed a significant reduction in the 4-week and the 6-week durations. The 2-week non-solarized plots had the highest number of Collembola, possibly because the soil was rototilled immediately before the solarization plastic was applied to plots, thus incorporating plant residue into the soil providing fungi, and consequently Collembola, with a food source.

In 2004, the second sampling revealed the highest Collembola population in the 6-week non-solarized treatment. This is the opposite of our findings in 2003 and may have been influenced by a short-term input of organic matter created by the application of herbicide. There were no significant differences in Collembola populations between solarized and non-solarized plots after the second sampling date (23 days post-treatment). As with the arthropod populations, the increase in precipitation due to seasonal hurricanes could have influenced establishing populations and recolonizing Collembola. In contrast with total arthropods, Collembola populations did not recover from the disturbance to recolonize by the final sampling date (65 days post-treatment).

Mites were consistently reduced by solarization treatments, significantly so on every sampling date in 2004. Oribatid mites were present in very low numbers and they did not affect the soil ecology after solarization treatment. Because non-oribatid mites are primarily fungivores or predators of other mites and nematodes (Coleman and Crossley, 1996), they are likely susceptible to direct and indirect effects of solarization treatment.

Conclusion

These data show the complexity of interactions among soil fauna. Phytoparasitic nematodes were reduced by solarization, directly through increased temperatures and indirectly through the management of weed hosts. Collembola are primarily fungivores that were reduced by solarization. Many non-oribatid mites are predators and followed similar patterns to the populations of Collembola. Unfortunately, oribatid mites, the major detritivores in this study were not numerous enough to have much impact on the soil ecology. Microarthropods recolonized the solarized areas more slowly than the non-solarized, which suggests a lasting effect of solarization on these organisms more than 2 months after treatment. Despite the reduction of beneficial microarthropods by

solarization, nutrient cycling of the green cowpea fertilizer was not reduced, as was evident from the performance and nutrient analysis of okra plant tissue (Seman-Varner, Chapter 4). An important element for future study is solarization effects on fungi and bacteria. These microorganisms may also play a fundamental role in balancing a system after solarization treatment.

Table 2-1. Plant-parasitic nematodes during 2003 summer solarization experiment.

	Nematodes per 100 cm^3 soil[z]					
	0 days post-treatment			43 days post-treatment		
Duration[y]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	9.8	15.2	12.5	13.2	14.2	13.7
4	8.2	9.8	9.0	6.0	17.0	11.5
6	5.0	8.8	6.9	6.4	13.6	10.0
Mean	7.7	11.3		8.5	14.9 *	

[y]Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[z] * indicates significant difference between solarized and non-solarized at $p < 0.05$. No symbol indicates no significant difference.

Table 2-2. Plant-parasitic nematodes during 2004 summer solarization experiment.

	Nematodes per 100 cm^3 soil[z]								
	5 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[y]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	8.0	7.0	7.5	4.0	2.2	3.1	17.8	15.6	16.7
4	4.4	2.2	3.3	2.8	9.4	6.1	6.2	71.2	38.7
6	4.4	4.4	4.4	5.8	13.0	9.4	14.2	67.2	40.7
Mean	5.6	4.5		4.2	8.2		12.7	51.3 *	

[y]Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[z] * indicates significant differences between solarized and non-solarized at $p < 0.05$. No symbol indicates no significant difference.

Table 2-3. Ring nematodes (*Mesocriconema* spp.) during 2003 summer solarization experiment.

	Ring nematodes per 100 cm^3 soil[z]					
	0 days post-treatment			43 days post-treatment		
Duration[y]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	9.8	15.2	12.5	13.2	14.2	13.7
4	8.2	9.8	9.0	6.0	17.0	11.5
6	5.0	8.8	6.9	6.4	13.6	10.0
Mean	7.7	11.3		8.5	14.9 *	

[y]Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[z] * indicates significant difference between solarized and non-solarized at $p < 0.05$. No symbol indicates no significant difference.

Table 2-4. Ring nematodes (*Mesocriconema* spp.) during 2004 summer solarization experiment.

	Ring nematodes per 100cm^3 soil								
	5 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	4.0	3.8	3.9	1.2	0.4	0.8 B[y]	3.0	2.2	2.6
4	3.0	0.6	1.8	1.8	0.8	1.3 AB	2.6	61.4	32.0
6	3.6	3.4	3.5	2.2	5.2	3.7 A	3.6	19.4	11.5
Mean	3.5	2.6		1.7	2.1		3.1	27.7+[z]	

[x]Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] + indicates significant differences between solarized and non-solarized at $p < 0.1$. No symbol indicates no significant difference.

Table 2-5. Total arthropods (including mites, Collembola, and other Insecta) during 2003 summer solarization experiment.

	Arthropods per 200 cm^3 soil								
	0 days post-treatment			21 days post-treatment			43 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	1.6 A	4.2 A+[yz]	2.9	6.4	6.6	6.5	4.4 A	13.8 A*	9.1
4	3.2 A	2.6 A	2.9	7.4	14.8	11.1	3.0 A	4.0 B	3.5
6	1.4 A	5.6 A*	3.5	5.4	10.6	8.0	3.8 A	7.4 B	5.6
Mean	2.1	4.1		6.4	10.7*		3.7	8.4	

[x] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] +, * indicate significant differences between solarized and non-solarized at $p < 0.1$, and 0.05, respectively. No symbol indicates no significant difference.

Table 2-6. Total arthropods (including mites, Collembola, and other Insecta) during 2004 summer solarization experiment.

	Arthropods per 200 cm^3 soil											
	5 days post-treatment			23 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0	3.8	1.9	1.2 A[y]	1.6 B	1.4	4.0	4.6	4.3	8.2	9.4	8.8 B
4	0.4	3.2	1.8	0.4 A	4.0 B*	2.2	7.4	2.4	4.9	9.6	16.2	12.9 AB
6	0.4	2.2	1.3	1.8 A	20.8 A+	11.3	2.8	5.0	3.9	11.4	23.0	17.2 A
Mean	0.3	3.1**[z]		1.1	8.8		4.7	4.0		9.7	16.2*	

[x] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns at 23 days post-treatment followed by the same letter do not differ at $p < 0.05$ according to LSD test, means in columns at 65 days post-treatment followed by the same letter do not differ at $p < 0.1$ according to LSD test.

[z] +, *, ** indicate significant differences between solarized and non-solarized at $p < 0.10$, 0.05, and 0.01, respectively. No symbol indicates no significant difference.

Table 2-7. Macroarthropods during 2003 summer solarization experiment.

	Macroarthropods per 200 cm^3 soil								
	0 days post-treatment			21 days post-treatment			43 days post-treatment		
Duration[y]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0.2	2.2	0.7	1.6	2.0	1.8	0.2	1.0	0.6
4	1.4	0.4	0.9	0.2	4.0	2.1	0.0	1.4	0.7
6	0.0	0.8	0.4	1.8	3.6	2.7	0.2	1.2	0.7
Mean	0.5	0.8		1.2	3.2*[z]		0.1	1.2*	

[y] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[z] * indicates significant differences between solarized and non-solarized at $p < 0.05$. No symbol indicates no significant difference.

Table 2-8. Macroarthropods during 2004 summer solarization experiment.

	Macroarthropods per 200 cm^3 soil											
	5 days post-treatment			23 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-sol	Mean	Sol	Non-sol	Mean	Sol	Non-sol	Mean	Sol	Non-sol	Mean
2	0.0	0.4	0.2	0.4	0.4	0.4	1.0	0.4	0.7	0.4	0.2	0.3 B[y]
4	0.2	0.4	0.3	0.4	0.6	0.5	4.6	0.4	2.5	1.0	1.6	1.3 A
6	0.0	0.2	0.1	0.6	2.0	1.3	1.0	0.6	0.8	1.0	0.8	0.9 AB
Mean	0.1	0.3+[z]		0.5	1.0		2.2	0.5+		0.8	0.9	

[x] Duration of solarized (Sol) and non-solarized (Non-sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.1$ according to LSD test.

[z] + indicates significant differences between solarized and non-solarized at $p < 0.10$. No symbol indicates no significant differences.

Table 2-9. Microarthropods (Collembola and mites) during 2003 summer solarization experiment.

	Microarthropods per 200 cm^3 soil								
	0 days post-treatment			21 days post-treatment			43 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-sol	Mean
2	1.4	3.0	2.2	4.8	4.6	4.7	4.2 A[y]	12.8 A*	8.5
4	1.8	2.2	2.0	7.2	10.8	9.0	3.0 A	2.6 B	2.8
6	1.4	4.8	3.1	3.6	7.0	5.3	3.6 A	6.2 B	5.0
Mean	1.5	3.3+[z]		5.2	7.5+		3.7	7.2	

[x] Duration of solarized (Sol) and non-solarized (Non-sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] +, * indicate significant differences between solarized and non-solarized at $p < 0.10$, and 0.05, respectively. No symbol indicates no significant difference.

Table 2-10. Microarthropods during 2004 summer solarization experiment.

	Microarthropods per 200 cm^3 soil											
	5 days post-treatment			23 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0.0	3.4	1.7	0.8 A[y]	1.2 B	1.0	3.0	4.2	3.6	7.8	9.2	8.5 B
4	0.2	2.8	1.5	0.0 A	3.4 B*	1.7	2.8	2.0	2.4	8.6	14.6	11.6 AB
6	0.4	2.0	1.2	1.2 A	18.8 A+	10.0	1.8	4.4	3.1	10.4	22.2	16.3 A
Mean	0.2	2.7*[z]		0.7	7.8		2.5	3.5		8.9	15.3*	

[x] Duration of solarized (Sol) and non-solarized (Non-sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test at 23 days post-treatment. Means in columns followed by the same letter do not differ at $p < 0.1$ according to LSD test at 65 days post-treatment.

[z] *, + indicate significant differences between solarized and non-solarized at $p < 0.05$, and 0.10, respectively. No symbol indicates no significant differences.

Table 2-11. Collembolans during 2003 summer solarization experiment.

	Collembola per 200 cm^3 soil								
	0 days post-treatment			21 days post-treatment			43 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0.2 A[y]	2.2 A*[z]	1.2	0.4	0.4	0.4	1.2	6.0	3.6 A
4	0.0 A	0.0 B	0.0	1.0	2.6	1.8	1.0	1.2	1.1 B
6	0.6 A	0.8 B	0.7	1.6	2.2	1.9	0.2	3.0	1.6 B
Mean	0.3	1.0		1.0	1.7+		0.8	3.4**	

[x] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[y] Means in columns at 0 days post-treatment followed by the same letter do not differ at $p < 0.05$ according to LSD test. Means in columns at 43 days post-treatment followed by the same letter do not differ at $p < 0.1$ according to LSD test.

[z] +, *, ** indicate significant differences between solarized and non-solarized at $p < 0.10$, 0.05, and 0.01, respectively. No symbol indicates no significant difference.

Table 2-12. Collembolans during 2004 summer solarization experiment.

	Collembola per 200 cm^3 soil											
	5 days post-treatment			23 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0.0	2.8	1.4	0.6 A[y]	1.0 B	0.8	2.4	4.2	3.3	6.0	6.0	6.0
4	0.2	0.2	0.2	0.0 A	1.2 B	0.6	1.6	2.0	1.8	7.0	10.8	8.9
6	0.4	0.6	0.5	1.0 A	17.0 A+[z]	9.0	1.6	4.2	2.9	7.4	14.8	11.1
Mean	0.2	1.2		0.5	6.4		1.9	3.5		6.8	10.5	

[x] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] + indicates significant differences between solarized and non-solarized at $p < 0.10$. No symbol indicates no significant differences.

Table 2-13. Mites (including non-oribatid and oribatid mites) during 2003 summer solarization experiment.

	Mites per 200 cm^3 soil								
	0 days post-treatment			21 days post-treatment			43 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	1.6	1.0	1.3	4.4	4.4	4.4 AB[y]	3.0 A	7.2 A*[z]	5.1
4	1.8	2.2	2.0	6.4	8.2	7.3 A	2.0 A	1.4 B	1.7
6	0.4	3.8	2.1	2.0	4.6	3.3 B	3.6 A	2.8 B	3.2
Mean	1.3	2.3		4.3	5.7		2.9	3.8	

[x] Duration of solarized (Sol) and non-solarized (Non-sol) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] * indicate significant differences between solarized and non-solarized at $p < 0.05$. No symbol indicates no significant difference.

Table 2-14. Mites during 2004 summer solarization experiment.

	Mites per 200 cm^3 soil											
	5 days post-treatment			23 days post-treatment			43 days post-treatment			65 days post-treatment		
Duration[x]	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean	Sol	Non-Sol	Mean
2	0.0	0.6	0.3	0.2	0.2	0.2	0.6	0.0	0.3	1.8	3.2	2.5 B[y]
4	0.0	2.6	1.3	0.0	2.2	1.1	1.2	0.0	0.6	1.6	3.8	2.7 B
6	0.0	1.4	0.7	0.2	1.8	1.0	0.2	0.2	0.2	3.0	7.4	5.2 A
Mean	0.0	1.5*[z]		0.1	1.4+		0.7	0.1*		2.1	4.8*	

[x] Duration of solarized (Sol) and non-solarized (Non-Sol) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] +, * indicates significant differences between solarized and non-solarized at $p < 0.10$, and 0.05, respectively. No symbol indicates no significant differences.

CHAPTER 3
WEED POPULATION DYNAMICS AFTER SUMMER SOLARIZATION

Introduction

Solarization is an effective method for the management of soil-borne pests, including weeds. Clear plastic mulch allows for the transmission of solar radiation that heats the soil to lethal or near-lethal temperatures (30-60°; Katan, 1981). Several mechanisms of weed control by solarization have been proposed. These mechanisms include direct thermal damage to seeds, germinating seeds, and shoots; morphological changes in shoots and other plant organs; breaking of dormancy and germination at greater depths; an imbalance of gases in soil; and indirect effects on soil microorganisms that might be seed pathogens (Rubin and Benjamin, 1984; Elmore, 1991; Chase et al., 1998).

Several studies have focused on thermal damage to a variety of weed species. Rubin and Benjamin (1984) found that weed species responded differently to exposure to temperatures from 30-90°C. Redroot pigweed (*Amaranthus retroflexus* L.) emergence was reduced when exposed to 30 minutes of 50°C; but even at 90°C sweet clover (*Melilotus sulcatus* Desf.) was not affected (Rubin and Benjamin, 1984). Rhizomes of bermudagrass (*Cynodon dactylon* (L.) Pers.) were killed when exposed to 30 minutes of temperatures above 40°C, but tubers of purple nutsedge (*Cyperus rotundus* L.) required temperatures above 60°C to show any reduction in viability (Rubin and Benjamin, 1984). Further study of thermal effects on velvetleaf (*Abutilon theophrasti* Medik) revealed that shorter, more frequent exposure to high temperatures, which would mimic the diurnal

heating produced by solarization, reduced germination rates compared to a single exposure (Horowitz and Taylorson, 1983).

The nutsedges (*Cyperus* spp.) have been of particular concern in solarization research, in part because they are among the world's worst weeds (Holm et al., 1977). Studies have focused on nutsedge control by various types of solarization plastic (Patterson, 1998; Chase et al., 1998; Chase et al., 1999). Purple nutsedge shoots were able to penetrate opaque polyethylene mulches and some clear mulches of various thicknesses and plastic types, but penetration was reduced when a 5-10 mm space was created between plastic and soil (Chase et al., 1998). Solarization treatment using clear mulch caused a morphological change in the nutsedge shoots that greatly reduced penetration and caused the shoots to be scorched under the plastic (Chase et al., 1998). Laboratory exposure to 50°C for 6 hours daily resulted in 100% mortality of nutsedge tubers, and exposure to 45°C reduced emergence of nutsedge shoots (Chase et al., 1999). This information can be applied to a management plan that includes solarization as a method of killing the shoots and depleting the plant reserves in the nutsedge tubers.

This study was designed to examine the effects of solarization on weed populations and a variety of summer weed species, including nutsedges, hairy indigo (*Indigofera hirsuta* L.), carpetweed (*Mollugo verticillata* L.), goosegrass (*Eleusine indica* (L.) Gaertn.), and southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler). The main hypothesis was that as solarization treatment duration increased, weed coverage would decrease. We further hypothesized that the residual effects (up to 67 days post-treatment) would vary based on initial treatment duration. Additionally, the effects of solarization were expected to vary by individual plant species.

Methods

The experiment was conducted during the summers of 2003 and 2004 at the University of Florida Plant Science Research and Education Unit in northern Florida. The soils in the experimental area were hyperthermic, uncoated, typic Quartzipsamments of the Candler series with a 0 to 5% slope (Thomas et al., 1979). Average soil pH of the site was measured as 5.9. The measured soil texture was 95% sand, with 3% clay, and 2% silt. A crimson clover *(Trifolium incarnatum* L. 'Dixie') cover crop was planted during the winter seasons prior to each experiment and disked two days before the first plots were constructed.

The experiment was designed as a split-plot with duration of treatment as the main effect and solarization as the sub effect. Five replicates were arranged in a randomized complete block on the main effect. The experimental plots were raised beds 6 m long, 1 m wide, and 20 cm high. The soil was moistened by overhead irrigation if it was not sufficiently moist before the application of solarization plastic. The solarization plastic was a single layer of clear, 25-µm-thick, UV-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC). Application of solarization treatments and non-solarization control treatments of 2, 4, and 6 week durations occurred during July and August of 2003 and 2004. Temperature data loggers (Watch Dog^{R} Model 425, Spectrum Technologies, Inc., Plainfield, IL) were inserted into the soil at depths of 5, 10, and 15 cm in 6-week solarized and non-solarized plots, 4-week solarized plots, and 2-week solarized plots in 2003 and 2004. The treatments started on sequential dates and concluded in mid-August both years.

Following solarization treatment, all plastic was removed and the middle 2.0 m of each 6.0-m plot was planted with 5-week old okra (*Hibiscus esculentus* L. 'Clemson spineless') seedlings and used to monitor plant nutrition, soil chemistry, and insect, and nematode populations (Seman-Varner, Chapters 2 and 4). On either side of the okra plants, a 1.0-m^2 subplot was established to monitor weed populations in the experimental plots. Weed populations were monitored at 2-week intervals following solarization treatment and plastic removal. The Horsfall-Barratt scale (Horsfall and Barratt, 1945) was used to determine the percent ground coverage by weeds in each plot on a scale from 1 to 12, where 1 = 0%; 2 = 0-3%; 3 = 3-6%; 4 = 6-12%; 5 = 12-25%; 6 = 25-50%; 7 = 50-75%; 8 = 75-88%; 9 = 88-94%; 10 = 94-97%; 11 = 97-100%; 12 = 100% of ground area covered. Individual plants were counted by species and then totaled for each plot. When plots reached 100% coverage, individual plants were no longer counted. A separate category for individual seedling counts was used for small seedlings that were visible but not easily identified and not a contributing factor to coverage. Final weed biomass was collected from a 0.25-m^2 section of the weed subplot and weighed fresh. During the first field trial, exposed trays [54.6 cm x 26.7 cm (21.5 x 10.5 in)] of sterilized soil were placed at each corner and each mid-point of the experimental area to determine how much of the weed seed population was dispersed by wind.

Weed coverage based on HB ratings, total and individual species plant populations, and weed biomass were compared among durations and between solarized and non-solarized treatments using analysis of variance. If significant differences were detected among duration treatments, means were separated using a Least Significant Difference

test at the $\alpha = 0.05$ level. All data were analyzed using MSTAT-C software (Michigan State University, East Lansing, MI).

During the field experiment in 2004, several events occurred that may have influenced the experiments and data. On 6 August 2004, herbicide [Roundup (propan-2-amine)] was applied accidentally to some of the plots. The control treatments were exposed while the solarized treatments remained under plastic. The error was immediately recognized and the areas affected were rinsed with water. Additionally three hurricanes occurred during the season that caused an increase in total rainfall over the experimental period [94 cm (37 in)] to more than twice that in the previous season [38 cm (15 in); Florida Automated Weather Network, 2005]. Further weather data was obtained from the Florida Automated Weather Network, including air temperature, precipitation, and solar radiation (Florida Automated Weather Network, 2005).

Results

Weed Cover

Significant interactions ($p < 0.05$) between solarization treatment and duration occurred on all sampling dates in 2003. The Horsfall-Barratt scale rating (HB) for weed coverage was significantly lower ($p < 0.05$) in solarized treatments than in non-solarized treatments on every sampling date in 2003 (Table 3-1). The HB ratings on the first and second sampling dates (0 and 14 days post-treatment) were between 1.0 and 2.0 in solarized plots and showed no significant differences among the three duration treatments. The coverage ratings in non-solarized treatments ranged between 2.0 and 10.0 and were higher than in solarized treatments ($p < 0.01$). Among non-solarized durations on both sampling dates, weed coverage was up to 35% and 72% lower in the 2-week treatment than in the 4- or the 6-week treatments, respectively ($p < 0.05$) and the 6-week

treatment was up to 56% higher than the 4-week treatment ($p < 0.05$). At 28 days post-treatment, weed coverage in solarized treatments was 54% to 73% lower than non-solarized treatments ($p < 0.05$). The HB rating in 6-week non-solarized treatments was significantly higher than the 2-week or the 4-week non-solarized treatment ($p < 0.05$). At 43 days post-treatment, the HB rating in solarized plots remained significantly lower than non-solarized plots by 35% to 68% ($p < 0.05$). In non-solarized duration treatments, the HB rating in the 6-week treatment was 50% higher than that in the 2-week treatment ($p < 0.05$). By the final sampling date (56 days post-treatment), weed coverage in the solarized treatments remained significantly lower than non-solarized treatments ($p < 0.01$). There were no significant differences among durations in solarized or non-solarized treatments.

When solarization plastic was removed in 2004 (0 days post-treatment), the HB ratings were significantly higher in the 6-week non-solarized plots than in any of the other non-solarized or solarized duration treatments ($p < 0.05$; Table 3-2). There was no difference between the solarized and non-solarized treatments of 2-week or 4-week durations. On the next 3 sampling dates (11, 25, and 39 days post-treatment), HB ratings were 44%, 37% and 24% lower in solarized treatments compared to non-solarized treatments, respectively. On the last two sampling dates (53 and 67 days post-treatment), significantly reduced HB ratings continued in solarized treatments ($p < 0.1$). On these dates, significant differences occurred among duration means; the 2-week treatments had the highest HB rating and the 4-week had the lowest, while the 6-week treatments were not different from either of the other durations.

Total Weed Populations

In 2003, total weed populations were significantly lower in solarized plots than in non-solarized plots at 0 and 14 days post-treatment, by as much as a factor of 200 ($p <$

0.05; Table 3-3). Among non-solarized treatments, there were significantly higher numbers of weeds per plot in the 6-week treatment than in the 4- or the 2-week treatments ($p < 0.05$). Some non-solarized plots reached 100% coverage by 28 days post-treatment, limiting the comparison of solarized plots with non-solarized plots. There were no significant differences in total weed populations among solarization duration treatments at 28, 43, and 56 days post-treatment ($p > 0.1$).

In 2004, total weed populations were initially reduced by 72% in solarized plots compared to non-solarized plots at 0 days post-treatment (Table 3-4). There were no significant differences ($p > 0.10$) in weed population on any of the subsequent sampling dates (11, 25, 39, and 53 days post-treatment). Means of the duration treatments were significantly different at 39 and 53 days post-treatment, with the 4-week treatment having the lowest total weed population, and the 6-week having the highest total weed population ($p < 0.05$). Plots of solarized and non-solarized treatments reached 100% coverage by 67 days post-treatment, and consequently individual plants were no longer counted.

Individual Weed Species Populations

Based on population levels of individual weeds in 2003, the most dominant species was hairy indigo. At 0 days post treatment, hairy indigo was eliminated in all solarized treatments and significantly lower than all non-solarized treatments ($p < 0.05$; Table 3-5). In non-solarized treatments, the 6-week plots had more than 6 times the number of hairy indigo plants than in the 2-week plots and almost 3 times the number in the 4-week plots ($p < 0.05$). By 14 days post-treatment, hairy indigo appeared in the 2-week solarized treatment in equal numbers to those in the 2-week non-solarized treatment. However, hairy indigo was completely suppressed in the 6-week solarized

treatments and only very few appeared in the 4-week solarized treatments. Both 4- and 6-week solarized treatments remained significantly lower than non-solarized treatments ($p < 0.05$). The 6-week non-solarized treatment had more than twice the number of hairy indigo plants than the 4-week non-solarized treatment and more than 5 times the number in the 2-week non-solarized treatment ($p < 0.05$). Once non-solarized plots reached 100% coverage (28 days post-treatment), hairy indigo numbers were significantly lower in 4- and 6-week solarization treatments than in 2-week solarization treatments.

Purple nutsedge was also an important species, based on the number of stems contributing to the total weed count (Table 3-6). Initially (0 days post-treatment), solarization treatments almost eliminated nutsedge plants, and significantly reduced the number of nutsedge sprouts in 4-week and 6-week treatments when compared to the non-solarized treatments ($p < 0.05$). At 14 days post-treatment, nutsedge sprouts remained low in solarized plots but were low in non-solarized plots as well, showing no significant difference from solarized. Once non-solarized plots reached 100% coverage by total weeds, there were no significant differences among durations of solarization treatment.

In 2004, weed density was dominated by goosegrass (*Eleusine indica*), southern crabgrass (*Digitaria ciliaris*), carpetweed (*Mollugo verticillata*), hairy indigo, and purple nutsedge. There were no significant effects of solarization treatments on any of the individual weed species during the 2004 field season.

Weed Biomass

Total weed biomass was reduced by 90% in solarized treatments compared to non-solarized treatments in 2003 (Table 3-7). Hairy indigo biomass was reduced by 98% in solarized treatments. Hairy indigo made up 75% of the total weed biomass in non-solarized plots. In solarized treatments, hairy indigo accounted for 16% of the total

biomass. Bermudagrass was the dominant species by weight in solarized plots and comprising nearly 30% of the total weed biomass. Carpetweed comprised the next largest proportion of total biomass with 18%.

In 2004, there was no significant difference in total weed biomass between treatments and no significant trend in biomass for individual species. Goosegrass was the dominant species in both solarized and non-solarized treatments, making up 62% and 45% of the total weed biomass in each treatment, respectively. Lambsquarter (*Chenopodium albu*m L.) was also very important and comprised 10% of weed biomass in solarized plots and 25% in non-solarized plots.

Wind-dispersed Seed

The wind-dispersed seed traps did not contain any germinated plants, indicating that all weeds were germinated from the soil seed bank.

Discussion

Solarization effectively reduced weed coverage based on the HB ratings and weed population counts in 2003. There were no significant differences in weed coverage among durations of solarization treatment for the first 28 days post-treatment. All five 6-week non-solarized plots reached 100% coverage by 28 days post-treatment in 2003. By the conclusion of the experiment, an additional two 4-week non-solarized plots reached 100% coverage, while no solarized plots ever reached 100% coverage.

In 2004, HB ratings were significantly lower in solarized treatments than in non-solarized treatments, despite the application of herbicide to the control plots. The herbicide decreased weed coverage in non-solarized plots, evident in the delay in the time it took to reach 100% weed coverage and the lower average maximum HB rating at the final sampling, which was 9.3 in 2004 and 10.9 in 2003. In contrast to the 2003

experiment, 67 days elapsed in 2004 (vs. 28 days in 2003) before 100% coverage was reached in any plots, which included three 6-week non-solarized plots, one 4-week non-solarized plot, two 2-week non-solarized plots, and one 2-week solarized plot. The inconsistency can be attributed to the application of herbicide to control plots. Most importantly, this reduction of weeds in control plots made it difficult to demonstrate significant differences between solarized and non-solarized treatments in 2004.

After solarization treatment in 2003, total weed counts were reduced to almost 0 and maintained a reduction of 80% or more compared to non-solarized plots. Maximum soil temperatures at 10 cm deep in solarized plots reached 40°C or more on 20 days of the 41 days of solarization treatment in 2003 (Figure 3-1). These high-temperature days would have damaged seeds and emerging plants at this depth. Although several control plots reached 100% coverage at 28 days post-treatment, which limited effective counting of weeds and analysis of variance between solarized and non-solarized treatments, average total weed count for each duration in solarized plots remained very low, with fewer than 7 stems m^{-2}. There were no differences among durations of solarization based on total weed count, suggesting that all solarization treatment durations were effective in decreasing weed emergence. The maximum soil temperatures indicate an equal distribution of high temperatures during the first 4 weeks of the treatment, or until mid-August (Figure 3-1). The final two weeks of the experimental period show a general decrease in the maximum temperatures reached each day, while still maintaining temperatures well above 35°C.

In 2004, total weed counts were reduced initially by solarization treatment. Soil temperatures were sufficiently high (42°C average daily maximum) to damage weed seed

in the soil (Figure 3-2). The application of herbicide to the non-solarized treatments caused an unintentional reduction in total weed counts for those control plots, influencing the total count on subsequent sampling dates. The last two sampling dates (39 and 53 days post-treatment) showed a significant trend where the 4-week treatment means were lower than the 6-week treatment means but not different from the 2-week treatment means, likely due to the herbicide application. The herbicide application interfered with the accurate assessment of solarization treatment effects by reducing weed populations in non-solarized plots.

Individual species counts from 2003 illustrated that the two dominant species, hairy indigo and purple nutsedge, were variably affected by solarization treatments. Other studies also have shown that high-temperature affects, like those caused by solarization or other methods, vary with species and depth of the seed (Horowitz et al., 1983; Standifer et al., 1984; Egley, 1990). Hairy indigo was reduced by solarization and continued to be affected by solarization of 4-and 6-week durations, up to 56 days post-treatment. Purple nutsedge was initially reduced by 4- and 6-week solarization treatments. However, at 14 days post-treatment, numbers of purple nutsedge had dropped to < 1.5 per m^2 in the non-solarized plots. The reduction in purple nutsedge may have been due to competition with the larger plants of hairy indigo, which quickly became the dominant weed in those plots. Therefore, at 14 days post-treatment and beyond, there were no significant differences among durations of solarization treatment on nutsedge populations. No weed species were individually affected by solarization or duration treatment in 2004, again due to herbicide application.

The 90% reduction in weed biomass in solarized treatments was another indicator that solarization was effective in reducing weed populations, even up to 56 days post-treatment. Solarization was also effective in reducing hairy indigo, the most dominant weed during 2003. There were no differences in weed biomass for the 2004 field season, primarily due to the application of herbicide early in August.

Conclusion

Solarization was effective in reducing weed coverage, density, and biomass in 2003. Increasing the duration of solarization treatment from 2 to 6 weeks did not significantly affect coverage ratings or total weed density. Studies have shown effective control of some winter and summer annual weed species with as little as 1-2 weeks solarization (Egley, 1983; Horowitz et al., 1983; Elmore, 1991). However, the effect of both 4- and 6-week treatments on Florida weed populations appears to continue beyond that of the 2-week treatment, in which weed populations begin to recover at an earlier date. Durations of 4 and 6 weeks also more effectively reduced individual weed species in Florida, specifically hairy indigo and purple nutsedge.

Further study on weed populations after plots reach 100% coverage may add to our understanding of the lasting effects of solarization. An in-depth study on individual species populations (e.g., hairy indigo, nutsedges, goosegrass, and southern crabgrass) would further our understanding of which species are more resistant to the effects of high temperature and how seeds in the soil seed bank resist damage or recover from solarization treatment.

Table 3-1. Horsfall-Barratt ratings for weed coverage during 2003 summer solarization experiment.

	Horsfall-Barratt rating[w] by sampling date														
	0 days			14 days			28 days			43 days			56 days		
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2	1.2 A[y]	2.0 C**[z]	1.6	1.8 A	3.4 C**	2.6	2.8 A	6.1 B*	4.4	5.2 A	8.0 B*	6.6	6.4 A	9.5 A**	7.9
4	1.0 A	3.1 B***	2.0	1.9 A	5.1 B***	3.5	2.1 A	7.4 B***	4.7	4.1 A	9.6 AB**	6.8	4.9 A	11.1 A***	8.0
6	1.2 A	7.1 A***	4.1	1.6 A	9.3 A***	5.5	3.2 A	12.0 A***	7.6	3.9 A	12.0 A***	8.0	4.5 A	12.0 A**	8.2
Mean	1.1	4.0		1.8	5.9		2.7	8.5		4.4	9.8		5.2	10.9	

[w] Rated on 1 (0% of plot area covered) to 12 (100% of plot area covered) scale (Horsfall and Barratt, 1945) for percentage of plot area covered by weeds.

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date (X days).

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[z] *, **, *** indicate significant differences between solarized and non-solarized at $p < 0.05$, 0.01, and 0.001, respectively.

Table 3-2. Horsfall-Barratt ratings for weed coverage during 2004 summer solarization experiment.

	Horsfall-Barratt rating[w] by sampling date																	
	0 days			11 days			25 days			39 days			53 days			67 days		
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2	2.0 A[y]	2.1 B	2.1	2.2	2.8	2.5	3.4	4.7	4.1	6.4	6.7	6.6	7.6	7.4	7.5 A	10.0	10.0	10.0 A
4	2.0 A	2.9 B	2.5	2.0	3.8	2.9	2.6	4.3	3.5	3.7	5.4	4.6	4.4	6.4	5.4 B	5.4	8.2	6.8 B
6	2.0 A	6.9 A**[z]	4.5	2.8	5.8	4.3	3.3	5.8	4.6	4.4	6.8	5.6	5.6	7.8	6.7 AB	6.8	9.6	8.2 AB
Mean	2.0	4.0		2.3*	4.1		3.1**	4.9		4.8*	6.3		5.9+	7.2		7.4+	9.3	

[w] Rated on 1 (0% of plot area covered) to 12 (100% of plot area covered) scale (Horsfall and Barratt, 1945) for percentage of plot area covered by weeds.

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 11 August 2004; post-treatment times measured after this date (X days).

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test; no letters indicate no differences at $p < 0.05$.

[z] +, *, ** indicate significant differences between solarized and non-solarized at $p < 0.10$, 0.05, and 0.01, respectively. No symbol indicates no significant difference.

Table 3-3. Weed population (number of plants or stems) during 2003 summer solarization experiment.

	Number of weed plants or stems per m^2								
	0 days			14 days			28 days[z]	43 days	56 days
Duration[w]	Sol	Non	Mean	Sol	Non	Mean	Sol	Sol	Sol
2	0.2 A[x]	16 B**[y]	8.1	1.9 A	10.4 B**	6.2**	5.8 A	6.6 A	6.2 A
4	0.0 A	58.6 B**	29.3	0.6 A	10.5 B**	5.6	2.2 A	2.5 A	2.6 A
6	0.8 A	200.8 A*	100.8	1.2 A	25.1 A***	13.2	6.5 A	4.5 A	6.0 A
Mean	0.3	91.8		1.2	15.3				

[w] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date (X days).

[x] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test.

[y] *, **, *** indicate significant differences between solarized and non-solarized at $p < 0.05$, 0.01, and 0.001, respectively.

[z] treatment plots reached 100% coverage by 28 days post-treatment, therefore only solarization treatments were examined for total weed counts.

Table 3-4. Weed population (number of plants or stems) during summer solarization experiment 2004.

	Number of weed plants or stems per m^2														
	0 days			11 days			25 days			39 days			53 days[z]		
Duration[w]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2	20.2	41.4	30.8	27.2	16.4	21.8	29.6	18.6	24.1	30.2	16.0	23.1 AB[x]	26.4	16.4	21.4 AB
4	36.0	68.6	52.3	14.2	18.0	16.1	10.0	12.2	11.1	11.4	10.0	10.7 B	10.4	13.4	11.9 B
6	8.8	121.2	65.0	11.2	25.2	18.2	16.2	20.6	18.4	31.4	26.2	28.8 A	44.0	30.4	37.2 A
Mean	21.7	77.1+[y]		17.5	19.9		18.6	17.1		24.3	17.4		26.9	20.1	

[w] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 11 August 2004; post-treatment days measured after this date (X days).

[x] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test; no letters indicate no differences at $p < 0.05$.

[y] + indicates significant differences between solarized and non-solarized at $p < 0.10$. No symbol indicates no significant difference.

[z] solarized and non-solarized treatment plots reached 100% coverage by 67 days post-treatment, therefore total weeds were not counted at 67 days.

Table 3-5. Number of hairy indigo (*Indigofera hirsuta*) plants during 2003 summer solarization experiment.

	Number of hairy indigo plants per m^2								
	0 days			14 days			28 days[z]	43 days	56 days
Duration[w]	Sol	Non	Mean	Sol	Non	Mean	Sol	Sol	Sol
2	0.0 A[x]	12.2 B*[y]	6.1	1.7 A	2.3 B	2.0	3.0 A	2.8 A	2.8 A
4	0.0 A	27.2 B**	13.6	0.4 A	4.8 B*	2.6	1.0 B	1.0 B	1.0 B
6	0.0 A	78.0 A**	39.0	0.0 A	12.4 A**	6.2	1.0 B	0.6 B	0.6 B
Mean	0.0	39.1		0.7	6.5				

[w] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date (X days).

[x] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test; no letters indicate no differences at $p < 0.05$.

[y] *, ** indicate significant differences between solarized and non-solarized at $p < 0.05$ and 0.01, respectively.

[z] treatment plots reached 100% coverage by 28 days post-treatment, therefore only solarization treatments were examined for hairy indigo plant counts.

Table 3-6. Number of purple nutsedge (*Cyperus rotundus*) stems during 2003 summer solarization experiment.

	Number of purple nutsedge stems per m^2								
	0 days			14 days			28 days[z]	43 days	56 days
Duration[w]	Sol	Non	Mean	Sol	Non	Mean	Sol	Sol	Sol
2	0.2 A[x]	1.2 B	0.7	0.0	1.4	0.7	0.9	1.1	0.8
4	0.0 A	2.6 B*[y]	1.3	0.1	0.9	0.5	0.6	0.2	0.4
6	0.6 A	11.2 A**	5.9	1.0	1.1	1.1	0.0	0.6	1.4
Mean	0.3	5.0		0.4	1.1				

[w] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003; post-treatment times measured after this date (X days).

[x] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test; no letters indicate no differences at $p < 0.05$.

[y] *, ** indicate significant differences between solarized and non-solarized at $p < 0.05$ and 0.01, respectively.

[z] treatment plots reached 100% coverage by 28 days post-treatment, therefore only solarization treatments were examined for total weed counts.

Table 3-7. Total weed biomass at conclusion of summer solarization experiments during 2003 (56 days post-treatment) and 2004 (67 days post-treatment).

	Fresh weight (g) of total weed biomass per 0.25 m^2					
	2003			2004		
Duration[y]	Sol	Non	Mean	Sol	Non	Mean
2	50.9	259.2	155.0	130.2	57.0	93.6
4	23.2	226.7	124.9	85.7	38.3	62.0
6	65.8	849.7	457.7	43.1	114.4	78.8
Mean	46.6	445.2**[z]		86.3	69.9	

[y] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003 and 11 August 2004.
[z] ** indicates significant differences between solarized and non-solarized at $p < 0.01$.

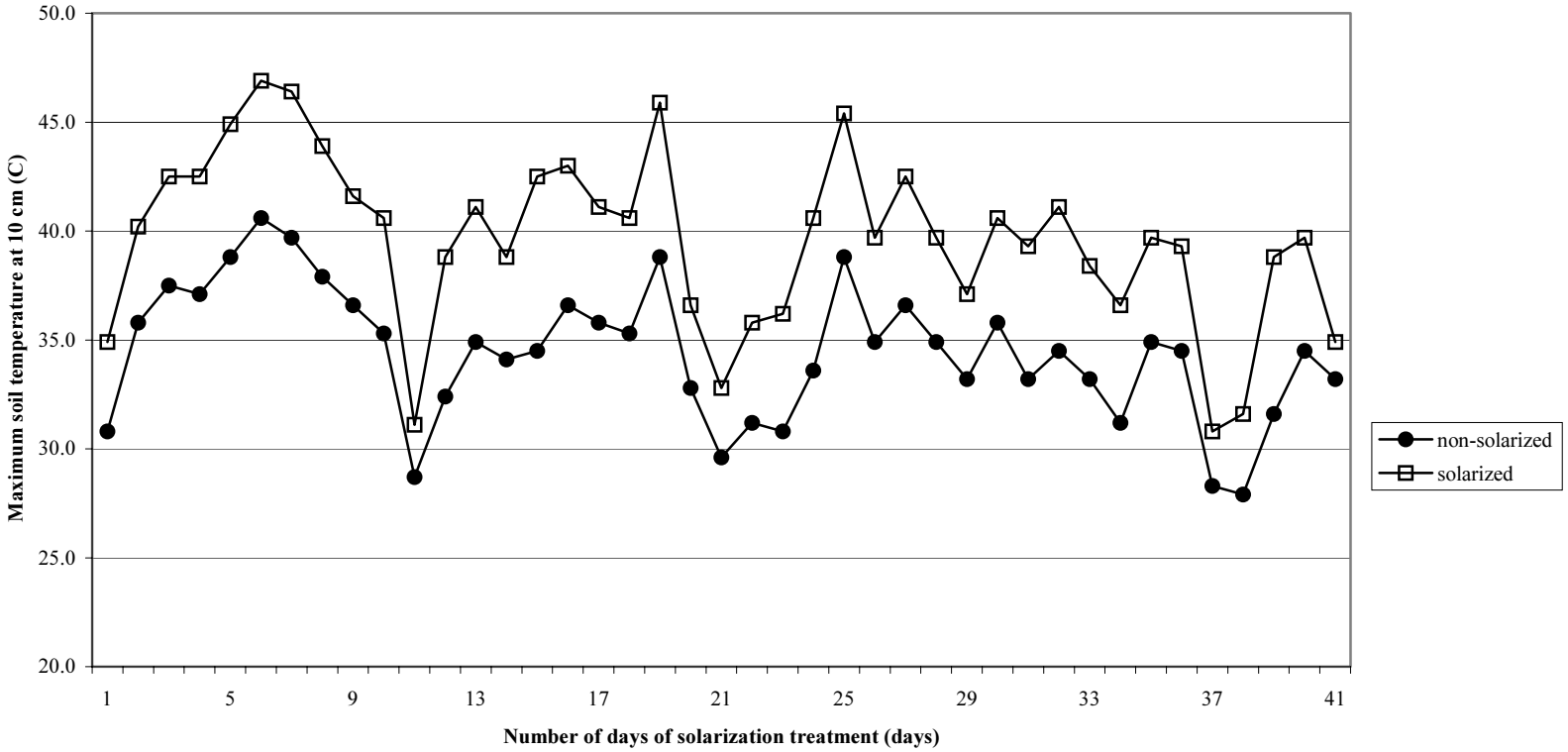

Figure 3-1. Daily maximum soil temperatures at 10 cm depth during 6-week solarized and non-solarized treatments in 2003.

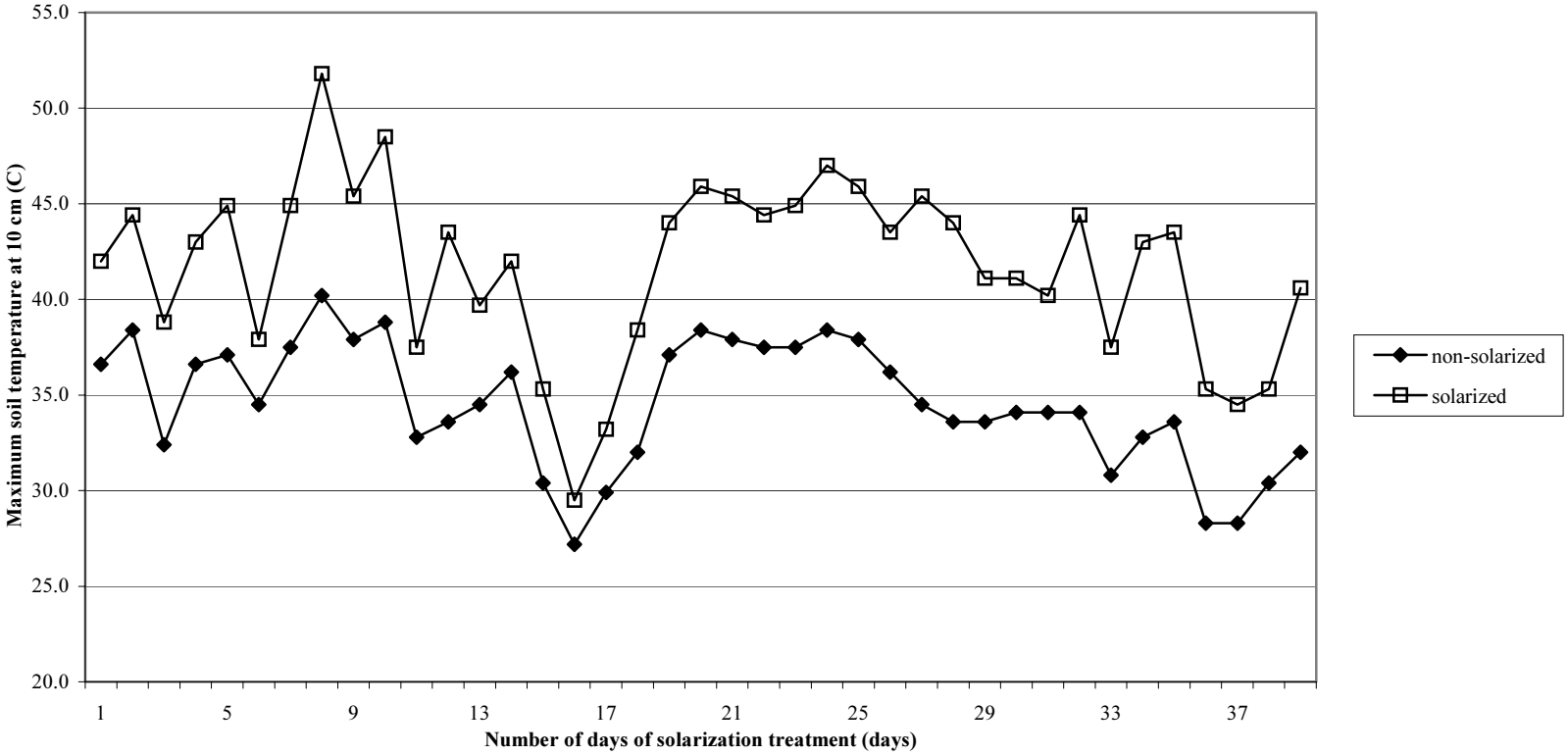

Figure 3-2. Daily maximum soil temperatures at 10 cm depth during 6-week solarized and non-solarized treatments in 2004.

CHAPTER 4
SOIL NUTRIENT AND PLANT RESPONSES TO SOLARIZATION IN AN AGROECOSYSTEM UTILIZING AN ORGANIC NUTRIENT SOURCE

Introduction

Soil solarization has been used to successfully manage soil-borne pests including fungal and bacterial pathogens, nematodes, and weeds. Use of solarization has increased crop yield at sites with various pest problems (Davis, 1991; Elmore, 1991; McGovern and McSorley, 1997). 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 (Chen and Katan, 1980; Stapleton et al., 1985).

Studies on solarization effects on mineral nutrients in soil have had mixed results. One study involving eight soil types found large increases in the concentration of NO_3^- and NH_4^+, which may have been the result of increased organic matter in the soil (Chen and Katan, 1980). In the same study, concentrations of Ca, K, Na, and Mg, and soil electrical conductivity increased consistently as well, while pH and P concentration remained the same or changed inconsistently (Chen and Katan, 1980). Stapleton et al. (1985) found similar results and confirmed the increase in NO_3^-, NH_4^+, Ca, and Mg concentrations with solarization in four soil types in California (Stapleton et al., 1985). Contrary to the findings of Chen and Katan (1980), Stapleton et al. (1985) found an increase in P concentration, no change in K concentration, and inconsistent results with electrical conductivity. The discrepancies were likely due to differences in soil types, sampling depth, and assay procedures (Stapleton et al., 1985).

Of the studies examining the effects of solarization on soil chemistry and physical properties, few 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 exhibited significant increases in plant height, leaf length, and whole plant dry weight when grown in solution from solarized soil (Chen and Katan, 1980). 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 (Stapleton et al., 1985). The study also included plant tissue analysis but found no significant differences in nutrient concentrations between treatments (Stapleton et al., 1985). 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 (Stapleton et al., 1985).

The primary objective of this study was to determine if duration of solarization treatment had an effect on soil mineral nutrients, soil properties, and plant leaf tissue nutrients. An additional objective was to determine the effects of solarization on plant nutrition in a system that utilized an organic nutrient source.

Methods

This experiment was conducted at the University of Florida's Plant Science Research and Education Unit (PSREU) near Citra, Florida, during the summers of 2003 and 2004. The soil at the study site was a hyperthermic, uncoated typic Quartzipsamments of the Candler series with a 0 to 5% slope (Thomas et al., 1979). Measured soil texture was 95% sand, 2% silt, and 3% clay. Measured soil pH 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 two days before 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 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 treatments of 2, 4, and 6 week durations were conducted during July and August. The 2003 and 2004 treatments began on sequential dates and concluded on 12 August 2003 and 11 August 2004, respectively.

Six soil cores 2.5 cm in diameter and 15 cm deep were collected from each plot at 0 days post-treatment in 2003 and 4 days post-treatment in 2004. The samples were air dried and sieved to pass a 2-mm stainless steel screen. Nitrogen concentration was determined for soil samples using a modified micro-Kjeldahl procedure (Bremner, 1965) and further modified as follows (Gallaher, personal communication, 2005). A 2-g sample was placed into a 100-ml Pyrex test tube followed by the addition of 3.2-g salt catalyst mixture (9:1 of K_2SO_4 : $CuSO_4$) and then 10 ml H_2SO_4. Samples were mixed using a vortex mixer. This was followed by the addition of two 1-ml increments of H_2O_2 after tubes were placed in the aluminum block digester (Gallaher et al., 1975). Pyrex funnels were placed on the top of each test tube to help conserve acid and increase reflux action during digestion for 3.5 hours at 375°C. Tubes were cooled and mixed with the vortex

mixer again while diluting with deionized water to 75 ml volume. Solutions were transferred to plastic storage bottles. Subsamples of solutions were placed in small test tubes and analyzed colorimetrically using a Technicon Autoanalyzer II. Nitrogen levels were recorded on a graphics printout recorder. The unknown readings were charted against known standards and concentrations determined using a simple regression model computer program (Gallaher, personal communication, 2005).

Mineral concentrations in solution were first extracted from the soil using the Mehlich I double-acid method (Mehlich, 1953). Soil Ca, Mg, Cu, Fe, Mn, Zn were determined by atomic absorption spectrometery, soil K and Na 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 (Hanlon et al., 1994). Mechanical analysis was used to determine percent sand, silt, and clay using a soil hydrometer method (Bouyoucos, 1936; Day, 1965). Percent organic matter was determined using the Walkley-Black method (Walkley, 1935; Allison, 1965). Cation exchange capacity was determined by the summation method of relevant cations (Hesse, 1972; Jackson, 1958).

Okra (*Hibiscus esculentus* L. 'Clemson spineless') seeds were planted and germinated in a growth room, then moved to a greenhouse for maturation. The 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, 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}. This hay was obtained from a cowpea cover crop growing in an adjacent field, which was cut at the early bloom stage,

and applied fresh to the plots on the same day it was cut. The cowpea was analyzed for nutrient concentration from samples collected at the time of application. The okra was 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 and cowpea plant material, plant material was weighed, dried, and ground and solutions were prepared using the Mehlich I double-acid method (Mehlich, 1953). Nitrogen concentration 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 (Bremner, 1965; Gallaher et al., 1975; Gallaher, personal communication, 2005). Leaf tissue concentrations of Ca, Mg, Cu, Fe, Mn, and Zn were determined by atomic absorption spectrometery, K and Na by atomic emission spectrometry, and P by colorimetry.

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 test at the $\alpha = 0.05$ level. All data were analyzed using MSTAT-C software (Michigan State University, East Lansing, MI).

During the field experiment in 2004, several events occurred that may have influenced the results. On 6 August 2004, herbicide [Roundup (propan-2-amine)] was applied accidentally to some of the plots. The control treatments were exposed while the solarized treatments remained under plastic. The error was immediately recognized and

the areas affected were rinsed with water. Further, three hurricanes occurred during the season that caused an increase in total rainfall over the experimental period [94 cm (37 in)] to more than twice that in the previous season [38 cm (15 in], which may have caused *Pythium* sp. infection of the okra plants (Florida Automated Weather Network, 2005). The hurricanes also brought high winds that damaged many of the okra plants, decreasing the number of replicates in the experimental plots.

Results

Soil Mineral Nutrients

In the 2003 experiment, a significantly ($p < 0.05$) higher concentration of Mn (mg kg^{-1}) was found in the soil of solarized treatments (Table 4-1). CEC (meq $100g^{-1}$) was also higher ($p < 0.05$) in solarized treatments (Table 4-2). Zinc (mg kg^{-1}) and organic matter (%) were significantly lower in solarized treatments ($p < 0.10$). The concentration of Na was reduced by 20 to 24% in the 2- and 4-week treatments compared to the 6-week treatment ($p < 0.01$).

Potassium, N, Cu, and pH showed significant interactions of solarization treatment x duration (Table 4-1). Potassium was 73% higher in 4-week solarized treatments when compared to the 4-week non-solarized treatments ($p < 0.05$). Among durations of solarization, K was highest in the 4-week treatment and lowest in the 2-week treatment ($p < 0.05$). 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 ($p < 0.05$). Copper was significantly lower in each duration of solarized treatment compared to non-solarized treatments, and Cu was highest 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-

week and 6-week durations compared to non-solarized plots (Table 4-2). 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 4-1), none of the mineral nutrients or soil properties was affected by the duration of solarization treatment.

In 2004, the concentration of Mn in solarized treatments was 22% higher than non-solarized treatments ($p < 0.05$; Table 4-3). Soil K was 54% higher in solarized plots ($p < 0.01$) and the concentration increased as duration increased ($p < 0.1$). Soil pH was reduced ($p < 0.01$) in solarized treatments (Table 4-4). Organic matter (g kg^{-1}) was significantly higher in solarized treatments compared to non-solarized treatments ($p < 0.05$).

Significant duration x solarization interactions were detected in the concentrations of soil Na and Cu in 2004 (Table 4-3). Sodium was higher in 4- and 6-week solarization treatments compared to the 2-week solarized treatment ($p < 0.05$). Sodium was also lower in the 2-week solarized treatment compared to the 2-week non-solarized treatment ($p < 0.01$) but higher in the 6-week solarized treatment compared to the 6-week non-solarized treatment ($p < 0.1$). Copper was 23% lower in the 6-week solarized treatment compared to the 6-week non-solarized treatment. Among solarized duration treatments, Cu concentration was higher in the 4-week treatment than in either the 2- or the 6-week treatments ($p < 0.05$).

Okra Leaf Tissue Nutrients

During the 2003 experiment, the concentration of K in leaf tissue was 40% higher in solarized treatments compared to non-solarized treatments ($p < 0.01$; Table 4-5). Nitrogen 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 Mn was 29% higher in solarized treatments than non-solarized treatments ($p < 0.05$).

In 2003, ANOVA of the concentrations of Mg, P, Na, and Zn in okra leaf tissue resulted in significant interactions between solarization duration and treatment (Table 4-5). Magnesium was 30% lower in 6-week solarized treatments compared to 6-week non-solarized treatments ($p < 0.05$). Phosphorous concentration was 29% lower in the 6-week solarized treatment compared to the 6-week non-solarized treatment, and among non-solarized 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 ($p < 0.05$). Sodium was 40% higher in the 4-week solarized treatment compared to the 4-week non-solarized treatment ($p < 0.05$). The concentration of Zn was 29% lower in the 6-week solarized treatment than in the 6-week non-solarized treatment ($p < 0.05$).

In 2004, the K concentration in okra leaf tissue was higher ($p < 0.05$) in solarized treatments (Table 4-6). Potassium concentration in leaves was higher in 6-week treatments than in the 4-week treatments ($p < 0.05$). No other leaf tissue nutrient concentration showed any treatment effects in 2004.

Okra Biomass

In 2003, the 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 4-7). Okra biomass was 67% lower in the 6-week non-solarized compared to the 2-week non-solarized treatment ($p < 0.05$). In 2004, okra biomass was almost three times higher in the 4-week solarized treatment than in the 4-week non-solarized treatment ($p < 0.01$).

There were no other significant differences in biomass based on solarization treatment or duration of treatment in 2004.

Discussion

Several soil mineral nutrients were affected by solarization treatments. Extractable N increased only in 2-week solarized soil in 2003, but not in 2004. The inconsistency between experimental years may have been due to the application of herbicide in the control plots in 2004 or the sandy soil type, which had relatively low levels of organic matter (1%). In both years, K and Mn in soil were higher in solarized treatments. This effect may have been due to reduced leaching by rainfall under solarization plastic during treatment; the amount of rainfall during solarization treatment was 20.9 cm in 2003 and 36.9 cm in 2004, with some 2-3 day periods receiving up to 7.6 cm (Florida Automated Weather Network, 2005). We also saw a decrease in Cu with solarization treatment in both years, a finding that is consistent with earlier research (Stapleton et al., 1985). In 2003, Zn decreased with solarization as well. In 2004, Na increased in 4- and 6-week solarization treatments, which is consistent with a previous 6 to 7 week solarization treatment on sandy soil (Chen and Katan, 1980). Soil pH decreased significantly with solarization treatment, although the maximum difference was 0.3, in the 2- and 6-week durations in 2003 and overall in 2004. Although these pH differences were small, this deviation from previous research, which found no change or inconsistent changes in pH in solarized soils (Chen and Katan, 1980; Stapleton et al. 1985), may be due to the sandy soil type, sampling methods, or analytical methods.

Prior solarization research examining plant tissue found no significant differences in nutrient concentrations (Stapleton et al., 1985). However, in the current experiment, K concentration in leaf tissue increased with solarization treatment in both years. This

increase may reflect the increase in K in solarized soil, a decrease in K in non-solarized plots due to weed competition, or may be influenced by other chemical and physical changes in the soil. In 2003, N, Mn, and Na increased in leaf tissue in solarized treatments, while Mg, P, and Zn decreased. The increase in N and Mn in leaf tissue may reflect the increase of these nutrients in solarized soil and may also be considered an indicator of overall plant health. In 2004, there were no differences in the concentration of nutrients other than K. The lack of differences in leaf tissue nutrient concentration 2004 may be attributed to the decrease in plant replication and the plant damage caused by the hurricanes.

In 2003, 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 (Seman-Varner, Chapter 3) and a likely reflection of overall plant health. The data from 2004 indicate a significant increase in okra biomass in 4-week solarized treatments compared to 4-week non-solarized treatments, while no significant difference appears between the 6-week treatments. This deviation from the data for the first year is due to the application of herbicide to the non-solarized plots, which would have impacted the 6-week non-solarized plots most because these had the most mature weeds at the time of herbicide application. Lower leaf tissue concentrations of Mn in 2004 compared to 2003 may have impacted okra biomass. The data from 2003 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.

Conclusion

In general, the changes in soil mineral nutrients were reflected in changes in leaf tissue nutrients, with only a few exceptions. Data from 2003 were more reflective of the effects of solarization on soil chemistry, leaf nutrients, and plant biomass, due to the herbicide application and anomalous weather in 2004. Overall, solarization increased concentrations of essential nutrients. 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 availability of 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.

Table 4-1. Extractable soil mineral nutrient concentrations from 2003 summer solarization experiment (0 days post-treatment).

	Soil nutrient concentrations (mg kg^{-1})														
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	----------N----------			----------P----------			----------K----------			----------Ca----------			----------Mg----------		
2	406 A[y]	340 B*[z]	373	38.9	38.1	38.5	21.4 C	22.7 A	22.1	103.4	115.0	109.2	10.8	13.0	11.9
4	385 A	408 A	397	38.6	46.5	42.6	37.0 A	21.4 A*	24.2	97.5	93.9	95.7	11.8	9.0	10.4
6	381 A	406 A	394	40.3	47.6	44.0	30.6 B	26.9 A	28.8	124.7	130.1	127.4	14.5	15.8	15.2
Mean	391	385		39.3	44.1		26.4	23.7		108.6	113.0		12.4	12.6	
	----------Zn----------			----------Cu----------			----------Mn----------			----------Fe----------			----------Na----------		
2	1.2	1.4	1.3	0.25 A	0.27 B*		2.1	2.0	2.0	9.9	10.7	10.3	7.4	7.3	7.4 B
4	1.4	1.4	1.4	0.26 A	0.29 AB*		2.2	2.0	2.1	10.5	11.5	11.0	8.5	7.1	7.8 B
6	1.3	1.5	1.4	0.24 A	0.31 A*		2.4	1.7	2.1	9.8	11.4	10.6	10.1	9.4	9.8 A
Mean	1.3	1.5**		0.25	0.29		2.2	1.9*		10.1	11.2		8.7	8.0	

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.

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

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

Table 4-2. Soil properties from 2003 summer solarization experiment (0 days post-treatment).

	pH			Organic matter (g kg^{-1})			CEC (cmol kg^{-1})		
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2	5.2 A[y]	5.3 B*[z]	5.3	10.5	11.0	10.7	2.7	2.5	2.6
4	5.3 A	5.3 B	5.3	10.6	12.2	11.4	2.6	2.6	2.6
6	5.3 A	5.6 A*	5.4	11.5	12.0	11.8	2.9	2.7	2.8
Mean	5.3	5.4		10.9	11.7+		2.7	2.6*	

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test. No letter indicates no significant difference.
[z] +, and * indicates significant differences between solarized and non-solarized at $p < 0.10$ and 0.05, respectively. No symbol indicates no significant difference.

Table 4-3. Extractable soil mineral nutrient concentrations from 2004 summer solarization experiment (4 days post-treatment).

	Soil nutrient concentrations (mg kg^{-1})														
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	----------N----------			----------P----------			----------K----------			----------Ca----------			----------Mg----------		
2	357	338	347	73.0	74.4	73.7	27.2	21.6	24.4 B	158.2	148.2	153.2	22.6	20.6	21.6
4	352	364	358	90.8	81.1	86.0	44.7	25.0	34.9 AB	260.1	200.0	230.0	39.3	29.3	34.3
6	355	347	351	79.1	84.0	81.6	47.8	31.2	39.5 A	187.4	195.0	191.2	33.5	34.2	33.8
Mean	355	350		81.0	79.8		39.9	25.9***[z]		201.9	181.1		31.8	28.0	
	----------Zn----------			----------Cu----------			----------Mn----------			----------Fe----------			----------Na----------		
2	1.4	1.7	1.6	0.26 B[y]	0.26 A	0.26	3.3	2.6	2.9	18.1	18.8	18.4	3.6 B	4.5 A**	4.0
4	2.1	1.9	2.0	0.32 A	0.28 A	0.28	3.6	2.8	3.2	19.1	18.6	18.8	5.3 A	5.0 A	5.2
6	1.8	1.8	1.8	0.23 B	0.30 A*	0.26	3.1	2.8	2.9	17.6	18.7	18.2	5.8 A	4.6 A+	5.2
Mean	1.8	1.8		0.27	0.27		3.3	2.7**		18.3	18.7		8.7	8.0	

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 11 August 2004.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test. No letter indicates no significant difference.

[z] +, *, **, and *** indicate significant differences between solarized and non-solarized at $p < 0.10$, 0.05, 0.01, and 0.001, respectively. No symbol indicates no significant difference.

Table 4-4. Soil properties from 2004 summer solarization experiment (4 days post-treatment).

	pH			Organic matter (g kg^{-1})			CEC (cmol kg^{-1})		
Dur[y]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
2	5.6	5.8	5.7	11.1	11.1	11.1	3.61	3.44	3.52
4	5.8	6.0	5.9	10.8	11.2	11.0	4.05	3.65	3.85
6	5.8	6.0	5.9	11.2	10.7	11.0	3.72	3.74	3.73
Mean	5.7	5.9**[z]		11.1	11.0*		3.79	3.61	

[y] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.
[z] *, and ** indicates significant differences between solarized and non-solarized at $p < 0.05$ and 0.01, respectively. No symbol indicates no significant difference.

Table 4-5. Okra leaf tissue nutrient concentrations at conclusion of 2003 summer solarization experiment (59 days post-treatement).

	Okra leaf nutrient concentrations														
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	--------N (g kg^{-1})--------			-------P (g kg^{-1})-------			--------K (g kg^{-1})--------			-------Ca (g kg^{-1})-------			--------Mg (g kg^{-1})--------		
2	41.2	38.6	39.9 A[y]	4.3 AB	4.4 B	4.3	33.4	28.2	30.8	66.4	55.4	60.9	7.0 A	8.4 A	7.7
4	37.3	29.2	33.3 B	4.9 A	4.9 B	4.9	38.1	22.2	30.2	56.2	67.3	61.8	7.6 A	7.3 A	7.4
6	30.1	29.2	29.7 B	4.0 B	5.6 A*	4.8	33.4	24.3	28.9	55.6	60.6	58.1	6.1 A	8.7 A*	7.4
Mean	36.2	32.3*[z]		4.4	5.0		35.0	24.9***		59.4	61.1		6.9	8.1	
	-------Zn (mg kg^{-1})------			------Cu (mg kg^{-1})-------			------Mn (mg kg^{-1})-----			--------Fe (mg kg^{-1})-----			--------Na (g kg^{-1})--------		
2	102 A	102 A	102	7.2	7.4	7.3	442	327	385	196	188	192	0.62 A	0.55 A	0.58
4	123 A	129 A	126	9.0	7.6	8.3	515	440	478	298	156	227	0.76 A	0.54 A*	0.65
6	99 A	139 A*	119	6.0	10.8	8.4	518	373	445	154	168	161	0.70 A	0.75 A	0.72
Mean	108	123		7.4	8.6		492	380*		216	171		0.69	0.61	

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test. No letter indicates no significant difference.

[z] *, and *** indicate significant differences between solarized and non-solarized at $p < 0.05$ and 0.001, respectively. No symbol indicates no significant difference.

Table 4-6. Okra leaf tissue nutrient concentrations at conclusion of 2004 summer solarization experiment (65 days post-treatment).

	Okra leaf nutrient concentrations														
Dur[x]	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean	Sol	Non	Mean
	-------N (g kg^{-1})--------			--------P (g kg^{-1})-----			---------K (g kg^{-1})----------			------Ca (g kg^{-1})-------			-----Mg (g kg^{-1})------		
2	49.9	51.7	50.8	4.3	4.5	4.5	27.6	23.9	25.7 AB[y]	25.9	26.7	26.3	6.9	8.5	7.7
4	48.3	49.6	49.0	4.2	4.3	4.3	24.9	24.8	24.8 B	25.7	26.6	26.2	7.3	7.6	7.4
6	50.6	50.0	50.3	4.5	4.5	4.5	30.3	24.3	27.3 A	26.2	24.2	25.2	7.2	7.2	7.2
Mean	49.6	50.4		4.3	4.4		27.6	24.3*[z]		25.9	25.9		7.1	7.8	
	----Zn (mg kg^{-1})-----			------Cu (mg kg^{-1})-----			-----Mn (mg kg^{-1})------			--------Fe (mg kg^{-1})-----			------Na (g kg^{-1})-----		
2	67	72	70	6.8	8.0	7.4	140	124	132	100	108	104	0.8	0.6	0.7
4	62	71	67	5.6	6.2	5.9	108	115	111	110	94	102	0.8	0.8	0.8
6	62	69	66	9.2	7.8	8.5	72	90	81	114	110	112	0.8	0.8	0.8
Mean	63	71		7.2	7.3		107	110		108	104		0.8	0.7	

[x] Duration (Dur) of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 11 August 2004.

[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test. No letter indicates no significant difference.

[z] +, *, **, and *** indicate significant differences between solarized and non-solarized at $p < 0.10$, 0.05, 0.01, and 0.001, respectively. No symbol indicates no significant difference.

Table 4-7. Dry okra biomass at conclusion of summer solarization experiments, 2003 (56 days post-treatment) and 2004 (67 days post-treatment).

	Dry weight of okra biomass (g)					
	2003			2004		
Duration[x]	Sol	Non	Mean	Sol	Non	Mean
2	181.0 A[y]	161.8 A[z]	171.4	37.8 A	43.6 A	40.7
4	247.4 A	81.6 AB**	164.5	106.3 A	35.7 A**	71.0
6	221.1 A	54.1 B***	137.6	96.8 A	85.2 A	91.0
Mean	216.5	99.2		80.3	54.9	

[x] Duration of solarized (Sol) and non-solarized (Non) treatments in weeks, ending on 12 August 2003 and 11 August 2004.
[y] Means in columns followed by the same letter do not differ at $p < 0.05$ according to LSD test; no letters in column indicate no differences at $p < 0.05$.
[z] ** and *** indicate significant differences between solarized and non-solarized at $p < 0.01$ and 0.001, respectively.

CHAPTER 5
EFFECTS OF SOLARIZATION ON RELATIONSHIPS BETWEEN OKRA BIOMASS, LEAF NUTRIENT CONTENT, AND SOIL PROPERTIES

Introduction

Recent restrictions on soil fumigants including methyl bromide have caused increasing research emphasis on non-chemical methods of soil disinfestation. Modern soil solarization developed in the 1970s and expanded to 38 countries by 1990 (Katan and DeVay, 1991). Within the last quarter century, soil solarization has been one of the most researched non-chemical methods of soil-borne pest management. This technique has successfully been used in the management of fungal, bacterial, nematode, insect, and weed pests.

Soil solarization involves the application of thin (25-30μm), clear polyethylene or polyvinyl chloride plastic that transmits solar radiation to heat the underlying soil and subsequently kills soil-borne pests (Katan, 1981; Katan and DeVay, 1991; McGovern and McSorley, 1997). During solarization treatments, the upper 30 cm of the soil is heated to temperatures usually within the range of 30-60°C, depending on soil type, soil moisture, climate, and treatment enhancements (Katan, 1981). Over the course of treatment, generally 4 to 8 weeks, the soil is diurnally heated with temperatures highest at shallower depths and maximum temperatures reached in the afternoon hours. The cyclic heating of the soil results in lethal temperatures sustained long enough to kill a variety of pests. Once the plastic is removed, the soil is disinfested and ready for planting.

Many studies have concluded that solarization positively affects crop yield by managing soil-borne pests (see reviews by Davis, 1991; Elmore, 1991; McGovern and McSorley, 1997). While the effects of solarization on soil organisms and crop yield have been extensively studied, its influence on extractable soil mineral nutrients has not been thoroughly researched. One review by Chen et al. (1991) cited examples of research conducted on the effects of sterilization, steam treatment, fumigation, and solarization on extractable soil mineral content. Solarized soils contained higher levels of NH_4^+, NO_3^-, N, Ca^{2+}, and Mg^{2+} (Chen and Katan, 1980). Phosphorous, K and Cl also increased in some soils (Chen et al., 1991). The few studies on soil mineral effects have not examined the effect solarization may have on relationships between soil nutrients and plant mineral nutrients. This important information will add to the understanding of crop nutrition in solarized soils.

The objectives of this study were to examine the indirect effects of solarization on the relationships between leaf biomass, soil nutrients, and leaf nutrient content. We specifically focused on soil and plant mineral nutrients including N, P, K, Ca, and Mg. We examined how solarization may have indirectly changed the relationships between leaf biomass and soil mineral nutrients. Then we examined the indirect effect of solarization on the relationships between nutrients found in leaf tissue and those in the soil.

Methods

This experiment was conducted at the University of Florida's Plant Science Research and Education Unit (PSREU) near Citra, Florida, during the summer of 2003. The soil at the study site was a hyperthermic, uncoated Candler Series sand with a 0 to 5% slope (Thomas et al., 1979). The soil texture was 95% sand, with only 2% silt and 3%

clay. Soil pH 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 two days before beds were constructed.

We used a split-plot experimental design where 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 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 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.

Six soil cores 2.5 cm in diameter and 15 cm deep were collected from each plot immediately following treatment. The cores were composited and a subsample was removed for the analysis of Mehlich I extractable (Mehlich, 1953) nutrients (N, P, K, Ca, Mg, Na, Cu, Fe, Mn, Zn) and properties (pH, CEC, OM; Marshall et al., 2002). Solutions were made by standard procedures. Nitrogen was analyzed with an aluminum block digester (Gallaher et al., 1975) and analyzed by a modified micro Kjeldahl procedure (Marshall et al., 2002). Phosphorous was analyzed with colorimetry. Flame emission spectrophotometry was used for K concentration. Calcium, Mg, Na, Cu, Fe, Mn and Zn concentrations were analyzed using atomic absorption spectrophotometry (Gallaher et al., 1973).

Okra (*Hibiscus esculentus* L. 'Clemson spineless') seed was planted and germinated in a growth room, then moved to a greenhouse for maturation. The 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, okra seedlings were planted in the experimental plots. An organic fertilizer 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 cowpea was analyzed for nutrient concentration at the time of application. The okra was harvested 6 weeks after planting, at early flowering. Leaf tissue was collected, dried, weighed and ground for nutrient analysis. For the analysis of both okra and cowpea plant material, solutions were prepared and nutrient content was analyzed using standard procedures similar to those used for soil mineral analysis (Gallaher et al., 1973; Gallaher et al., 1975).

Okra leaf nutrient concentrations (g kg^{-1}) were transformed into nutrient contents (mg of nutrient/leaf) by multiplying the concentration by the total dry matter per number of leaves in the sample. Leaf dry matter, leaf nutrient content, and extractable soil nutrient data were analyzed by computing correlation coefficients (r) in solarized and non-solarized treatments using MSTAT-C software (Michigan State University, East Lansing, MI).

Results

Leaf tissue analysis of the cowpea green hay provided the nutrient concentration of the organic fertilizer, which included 21.0 g kg^{-1} N (Table 5-1). Okra leaf dry matter was positively correlated with soil Ca ($r = 0.64$; $p < 0.01$) and Mg ($r = 0.61$; $p < 0.05$) in solarized treatments but not correlated ($r = 0.43$ for Ca, $r = 0.46$ for Mg; $p > 0.05$) in non-solarized plots. The correlation coefficients of dry matter with other nutrients, including

N, P, and K, were not significant ($p > 0.05$) in solarized or non-solarized treatments (data not shown). Correlations of the same mineral nutrient in the leaf tissue with its concentration in soil were positive and highly significant ($p < 0.02$) for Ca and Mg and significant ($p < 0.10$) for N, Mn, and Zn in solarized plots (Table 5-2). When correlating different plant nutrients with soil mineral nutrients, we found several positive relationships ($p < 0.05$) in solarized plots, while the non-solarized plots did not show significant ($p > 0.05$) relationships (Table 5-3).

Discussion

Leaf biomass was positively correlated with leaf Ca content and leaf Mg content in solarized plots. Calcium is an important nutrient involved in the structural support of the plant cell wall. Magnesium is essential to photosynthesis and energy production (Mills and Jones, 1991). Both nutrients positively influenced leaf production and biomass. The lack of significant correlation between leaf biomass and leaf nutrient content in non-solarized treatments may be due to weed competition.

Essential nutrients available in the soil should show a positive correlation with the same nutrients in leaf tissue. This expectation was supported by the data in the solarized plots, with significant positive correlation coefficients for Ca, Mg, N, Mn, and Zn in soil and leaf tissue ($p < 0.1$). Calcium in soil and Ca in the leaf, and Mg in soil and Mg in the leaf were more strongly correlated than the other nutrients with $r = 0.75$ and $r = 0.58$, respectively. These correlations may be due to the concentration of K in the soil, which may have limited Ca and Mg uptake by the plant (Gallaher and Jellum, 1976). As the N, Mn, and Zn content in soil increased, the content in the plant also increased. This relationship can be explained by the necessity of N or by the limited availability of Mn and Zn.

The correlation coefficients relating mineral nutrients in the plant to different mineral nutrients in the soil in solarized plots show positive relationships. Both Ca and Mg positively influence P uptake, as these data support. It is thought that Ca stimulates the transport of P, and Mg activates enzymes involving P (Mills and Jones, 1991). A positive correlation was also expected between K and N due to their close functioning, and this was indeed the case. Nitrogen measured was in elemental form and so we cannot deduce what mechanism of influence it may have had on Ca and Mg, although the data suggest a positive correlation. An inverse relationship was expected between Ca and Mg, but we found a positive correlation. This deviation may be due to concentration levels, other soil chemical properties (such as soil K), or the specific needs of okra plants.

In solarized plots, the strength of relationships between leaf biomass and extractable soil nutrients and between leaf nutrient content and extractable soil nutrients is probably due in part to a decrease in weed competition directly caused by solarization. The high weed population in non-solarized plots would have influenced leaf biomass and nutrient concentration through direct competition and indirectly altered the relationships between leaf biomass, leaf nutrient content, and levels of extractable soil nutrients.

Conclusion

Solarization improved plant growth and nutrient uptake as is represented in the positive correlations of leaf biomass, leaf nutrient content, and soil nutrients in the solarized plots. The lack of significant correlation coefficients in the non-solarized plots suggests some interference, possibly weed competition, reduced soil nutrient mineralization due to lower soil temperatures, or increased leaching due to exposure to rainfall. Solarization benefited the plant and positively influenced nutrient uptake from

the soil and from an organic fertilizer source. The correlations suggest that solarization facilitates growth and nutrient uptake by the plant.

Table 5-1. Cowpea green fertilizer nutrient concentration and content for each 3.5 kg m^{-2} application.

Cowpea nutrients	Concentration	Fertilizer nutrient content
	----------g kg^{-1}----------	---------- mg m^{-2} ----------
N	21.0	18.4
P	3.3	2.9
K	28.4	33.6
Ca	13.9	12.2
Mg	3.1	2.7

Table 5-2. Correlation coefficients (r) and levels of significance (p) of the relationship between okra leaf tissue nutrient content and extractable soil nutrients in solarized treatments.

Plant/Soil[+]	r	p
Ca/Ca	0.75	<0.01
Mg/Mg	0.58	0.02
N/N	0.49	0.06
Mn/Mn	0.45	0.09
Zn/Zn	0.50	0.06

[+] indicates nutrient content of okra leaf tissue correlated with extractable soil nutrient

Table 5-3. Correlation coefficients (r) and level of significance (p) for correlations between leaf tissue nutrients and soil minerals in solarized and non-solarized treatments.

	Solarized		Non-solarized	
Plant/Soil[+]	r	p	r	p
Ca/Mg	0.68	<0.01	0.38	0.16
Mg/Ca	0.59	0.02	0.49	0.06
Mg/N	0.57	0.03	-0.19	0.49
K/N	0.51	0.05	-0.20	0.48
P/Ca	0.58	0.02	0.43	0.10
P/Mg	0.57	0.03	0.48	0.07
N/Ca	0.61	0.02	0.40	0.13
N/Mg	0.57	0.03	0.43	0.11

[+] indicates nutrient content of okra leaf tissue correlated with extractable soil nutrient

CHAPTER 6
CONCLUSIONS

Solarization experiments conducted during summer 2003 and summer 2004 had various results in the management of specific organisms. Although the experimental site did not have an infestation of nematodes initially, nematodes recolonized solarized plots at a slower rate than non-solarized plots. The decrease in recolonization rate in solarized treatments was likely aided by the significant reduction in alternative weed hosts in solarized plots compared to non-solarized plots. Duration of solarization did not affect nematode population levels. Collembola and mites were generally reduced by solarization and remained lower in solarized plots than in non-solarized plots up to 2 months post-treatment. Duration of solarization treatment did not affect microarthropod populations. Despite the reduction in microarthropods by solarization, the availability of nutrients from an organic fertilizer was not affected, suggesting the importance and rapid recovery of fungal and bacterial detritivores.

Solarization significantly reduced weed cover throughout the experiment (up to 65 days post-treatment), although there were no differences among duration (2, 4, and 6 weeks) of solarization. The number of plants or stems was greatly reduced by solarization as well. In 2003, non-solarized plots reached 100% coverage by 28 days post-treatment. Individual species were affected differently in 2003. *Indigofera hirsuta* was more effectively reduced by 4- and 6-week solarization than by the 2-week treatment. *Cyperus* spp. were reduced initially by the 4- and 6-week solarization treatments, but differences were not detected post-treatment when numbers remained low in solarized plots and were

reduced in non-solarized plots by competition by other weed species. Weed biomass was reduced by 90% due to solarization in 2003. The data from 2004 were confounded by the application of herbicide to some of the control plots, making some analysis unclear and changing the species composition of the weed plots.

Potassium and Mn consistently increased in solarized soil, while Cu decreased. These data do not support earlier findings of increased NH_4^+ and NO_3^- concentration in soil (Chen and Katan, 1980; Stapleton et al., 1985), which may be due to soil differences, anomalous weather, or differences in sampling and analysis. Another unique result of this experiment is a slight reduction in soil pH due to solarization; this too may be related to soil type, sampling, or analysis. Concentrations of K in leaf tissue consistently increased in solarized treatments, another unique result that may be a reflection of K increase in the soil. In 2003, concentrations of leaf tissue N, Mn and Na also increased, while Mg, P, and Zn decreased. These results were not repeated in 2004, possibly due to experimental differences caused by weather or herbicide.

In 2003, okra biomass was tripled in 4-week solarization treatments and quadrupled in 6-week solarization treatments compared to non-solarized treatments of the same durations. There was no difference between 2-week solarized and non-solarized treatments. The increased biomass is likely due to a reduction in weed competition in the 4- and 6-week solarized plots. Based on these data on okra performance, the availability of an organic nutrient source was not hindered by solarization. These data also suggest that solarization treatments of 4- and 6-weeks are more effective in increasing overall crop health and biomass than a 2-week treatment, not only due to pest reduction but also

due to an increased growth response associated with improved soil nutrients and properties.

Examination of the relationships between soil nutrient content and properties, leaf tissue nutrient content, and leaf biomass, also supported the result that solarization improved overall plant health. Biomass was positively correlated with Ca and Mg contents in the leaf in solarized treatments, reflecting the importance of these nutrients to leaf structure and photosynthesis. In solarized treatments, there were also positive correlations between Ca, Mg, N, Mn and Zn in soil and the same nutrient in leaf tissue. In general, nutrients in soil were positively correlated with nutrients in leaf tissue in solarized treatments, while the same correlations were insignificant or weaker in non-solarized treatments. These differences between solarized and non-solarized treatments are likely due to weed competition in non-solarized plots that would have interfered with the relationships between soil nutrients and properties, leaf tissue nutrients, and leaf biomass.

Solarization was an effective method of managing weeds, nematodes, microarthropods, and soil and crop nutrients. Solarization reduced nematode, Collembola and mite populations; although solarization did not hinder the availability of nutrients from an organic fertilizer source. Four and 6-week solarization durations were more effective in reducing populations of certain weed species (e.g. *Indigofera hirsuta* and *Cyperus* spp.). Solarization increased K and Mn in soil and subsequently K in leaf tissue. Solarization treatments of 4- and 6-week durations were more effective in increasing crop biomass than the 2-week treatment. In general, these data suggest that the optimal solarization duration for summer in north Florida is 4- or 6-weeks, but may vary for

management foci or target species. These data also suggest that solarization is a useful management technique due to effective pest management (weeds and nematodes), and increased growth responses related to soil chemistry and properties. This non-chemical method of soil disinfestation could be further optimized by more studies on individual organisms, particularly weed species, and including research on soil fungi and bacteria. Solarization continues to be an effective, versatile, and environmentally-sound alternative to the use of soil fumigants.

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BIOGRAPHICAL SKETCH

Rachel Seman-Varner first became interested in natural science as a young girl. She spent many afternoons exploring the small patches of forest that remained around her suburban Tampa home. During her senior year of high school, her academic interests shifted from literature to science because of her first physics class and the incredible teacher who inspired her there. As a freshman she enrolled in an introductory botany class and decided then on her major. During her last year in the Department of Botany at the University of Florida, Rachel was honored with an undergraduate research scholarship. She developed hypotheses and methods, conducted research, and analyzed and presented an independent research project on the eco-physiology of south Florida mangroves. After graduation, Rachel delayed her application to graduate school and accepted an internship on an organic farm in Gainesville. On the farm she learned how scientific research, plant ecology, and environmental conservation could be merged to improve sustainable agricultural practices. Her entry into a master's program, with a focus on agricultural ecology, marked the synthesis of love of the natural world, education in plant biology, experience in scientific research, and dedication to sustainability. It was during her master's program that her loving and inspiring marriage, and the birth of her first daughter reinforced the necessity to secure a sustainable future.