

**AGROECONOMIC EFFECT OF SOIL SOLARIZATION ON FALL-PLANTED
LETTUCE**

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ABSTRACT

The effects of summer soil solarization on the production and economics of four lettuce cultivars were evaluated in two plantings conducted during the fall growing season of 2001, to determine the feasibility of integrating strip-solarization in plasticulture cropping systems. Soil was solarized for 53 and 34 days for the first and second plantings, respectively, using transparent (T4, T5) and black films (T6) that were kept in place as plastic mulches in raised beds through the fall season. Soil temperatures were recorded at 5 and 10-cm depths at 1-hour intervals during the solarization period. Mulch on T5 was painted black before planting the crop using diluted oil-based paint. Non-solarization treatments included bare ground (T1), fall black plastic mulch (T2) and fall plastic mulch + soil pesticides (T3). Soil pesticides applied on T3 during the first and second plantings were Mefenoxam (MEF) and a mixture of 1,3-Dichloropropene and Chloropicrin (TC-35), respectively. Temperature regimes below clear and black plastic mulches were equivalent, although clear film consistently showed longer periods of sustained high temperatures. Solarization with clear and black mulches equally increased lettuce yield by enhancing plant growth and head weight, as plant stand was uniform for all the treatments. MEF did not affect yield, and TC-35 decreased head weight due to phytotoxicity. Solarization reduced weed densities, especially from grasses. Enhanced weed suppression was achieved by using black plastic for solarization and mulching. MEF increased weed populations while TC-35 caused maximum weed suppression. Cost analysis revealed that yield increases required to cover solarization expenses in bare-ground and fall-mulch systems are generally lower than yield increases reported in previous solarization research.

CHAPTER 1

INTRODUCTION

Soil solarization is an application of soil mulching used to increase soil temperatures to levels that are lethal to microorganisms that cause diseases in crops of economic importance. This technology originated during the 1970s that was intended for soil disinfestation by means of solar energy. At the time, the deleterious effect of high temperatures on soil-borne pathogens was already known, but heat treatment of soils was not widely implemented due to economic considerations and practicality issues. Soil mulching was also a well-known practice that was utilized to increase the productivity of crops by manipulating the environment to enhance plant development and growth.

Soil solarization was initially pioneered in countries in the Middle East, where intense solar radiation and high temperatures are appropriate for solar heating. Although a great amount of solarization research is still done in that region, the technology has been studied in many countries of the world. A better understanding of the factors determining the performance of soil solarization has allowed researchers to implement solarization in areas with less than optimal climates, often with favorable results.

Environmental and health concerns have prompted the appearance of stricter regulations for the usage of agricultural pesticides. This, in turn, has motivated the development and application of alternative technologies such as soil solarization. Soil solarization has already been implemented in commercial production systems, and has a great potential for organic produce growers, where efficient control methods for weeds and soil-borne pathogens are almost nonexistent.

Despite all the investigative work that has been conducted on the subject, a better understanding of solarization is needed. The inherent complexity of the technology makes it difficult to implement and prone to yield erratic results. Solarization has been known to affect not only soil-borne pathogens, but also many other organisms and abiotic factors that indirectly affect plant development and growth. In addition, the effects of solarization in the production and economics of crops can be influenced by many factors, making field validation an indispensable step before formulating a recommendation regarding soil solarization.

Known limitations of soil solarization are high implementation costs, and the requirement of special logistics and managerial abilities. Because of these limitations, solarization is used primarily for high-value crops such as lettuce and other vegetables. The lack of information about soil solarization for vegetable crops in the southeastern/gulf region motivated this investigation. The objective of the present study was to assess the effects of soil solarization on the production aspects and the economics of lettuce.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Soil solarization is a process in which soil temperature is increased by using solar radiation as an energy source. It was initially intended as a method for controlling soil pathogens (Katan et al., 1976) but research has shown that it has other effects on soil characteristics that can influence the performance of crops, such as nutrient concentration (Chen et al., 1991) and soluble organic matter content (Chen et al., 2000).

The physical, chemical and biological principles of soil solarization, as well as its commercial implementation have been researched in many countries around the world. The effects of solarization have been investigated for many vegetable crops such as artichokes, bell pepper, cabbage, cucumber, eggplant, garlic, melon, onion, potato, strawberry, sweetpotato and tomato, among others. Katan et al. (1987) provided an extensive list of documents published during the first decade of soil solarization.

2.2. Principles of Soil Solarization

Soil solarization is accomplished by manipulating the energy balance of the soil. This balance depends on the direction and magnitude of the net heat exchange between the soil and the atmosphere. As soil is exposed to solar radiation, it accumulates heat throughout the day. Under normal circumstances this energy is eventually released by radiative and convective processes. Soil temperatures are maintained within a range determined by local conditions such as climate and soil characteristics. During solarization, soil is covered with mulch that reduces heat losses without significantly interfering with the absorption of solar energy, resulting in increased soil temperatures.

2.2.1. Soil Energy Balance

Gutkowski and Terranova (1991) and Mahrer (1991) discussed the mechanisms that affect the soil energy balance on bare and mulched soils. Soil energy balance can be mathematically described as follows:

$$R_s + R_l - S - H - E = 0$$

Where R_s and R_l are the net fluxes of short and long wave radiation at the soil surface (radiative fluxes), S is conduction of heat in the soil (soil heat flux), H is the net heat exchange due to convection (sensible heat flux) and E is the net heat exchange due to evaporation and condensation of water (latent heat flux). These fluxes determine the temperature regime of the soil, and can be manipulated by covering the soil with appropriate mulches.

Radiative fluxes are determined by the photometric characteristics (transmission, absorption and reflection of electromagnetic radiation) of both the soil and the mulch. Soils of darker colors tend to have higher temperatures due to increased light absorption. Mulches that are transparent to short-wave radiation and reflective to long-wave radiation increase the influx of heat into the soil by inducing a greenhouse effect.

The soil heat flux influences the heat storage capacity of the soil, as it determines how deep the heat wave can penetrate into the soil during exposure to solar radiation. It depends on the thermal conductivity and the specific heat capacity of the soil, properties that are influenced by the soil water content. Heat conductivity is higher in soils with higher water content.

Mulching reduces sensible heat fluxes, because air circulation between the soil and the atmosphere is limited. In mulched soils, sensible heat exchanges take place through the air layer trapped between the soil and the mulch and by convection from the mulch to the ambient air.

Sensible fluxes depend on the heat transfer capacity and the temperature of the mulch (determined by its optical properties), and on the thickness of the air layer between the soil and the mulch. These fluxes can be affected by heat leaks due to loss of integrity of the mulch.

Latent heat fluxes are determined by the evaporation and condensation of water from the soil, processes that require and release energy, respectively. Part of the energy lost through evaporation is recovered as water condenses on the mulch of soils under solarization. Water condensation on the mulch will modify its optical characteristics, affecting both radiative and sensible heat fluxes.

In order to manipulate the soil energy balance to attain maximum temperatures for soil solarization, the absorption of solar energy by the soil has to be maximized while minimizing its heat losses. Such conditions can be achieved by using mulch that is transparent to long-wave radiation and reflective to short-wave radiation. Temperatures can be further increased by installing the mulch over moistened soil, separated from the ground by a layer of a few centimeters of air.

2.2.2. Plastic Mulches for Soil Solarization

Mulches used for solarization are films of plastic polymers, usually polyethylene (PE), polyvinyl chloride (PVC), or ethylene-vinyl acetate (EVA). PE films are the most widely used. Among the desirable characteristics that make PE films popular are tensile strength, resistance to tearing when exposed to strong winds and low cost (Brown et al., 1991^b; Stevens et al., 1991).

The optical properties of PVC and EVA are more desirable than those of PE for soil solarization, but their manufacture is more complicated and therefore, they are more expensive (Lamberti and Basile, 1991). Gutkowski and Terranova (1991) observed that temperatures in soils mulched with EVA films are higher than in soils mulched with PE films. Noto (1994) found

that temperatures for PVC film were slightly higher than those for PE. Cascone and D'Emilio (2000) compared the performance of EVA and co-extruded EVA-EVA and EVA-PE films on the effectiveness of greenhouse soil solarization for controlling soil-borne pathogens, but since the mulches were of different color and thickness, an identification of the polymer effects could not be done.

Plastic films can contain additives that improve their properties for use in solarization. Additives include pigments, heat-retaining substances, wetting agents, ultraviolet stabilizers and photodegradable or biodegradable additives (Brown et al., 1991^b; Stevens et al., 1991).

Pigments alter the photometric characteristics of plastic films. Since the optical properties of the mulch determine the irradiative and sensible heat fluxes in soil under solarization (Ham et al., 1993), pigmentation of the plastic plays an important role on the efficiency of the mulch in soil energy management. Alkassy and Alkaraghoul (1991) tested the performance of different color plastic mulches for soil solarization and reported that soil temperatures decreased for the colors in the following order: red, transparent, green, blue, yellow and black. Traditionally, soil solarization has been implemented using either transparent or black mulches. Black PE films are usually pigmented with carbon black fillers, while transparent films have no pigment at all.

Abu-Gharbieh et al. (1991) reported that the use of black mulch improved plant growth and yield of several crops in a magnitude equivalent to that of transparent film. Since black film had lower temperatures and was slightly inferior in reducing populations of soil-borne pathogens, mechanisms other than thermal death were suggested to explain the equivalent yield response. Chase et al. (1999^b) and Campiglia et al. (2000) observed that soil temperatures under transparent film were higher than under black mulch, while Ham et al. (1993) reported the

opposite. Rieger et al. (2001) found black and clear mulches equally effective for increasing soil temperatures.

Heat-retaining substances and wetting agents also play a role in the photometric characteristics of mulch. Mineral additives such as aluminum silicates can be added to PE films to increase their opacity to long-wave radiation and enhance the greenhouse effect in the soil (Brown et al., 1991^b; Stevens et al., 1991; Chase et al. 1999^b). Wetting agents in the film allow humidity to condense in a thin, continuous layer that also traps heat without significantly reducing the light transmittance of the plastic (Lamberti and Basile, 1991).

Plastic films degrade when exposed to ultraviolet (UV) radiation, one of the components of natural light. This degradative process compromises film integrity, which is required in order to minimize heat losses from the soil. Plastic degradation due to exposure to natural radiation has been slowed down by the addition of UV stabilizers, such as benzophenones, nickel compounds and hindered amines. Carbon black, a common pigment for black films, also acts as a UV stabilizer: as a general rule, black films last longer than films of other color (Abu-Irmaileh, 1991; Brown et al., 1991^b; Stevens et al., 1991).

The durability of plastic films can be further controlled by the addition of other substances that increase the rate of degradative processes. Photodegradable PE films contain substances that accelerate the degradation of plastic exposed to light (for example, ferric ion complexes or calcium carbonate). Biodegradable plastics include substances in the polymer matrix that can be metabolized by microorganisms in the soil, accelerating the disintegration of the film into small particles. Film degradation has been considered as an alternative to inconvenient and costly removal and disposal procedures traditionally used for plastic mulches (Brown et al., 1991^a; Stevens et al., 1991).

2.3. Effects on Agroecosystems

Solar radiation heats the soil in daily cycles, inducing temperature fluctuations within a range that decreases with depth. Peak high temperatures normally take place during the afternoon, occurring later as depth increases (Katan and DeVay, 1991). Soil mulching with plastic films increases soil temperature in a magnitude that depends on soil characteristics, mulch properties and environmental conditions (Gutkowski and Terranova, 1991; Mahrer, 1991).

The utilization of plastic mulches for soil solarization differs from their use in traditional plasticulture, where mulching is intended to warm the soil for early plant growth. In solarization, soil is mulched in an attempt to increase temperature to lethal or near-lethal levels during the hottest periods of the year (Katan and DeVay, 1991). Solarization is intended mainly as a means of controlling soil-borne pathogens. However, increases in both plant growth and yield unrelated to pest control have been documented for soil solarization (Chen et al., 1991).

2.3.1. General Biological Effects

The rise in temperature achieved during solarization has a direct effect on soil ecology. Many soil-inhabiting organisms are inactivated when exposed to the high temperatures achieved during this process (Stapleton, 1991). Research suggests that thermal inactivation is caused mainly by the loss of integrity in cellular membranes, which occurs as the fluidity of membrane lipids increases when temperatures rise. Another possible mechanism of thermal inactivation involves the sustained inhibition of enzymatic systems, especially those involved in respiratory processes.

The sensitivity of an organism to high temperatures is strongly determined by the proportion of saturated to unsaturated lipids in its membranes: thermotropic transition from a solid phase to a fluid-liquid crystalline phase occurs at lower temperatures for unsaturated lipids.

Mesophilic microorganisms cannot survive exposure to high temperatures because of the high content of unsaturated lipids in their cellular membranes, which suffer from functional breakdown and instability under such conditions (DeVay and Katan, 1991).

Thermotolerance appears to be also determined by the production of heat shock proteins, which are synthesized by many eukaryotic organisms when exposed to high temperatures. Although survival of thermal stress has been improved in organisms previously incubated at moderate temperatures, the role of heat shock proteins in the survival of such organisms during soil solarization is unclear.

Responsiveness of heat shock protein synthesis to changes in temperature over the stress threshold depends on the species. Nevertheless, research suggests that the heat shock response in most organisms subjected to high temperatures is sustained until death occurs. Tolerance to high temperatures can be influenced by agents that affect the synthesis of heat shock proteins, such as cycloheximide (inhibitor), ethanol, sodium arsenite and anoxic conditions (elicitors). The influence of these agents suggests that interactions between organic compounds and other organisms in the soil could have an effect on heat tolerance (DeVay and Katan, 1991).

The term thermal death refers to permanent thermal inactivation of an organism. Since individuals within a population can show different degrees of susceptibility to heat injury, the notion of thermal death is applied through the concept of lethal dose (LD). The LD value represents the dose of heat required to kill a given proportion of the individuals in a population, commonly 90% for soil solarization. Such heat doses are expressed as a combination of temperature and time of exposure, and they are organism-specific (Elmore, 1998).

The set of time-temperature combinations that can be used to achieve a LD form a thermal death curve. Pullman et al. (1981) and Tamietti and Valentino (2001) estimated the

thermal death curves (LD₉₀) for the soil-borne pathogens *Verticillium dahliae*, *Pythium ultimum*, *Rhizoctonia solani* and *Thielaviopsis basicola*, concluding that time to thermal death is a log-linear (exponential) function of temperature. Although these curves are usually estimated for microbial agents, the concept has been extended to other organisms. Economou et al. (1998) estimated thermal death curves (LD₁₀₀) for three weed species. Sasanelli and Greco (2000) described a functional form for estimating thermal death curves for nematodes. Thermal death curves also have been estimated for fixed temperatures, where mortality is expressed a function of time (Pullman et al., 1981; Lazarovits et al., 1991^b).

Thermal death curves are estimated under continuous temperature regimes. Since soil temperatures in the field fluctuate over time, information obtained from thermal death curves should be applied to field situations with extreme care. Economou et al. (1991) investigated the effects of thermal degree hours on the seeds of the weeds *Avena sterilis*, *Bromus diandrus* and *Sinapis arvensis* under laboratory and greenhouse conditions. A thermal degree hour is accrued for each additional degree Celsius above a species-specific base temperature during a one-hour exposure. As expected from thermal death curves, the effect of thermal degree hours on weed seed death is non-linear and increases with temperature. Base temperature is chosen from thermal death curves to achieve control in a reasonable amount of time. The results of this study showed that temperature fluctuations in greenhouse conditions caused an increase in the LD₅₀ requirement of thermal degree hours that ranged between 46 and 72%.

Environmental factors other than temperature can also affect the sensitivity of organisms to heat, altering their thermal death curves. Besides influencing soil heat conductivity, moisture stimulates the metabolic activity of organisms in the soil, rendering them more susceptible to

thermal inactivation (Egley, 1990; Stapleton, 1991). Organisms are more tolerant to heat exposure when dormant or inactive under dry conditions (Elmore, 1998).

Sublethal heating can also have detrimental effects in soil-inhabiting organisms, such as reduction of growth, weakening of propagules and increased susceptibility to natural enemies (Stapleton, 1991; Tjamos and Fravel, 1995; Chase et al., 1999^a).

2.3.2. Chemical and Physical Changes in Soil

Solarized soils commonly undergo an increase in soluble substances that can be detected as a rise in the electrical conductivity (EC), or a decrease in the freezing point of the soil solution (Chen et al., 1991). This change has been attributed to an increase in the rate of decomposition of organic matter at high temperatures (Chen and Katan, 1980). Mesophilic organisms are killed and degraded during solarization, also liberating soluble substances into the soil (Stapleton, 1991). Chen et al. (2000) found that concentrations of dissolved organic matter (DOM) in saturated paste soil extract increased more than 100% in solarized soil. They suggested that processes taking place in solarized soil involved mainly the solubilization of low molecular weight humic substances instead of an increase in their formation. They also found that solarization had no effect in the composition of DOM.

Chen et al. (2000) documented an increase in the concentration of amino acids in solarized soils. This increase was attributed to enhanced microbial synthetic activity due to high temperatures. An increase in carbohydrate content was expected, but not found. Among other fractions of organic matter, carbohydrates play a significant role in soil-aggregate stabilization, property that affects soil hydraulic conductivity (Chen et al., 1991).

It is believed that solarization also affects the transport of ions to the soil surface (and therefore solute concentration) by interfering with water movement in the soil, as water

evaporating from the soil condenses in the mulch instead of escaping to the atmosphere (Chen et al. 1991). However, since both increases and decreases in ion concentration have been attributed to soil solarization, a definitive explanation about these mechanisms has yet to be formulated.

Increases in soluble mineral nutrients including NH_4^+ -N, NO_3^- -N, Phosphorus, K^+ , Ca^{+2} , Mg^{+2} , Mn^{+2} , Fe^{+3} , Cl^- and Cu^{+2} have been detected in solarized soils in several studies (Chen et al., 1991) although sometimes inconsistently (Daelemans, 1989; Moura and Palminha, 1994; Coates-Beckford et al., 1998), especially for the minor elements (Stapleton, 1998; Grunzweig et al. 1998). Wet soils covered with plastic mulch and protected from solar irradiation and heating did not differ in chemical properties from untreated control soils (Stapleton et al., 1985). This suggests that heating causes the release of soluble mineral nutrients from soil organic matter, although mulches can also increase nutrient concentrations by reducing leaching of solutes (Stevens et al., 1991).

The effect of solarization on the concentration and form of N in the soil has been studied due to the importance of this nutrient for plant growth. Generally, alternative procedures for soil disinfection result in an increase in its NH_4^+ -N content (fumigation with biocides) that can be accompanied by a decrease in NO_3^- -N concentrations (treatment with steam). Stapleton et al., (1985 and 1990) and Stapleton, (1998) suggested that since the concentrations of both nitrogen forms generally increase in solarized soils, N buildup is not exclusively caused by high temperatures. Solarization effects on the fraction of soil microflora involved in N cycling are different from those of fumigation or steaming (Stevens et al., 1991). While studying the effect of solarization in populations of nitrogen-fixing bacteria, Linke et al. (1991) observed that levels of NO_3^- -N in solarized soils were lower than those of nonsolarized soils during the rapid growth

stage of legumes. The difference was attributed to accelerated N consumption by plants growing with enhanced vigor on solarized plots.

2.3.3. Effects on Soil Microflora and Plant Pathogens

Solarization creates a partial biological vacuum in the soil. Although heat tolerance varies among organisms, generally only minutes are required at temperatures above 45°C to reach LD₉₀ levels (Stapleton, 1991). However, populations of mesophilic organisms decline at faster rates during solarization. For these organisms, accumulation of heat effects above 37°C over time is lethal (DeVay, 1991). Thermotolerant and thermophilic organisms usually survive the solarization process, but become weakened and vulnerable to changes in their ecosystem. Most plant pathogens and pests are mesophilic, being unable to grow at temperatures above 31-32°C (DeVay and Katan, 1991).

The success of soil solarization relies partially on the fact that plant pathogens tend to be less competitive than saprophytic microorganisms. Soon after the end of a solarization treatment, microorganisms begin to re-colonize soil, with highly competitive organisms proliferating at increased rates and faster than other organisms (Chen et al., 1991). Saprophytes become dominant after soil treatment, outcompeting soil-borne pathogens (DeVay and Katan, 1991).

Despite the fact that soil solarization was initially developed as a technique to control soil-borne pathogens (Katan et al., 1976), studies of the effects of soil solarization on the competitiveness of microorganisms have not been limited to pathogen control. Soil solarization reportedly reduced *Rhizobium* populations in solarized soil. However, populations quickly recovered after the establishment of a legume crop (Linke et al., 1991). Rupela and Sudarshana (1990) used this phenomenon to displace native strains of *Rhizobium* by an inoculant strain using soil solarization.

A large amount of research on the use of solarization for pathogen control has been conducted since its inception (Katan et al. 1987). Davis (1991) summarized the responses of representative plant pathogens and pests to soil solarization. Research on the performance of soil solarization as a method for controlling soil-borne diseases has been continuously conducted, especially for crops where alternative control methods are not available or disappearing. Solarization has been evaluated as an alternative to soil fumigation on many vegetable crops. Recent work in the area includes successful tests on basil, bean and lettuce (Minuto et al., 2000^a), strawberries (Rieger et al., 2001) and tomato (Ioannou, 2000).

Pathogens that survive exposure to the high temperatures of soil solarization are usually rendered more susceptible to other control agents, such as fumigants and biocontrols. Significant improvements in disease control can be achieved by synergistic combinations of soil solarization and alternative treatments (Davis 1991). Gamliel et al. (2000^a) successfully controlled *Fusarium oxysporum* and *Monosporascus cannonballus* in tomato and melon, respectively, by combining soil solarization and fumigation with either methyl bromide or metham sodium at reduced rates. Minuto et al. (2000^b) reduced fumigation rates of dazomet in half by implementing soil solarization, effectively controlling *Fusarium*, *Verticillium* and *Sclerotium* in tomato, basil and lettuce crops.

Tjamos and Fravel (1995) documented a synergistic interaction between heating and exposure to the biocontrol *Talaromyces flavus* that increased the mortality of *Verticillium dahliae* microsclerotia in laboratory experiments. Sivan and Chet (1993) tested the combined use of *Trichoderma harzianum* and soil solarization under field conditions, successfully controlling *F. oxysporum* f. sp. *radicis-lycopersici* and increasing tomato yield. On the other hand, Minuto et al. (1995) reported that the integration of the antagonistic microorganisms *T.*

harzianum and *Fusarium spp.* did not consistently enhance the control of *Rhizoctonia solani*, *Pythium ultimum* and *F. oxysporum* f. sp. *basilicum* achieved by solarization alone under plastic high tunnels.

Increased plant growth responses (IGR) following solarization on the absence of pathogens prompted research on the effects of soil heating on non-pathogenic microbial communities. Stapleton and DeVay (1984) investigated the effects of soil solarization on soil-borne pathogens, antibiotic-producing bacteria and symbiotic root microorganisms such as mycorrhizae. They reported a reduction in the populations of *Pythium spp.* and *V. dahliae*, and increases in the populations of beneficial gram-positive bacteria and plant growth-promoting rhizobacteria (PGPR), while root infection by vesicular-arbuscular mycorrhizae was apparently not affected by soil solarization.

Populations of *Bacillus spp.*, a gram-positive bacteria beneficial to plant growth and antagonistic to plant pathogens, reportedly increased after soil solarization, probably due to the thermophilic nature of the organism (Stapleton and DeVay, 1984). Fluorescent pseudomonads, an important heat-sensitive group of PGPR, rapidly colonized soil after the initial decline of their populations caused by solarization (Chen et al. 1991). Both *Bacillus spp.* and fluorescent pseudomonads are rhizosphere-competent and have been related to disease suppression in soils (DeVay and Katan, 1991).

Gamliel and Katan (1992^a and 1992^b) observed that chemotaxis of fluorescent pseudomonads towards tomato seed and root exudates is enhanced in solarized soils, improving the ability of these bacteria to compete for such exudates and colonize roots. Solarization increased the content of amino acids and lowered the sugar content in seed and root exudates, making them less favorable for growth of fungi and other bacteria. Similar results were reported

by Gamliel et al. (1989^a and 1989^b) who observed a decrease in the population of deleterious fungi and an increase in fluorescent pseudomonads after solarization of both soil and container media. Gamliel and Katan (1991) reported population increases of up to 130-fold in solarized soils.

Bendavid-Val et al. (1997) reported that indigenous populations of mycorrhizae were reduced to zero after 2 to 4 weeks of solarization. However, high temperatures did not affect mycorrhizae spore viability in their laboratory experiments, suggesting that temperatures cannot solely account for reduced populations in the field. Schreiner et al. (2001) suggested that solarization indirectly reduces mycorrhizae populations by eliminating the weeds that maintain infective propagules over the winter.

2.3.4. Effects on Weeds

Polyethylene mulching has been widely used for weed control in plasticulture. Opaque films block light and inhibit photosynthesis, killing weeds during crop development. The initiative of using soil solarization to control weeds started after its effects on organisms other than soil-borne pathogens became evident. Solarization is used for weed control especially when no other satisfactory method is available, which is the case for many weeds such as *Malva parviflora*, *Convolvulus arvensis* and *Abutilon theophrasti* (Elmore, 1991^a and 1991^b). However, solarization can offer a better alternative even when traditional methods of weed control are available. Stevens et al. (1990) achieved better weed control with solarization than with applications of the herbicide chlorthal-dimethyl. Root branching and fresh weight, rhizosphere microflora and yield of collards were negatively correlated with the application rate of the herbicide and increased by soil solarization.

The effectiveness of soil solarization for weed control is species-dependent. Linke (1994) studied the effect of soil solarization on 57 weed species, reporting that species with heat-tolerant seeds, bulbs, deep root systems or other perennial organs were poorly controlled and sometimes even stimulated by high temperatures. Tamietti and Valentino (2000) observed changes in the composition of the weed communities in solarized soil, reporting that monocotyledons were less susceptible to solarization. Satour et al. (1991^a) also reported differences in tolerance to soil solarization between several weed species.

As for other organisms, the ability of weeds to withstand high temperatures improves with dry conditions. Egley (1990) subjected the seeds of 8 weed species to temperatures of 70°C, observing that at 19% moisture most seeds survived for up to 3 days. At 2% moisture, most seeds survived for 7 days. However, the effect of moisture in thermotolerance is not always evident. Osman et al. (1991) reported that irrigation did not affect germination or viability in *Striga asiatica* seeds.

Depth also affects the susceptibility of weeds to soil solarization. Osman et al. (1991) reduced the germination, viability and emergence of seeds of *S. asiatica* by burying them in soil that then was solarized with transparent mulch. However, the mulch enhanced the emergence of *Striga* plants in field conditions. Such plants were assumed to have come from seeds buried at depths where solarization was not effective. Peachey et al. (2001) reported that solarization reduced *Poa annua* seed survival only in the upper 5 cm of soil while enhancing survival below.

Film opacity reportedly affects the performance of weed control in soil solarization. Campiglia et al. (2000) observed increased temperatures and better weed control with clear film compared to black mulch. However, the effect of film color on weeds appears to be related not only to temperature, but also to light. *Cyperus sp.*, a weed difficult to control, is a common target

for soil solarization. However, it is considered resistant to high temperatures that in some cases enhance germination and bud sprouting (Elmore, 1991^b). Kumar et al. (1993) reported that solarization with transparent plastic controlled *C. rotundus* seed germination while increasing emergence from tubers. Control increased with time of exposure, but it was restricted mainly to the first 5 cm below soil surface.

The increase in *Cyperus spp.* tuber emergence on mulched soils can become a problem since the emerging weed can perforate the film under certain conditions. Patterson (1998) observed in growth-chamber experiments that while nutsedge pierces opaque mulch under any light condition, it only punctures translucent mulch in the absence of light.

Chase et al. (1998) studied the effects of light on rhizome morphogenesis and mulch piercing by *Cyperus spp.* with similar results. Light changes development from rhizome elongation to leaf expansion, resulting in the plant being trapped and eventually scorched under clear mulches. This effect is enhanced when the film is not in close contact with the soil surface.

Interactions between temperature, moisture, light and thermotolerance are important for the long-term management of weeds in the soil bank. Since some weeds can tolerate exposure to high temperatures in moist soil, immediate or full weed control cannot be achieved with soil solarization. However, high temperatures can reduce potential weed pressure by reducing the viability of heat susceptible seeds and by breaking the dormancy of latent seeds stored in the seed bank (Egley, 1990).

2.3.5. Effects on Nematodes

Thermal treatment of soil and plant materials was a common method of nematode control before the development of chemical nematicides. Due to environmental and health concerns, finding alternatives to chemical control has become a research priority. Investigative efforts have

been reverted towards assessing the effect of soil heating on phytoparasitic nematodes (Stapleton and Heald, 1991).

Heald and Robinson (1987) investigated the effects of high temperatures on *Rotylenchus reniformis*, reporting that sublethal exposure times at lethal temperatures had a cumulative effect on thermal death. Repeated heat stress also reduced nematode motility and delayed egg hatch. These results support findings by Chellemi et al. (1994), who assessed the effectiveness of soil solarization for nematode control on tomato under sub-optimal climatic conditions. Solarization reduced nematode populations in a region of heavy rainfall and extended cloud cover, in some cases to levels equivalent to those achieved by methyl bromide fumigation.

Solarization reportedly reduces nematode populations in the soil. Barbercheck and von Broembsen (1986) reported reductions between 37 and 100% in nematode populations on soil solarized with clear plastic mulch. Satour et al. (1991^b) studied the effect of solarization on nematode populations on broad bean, corn, onion, potato, rape, strawberry and tomato crops, observing consistent reductions in nematode populations that normally tend to increase in non-solarized soils.

While the results of several studies on the control of nematodes by soil solarization appear to be relatively consistent, subsequent effects on host plants have been erratic. Sotomayor et al. (1999) observed that although solarization reduced *Meloidogyne arenaria* populations, it did not reduce galling in tomato roots. Noto (1994) reported that damage to tomato plants caused by *Meloidogyne spp.* was reduced by soil solarization. However, the magnitude of this effect depended on the tomato cultivar. Additionally, yields were higher on solarized soils but not always related to decreases in root infection. Coates-Beckford et al. (1997 and 1998) associated increases in growth and yield of cucumber with reductions in parasitic nematode populations

achieved by soil solarization with clear plastic. Lazarovits et al. (1991^a) observed reductions of *Pratylenchus penetrans* populations in the surface layer of solarized soil that did not result in significant responses in potato yield.

Results on replacement of chemical control methods have also been erratic. Stapleton and DeVay (1983) observed that soil solarization resulted in a significantly better control of nematodes than fumigation with 1,3-dichloropropene. Stephan et al. (1991) reported significant decreases in populations of *Meloidogyne javanica* and increased cucumber and eggplant yields after soil solarization. When compared to several chemical control methods, solarization was one of the most effective treatments, but its results were inconsistent. Ioannou (2000) reported that control of *Meloidogyne incognita* by soil solarization was inferior to fumigation with methyl bromide, which also was superior in residual effectiveness. However, both treatments resulted in similar increases in the yield of greenhouse tomato.

Among the practical limitations of solarization as a replacement for chemical nematode control, are its poor residual effectiveness and its reduced performance at increased depths. Kumar et al. (1993) reported that soil solarization reduced the populations of plant parasitic nematodes by approximately 90%. However, control was restricted to the upper 5 cm of soil, and nematode populations recovered significantly after 70 days. McSorley et al. (1999) observed that summer soil solarization reduced population levels of *M. incognita* in the fall, but this reduction did not persist into the spring. A partial explanation for this persistence was given by Lamberti and Greco (1991). After reviewing previous work in nematode control by soil solarization, they observed that while soil temperatures do not reach lethal levels at more than 30 cm deep, root systems in some annual plants can reach 40-50 cm deep, providing a potential refuge for plant

parasitic nematodes. Nevertheless, they acknowledged the usefulness of solarization as a practical means for short-term control of nematode populations.

2.3.6. Increased Growth Response (IGR)

Soil solarization often enhances plant growth and yield in pathogen-free soils. Noto (1994) reported higher yields and reduced nematode damage for tomato plants grown on solarized soil, compared to those planted in non-treated soil. However, yield was not related to root infection, indicating that solarization effects could be attributed to mechanisms other than nematode control. Abd El-Megid (1998) documented increased plant growth of onion transplants produced in solarized seedbeds, apparently without incidence of diseases. These reports correspond to a phenomenon known as increased growth response (IGR) that has been attributed to several mechanisms, including increases in nutrient levels in the soil solution, stimulation of beneficial organisms and control of minor pathogens (Gruenzweig, 1993).

As discussed in a previous section, the influence of solarization on the chemical and physical characteristics of soil has been documented. Increases in soluble mineral nutrients (Chen and Katan, 1980; Stapleton et al., 1984) and dissolved organic matter (Chen et al., 2000) have been related to soil solarization and IGR in plants. Chemical characteristics of soil determine the nutritional status of plants, therefore affecting its growth and development. Gruenzweig et al. (1998) documented increased concentrations of N, Cu, and decreased Cl and SO₄ in the xylem sap of tomato plants grown in solarized soil. Levels of N and Cu were positively related to shoot growth, whereas Cl and SO₄ showed the opposite. It was suggested that N and Cl play a major role in IGR and the effect of solarization.

Solarization can induce IGR also by enhancing biocontrol processes. Le Bihan et al. (1997) documented significant decreases in damping-off on solarized soils that were associated

with frequent isolations of *Trichoderma spp.*, a well-known biocontrol. Tjamos and Fravel (1995) reported a synergistic interaction between soil heating and the activity of the biocontrol *Talaromyces flavus* that increased the mortality of microsclerotia of *Verticillium dahliae*. Solarization can also give competitive advantage to facultative-saprophytic biocontrols by controlling other organisms that use the same resources. Gamliel and Stapleton (1995) reported that solarization with organic amendments did not affect populations of fluorescent pseudomonads and *Bacillus sp.* Anith et al. (2000) documented a synergistic interaction between *Pseudomonas fluorescens* and soil solarization that decreased *Ralstonia solanacearum* bacterial wilt and increased the yield of ginger. Yücel and Çali (1998) reported a synergistic interaction between soil solarization and the application of *Trichoderma harzianum* that increased tomato yields to levels equivalent to those obtained by fumigation with methyl bromide. The yield increase was attributed to an improvement in the control of *Fusarium oxysporum* f.sp. *lycopersici*, a thermotolerant vascular pathogen with saprophytic abilities.

Gruenzweig et al. (1993) studied the effects of solarization on growth patterns and physiological processes as related to IGR for tomato, corn, cucumber, sorghum and tobacco. Increased growth, accelerated development, extended photosynthetic activity, increased protein levels and delayed senescence of tissues were documented for plants grown in solarized soils. Differences observed between plants grown in solarized and non-solarized soils became more accentuated in late developmental stages of the plants.

Solarization seems to affect many physiological processes in plants, sometimes involving the alteration of normal hormonal balances. Grunzweig et al. (2000) investigated the involvement of giberellins in the regulation of increased tomato growth in solarized soil. Seedlings from solarized soil had higher dry weights and leaf weight ratios. Seedlings grown in

solarized soil had higher concentrations of GA₁ and GA₃, which were linearly related to the increase in leaf dry weight.

In some instances, soil disinfestation has produced effects opposite to IGR. This phenomenon is known as decreased growth response (DGR), and can be regarded as a negative side effect of soil disinfestation. DGR has been attributed to increased concentrations of certain toxic elements in the soil solution, namely Mn⁺² and NO₂⁻. However, these damaging effects are not common in soil solarization due to the mild nature of the process (Chen et al., 1991).

It is possible that beneficial organisms could be negatively affected by soil solarization, leading to DGR in associated plants. Caussanel et al. (1998) observed that soil solarization eliminated natural root infection by mycorrhizae, recommending re-inoculation before growing mycorrhizae-dependent crops such as *Valerianella locusta*. Bendavid-Val et al. (1997) reported that indigenous mycorrhiza populations were reduced to undetectable levels after solarization or fumigation, while *Glomus intraradices* inoculated in the soil remained viable after 8 weeks of solarization. Onion and carrot plants showed growth retardation when sown on solarized soil, whereas wheat showed IGR. Temperatures of 45°C did not affect the viability of mycorrhizae in the laboratory, indicating that temperatures cannot solely account for loss of viability in the field. Schreiner et al. (2001) suggested that soil solarization reduced mycorrhizae in soil indirectly by eliminating weeds that host their propagules during the winter season. However, direct reductions in soil mycorrhizae were observed after fumigation with methyl bromide or metam sodium, suggesting solarization is a low-impact disinfestation method.

2.4. Implementation of Soil Solarization

New regulations phasing out chemicals considered to be hazardous to the environment and public health have prompted the development and application of alternative technologies

such as soil solarization (Stapleton, 1996). Solarization has already been implemented in large commercial operations (Grinstein and Ausher, 1991), where it is used mainly for the disinfestation of greenhouse soil, seedbeds, containerized planting media and cold frames. Solarization in open fields has been implemented at a slow rate in areas with high temperatures (Stapleton, 2000).

Ideally, soil solarization should be applied only to the entire field to avoid border effects. Heat is lost near the borders of the mulch, decreasing temperature and reducing the local effects of solarization (Jacobson et al., 1980). However, complete field covering is complicated, involving increased costs and specialized equipment (Grinstein and Hetzroni, 1991). An alternative to complete field covering is strip mulching, where plastic film is installed on top of raised beds, leaving the furrows uncovered. It is generally a mechanized process that can be performed with equipment designed to install plastic mulch for plasticulture. The machine opens two trenches at each side of the bed, where the edges of the mulch are placed by two guide wheels that also stretch the film. Discs on the back of the machine return the soil to the trench, anchoring the film in it (Grinstein and Hetzroni, 1991). The main advantage of strip mulching is that its adoption in crops that are usually grown on mulched beds is relatively inexpensive, because solarization film can be kept in place to be used as post-solarization mulch (Grinstein and Ausher, 1991).

As previously reviewed, research has been done on the integration of soil solarization with complementary pest control tactics, such as biological control. One of the most promising areas of research on the subject is biofumigation. During biofumigation, soils amended with organic matter are solarized, promoting microbial activity and the generation of liquid and gaseous compounds that at certain concentrations can be toxic to plant pathogens. The toxicity of

such compounds increases with high temperatures, providing enhanced control of target pests (Gamliel et al., 2000^b). Gamliel and Stapleton (1995) found that root colonization by beneficial bacteria such as fluorescent pseudomonads and *Bacillus spp.* was not affected by the addition of amendments to the solarization treatment, suggesting that biological control could also be integrated with biofumigation. Several toxic volatiles such as alcohols, aldehydes, sulfides and isothiocyanates, have been detected in decomposing crucifer amendments that make them ideal for biofumigation (Gamliel et al., 1997). Crucifer plants have a high content of glucosinolates in their tissues. When subjected to enzymatic degradation, glucosinolates are hydrolyzed into various sulfur compounds with anti-microbial properties (Gamliel, 2000). Lodha et al. (1997) reported that irrigation and amendment with cruciferous residues improved the efficiency of soil solarization for the control of *Macrophomina phaseolina*. Coelho et al. (2000) found that adding cabbage residue to the soil reduced the time required for thermal inactivation of chlamydo spores of *Phytophthora nicotianae* during soil solarization. The effect of cabbage residues and other amendments on the efficiency of soil solarization has not been consistent, and is not yet fully understood. Coelho et al. (1999) observed that the incorporation of cabbage into the soil did not enhance the effectiveness of solarization in reducing populations of *Phytophthora spp.* regardless of the gas permeability of the plastic. Keinath (1996) reported that the incorporation of cabbage amendments prior to soil solarization increased the growth and yield of watermelon, but such increase could not be associated with changes in mineral nutrition or reductions in the populations of plant parasitic nematodes.

2.5. Economics of Soil Solarization

Solarization has to be economically feasible in order for it to be successful. Therefore, it is important to determine the costs and returns resulting from solarization, and how field factors

affect them (Yaron et al., 1991). Traditionally, the economic results from solarization have been assessed by comparison against results from untreated soils. Results from these comparisons are usually favorable to solarization. However, in order to get useful results, solarization has to be compared to alternative technologies available (Elmore, 1991^c).

Previous short-term studies on the economics of solarization have shown that due to high implementation costs, solarization is feasible only for high-value crops. Additionally, high costs increase the risk for the farmer (Elmore, 1991^c). Long-term studies have shown additional benefits of soil solarization, such as reduced pest pressure and improved yields (Yaron et al., 1991) that eventually will be reflected as an increase in net benefits. Also, solarization can help farmers access organic markets where high prices can compensate the additional cost and risk of solarization.

The use of soil solarization involves subjecting fields to 6-8 weeks of idle time at the peak of the summer season. Considering that land is often a limiting production factor, one must account for the idle time inherent in solarization (Yaron et al., 1991). Mansour et al. (1991) utilized the cost of renting land as an estimate of the opportunity cost of solarization.

Bell (1998) compared the costs of conventional farming and soil solarization for five vegetable crops in the Imperial Valley, California, and calculated the increases in yield required to cover the cost of solarization. Such increases ranged between 4.8 and 14% for broccoli, cabbage, carrot, crisphead lettuce and onion. Considering that in some cases solarization improves the quality of the produce resulting in a price premium, as for onions (Elmore, 1991), the required yield increments could be even smaller.

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CHAPTER 3

AGROECONOMIC EFFECT OF SOIL SOLARIZATION ON FALL-PLANTED LETTUCE

3.1. Introduction

The effects of soil solarization on pests and the yields of vegetable crops have been well documented. Solarization has been studied on artichoke, bell pepper, cabbage, cucumber, eggplant, garlic, melon, onion, potato, strawberry, sweetpotato and tomato among others (Katan et al., 1987). Solarization reduces pest and weed pressure, enhances the physical and chemical properties of the soil and increases the yield of subsequent crops (Davis, 1991). However, widespread adoption of solarization has been limited by high costs, since the additional expenses are not always recovered despite yield increases (Yaron et al., 1991). In addition, solarization results depend on non-controllable soil and climatic conditions (Gutkowski and Terranova, 1991), requiring field validation for regions where such conditions are less than optimal.

Strip-solarization has been successfully integrated into post-summer plasticulture cropping systems because little additional expense is required (Grinstein and Ausher, 1991). Films are installed over raised beds during the summer and left in place throughout the growing season, providing the benefits of both soil solarization and mulching. However, the effectiveness of soil solarization decreases when applied in strips, due to border effects caused by reduced temperatures at the edges of the mulch (Grinstein and Hetzroni, 1991). Therefore, it is important to determine if strip mulching can be reliably used to obtain the benefits of soil solarization.

Specialty lettuce crops are good candidates for soil solarization due to their high value. The effect of soil solarization on lettuce has been previously researched by Palumbo et al. (1997) and Campiglia et al. (1998), who reported increased lettuce yields in bare ground culture following soil solarization. Their results, however, were not consistent. The information

available on the utilization of strip-solarization for lettuce is scarce. The purpose of this study was to determine the effects of strip-solarization on the yield and the economics of fall-planted lettuce grown under a plasticulture system. Effects on soil temperatures and weed pressure were also examined.

3.2. Materials and Methods

Field experiments were conducted to evaluate the effect of strip soil solarization strategies on the production of fall planted lettuce. Experiments were conducted during the summer/fall seasons of 2001, at the Burden Research Center, Baton Rouge, Louisiana. Solarization strategies (treatments) were designed to test summer solarization with fall plastic mulch treatments using low-density polyethylene films. Treatments are listed in table 3.1.

Table 3.1. Solarization strategies evaluated in the study. Plastic films used during the solarization stage were left in place through the fall cropping season.

Treatment	Summer solarization	Fall mulch
T1	Bare ground	Bare ground
T2	Bare ground	Black film
T3	Bare ground	Black film + soil pesticide
T4	Transparent film	Transparent film
T5	Transparent film	Transparent film + black paint
T6	Black film	Black film

Treatments were evaluated for two plantings on four lettuce cultivars: "Buttercrunch" (Harris, Rochester, New York), "Two Star" (Orsetti, Hollister, California), "Tania" and "Waldmanns Dark Green" (Harris Moran, Modesto, California). Buttercrunch and Tania are Bibb and Butterhead-type cultivars, respectively, while the others are loose-leaf type cultivars. Treatments and varieties were assigned to experimental units following a split-plot design, with

treatments as main plots and varieties as subplots. Both plantings were blocked due to a soil fertility gradient. Experimental units (subplots) consisted of three raised beds 2.3 m long.

Polyethylene films were 1.22 m wide and 38 μm thick. Black and clear films (Climagro, St-Laurent, Quebec) were installed over pre-shaped beds using a plastic mulch layer (Kennco, Ruskin, Florida), with drip irrigation tape (Turbulent Twin-Wall, Chapin Watermatics, Watertown, New York) buried 7 cm deep in the center of the beds. Beds were 1.22 m apart and had a height of 23 cm and width of 36 and 53 cm at the top and bottom, respectively. Row middles of all treatments and beds on bare ground plots (T1) were kept weed-free with a mixture of 3.36 $\text{kg}\cdot\text{ha}^{-1}$ of Kerb 50 WP (50% Pronamide, Rohm and Haas, Philadelphia) and 2.37 $\text{L}\cdot\text{ha}^{-1}$ Gramoxone Extra (37% Paraquat dichloride, Syngenta, Greensboro, North Carolina).

Clear (T4, T5) and black (T6) solarization films were installed on 26 June and 24 July for the first and second plantings, respectively. These films were kept in place through the fall growing season. Fall mulch treatments (T2, T3) were installed on 19 Sept. and 10 Oct. Soil pesticides used for T3 differed between plantings. Ridomil Gold EC (47.6% Mefenoxam, Novartis, New York) was applied to the tops of the beds at a rate of 2.34 $\text{L}\cdot\text{ha}^{-1}$. Mefenoxam (MEF) was sprayed and incorporated with a rotary tiller before film installation for the first planting. For the second planting, Telone C-35 (61.1% 1,3-Dichloropropene + 34.7% Chloropicrin, Dow Agrosiences, Indianapolis, IN) was applied at a rate of 187 $\text{L}\cdot\text{ha}^{-1}$ while installing the film. Telone (TC-35) was injected approximately 5 cm off-center of the bed at a 30 cm depth. Before crop planting, mulch on treatment T5 was painted black using a backpack sprayer to cover the films with 495 $\text{L}\cdot\text{ha}^{-1}$ of a 43% (v/v) dilution of oil based paint in mineral spirits (Ramon Arancibia, personal communication) so that it was opaque.

Lettuce seedlings were grown in a greenhouse for 26 days, using 98-cell polyethylene trays (26.2 cm³ round cell, TLC Polyform, Plymouth, Minnesota) and germination media (Sunshine LG3, Sungro, Bellevue, Washington). Seedlings were hand-transplanted to the field on 21 Sept. and 20 Oct. Plants were staggered in beds in double rows at 26 cm between rows and 30 cm in-row spacing. Pre-plant fertilizer 8N–24P–24K was applied at a rate of 629 kg·ha⁻¹ before planting in bare ground plots, and before film installation in the rest of the treatments. N requirements were supplemented with 300 kg·ha⁻¹ of NH₄NO₃ administered in weekly intervals through the irrigation system. The soil was an Olivier silt loam (Typic Paleudults).

3.2.1. Soil Temperature

Soil temperatures were measured 5 and 10 cm below the top of the bed for each treatment on one block for both plantings. Copper-constantan double insulated thermocouples and a CR10X data logger (Campbell Scientific, Logan, Utah) were used to collect the data. Average, maximum and minimum hourly temperatures were measured and recorded for 53 and 34 days during the solarization periods for the first and second plantings, respectively.

Frequency distributions of hourly minimum temperatures and mean times with a continuous minimum temperature above 37°C were calculated for each mulch treatment (bare ground, clear and black film). Curves describing the evolution of mean temperatures along the diurnal cycle were constructed using mean temperatures for every hour. A linear model for mean temperatures between 8:00 and 24:00 was fit by the ordinary least squares criterion, where curves for the three mulches were simultaneously modeled for each depth. Although the actual functional form for each mulch/depth combination appeared to be either cubic or quadratic, third degree polynomials were used to provide consistency, as they adequately fit the two functional forms. The effect of plastic mulches on soil temperature was assessed by analysis of variance.

Comparisons were performed between estimates of the areas below the temperature curves, equivalent to thermal degree hours accumulated per day for a base temperature of 0°C (Economou et al., 1997). Maximum average temperature and its time of occurrence were estimated for each mulch/depth combination by calculating the roots of the first derivative of the corresponding polynomial.

3.2.2. Yield

The first lettuce harvest was on 25 Oct. and 21 Nov. for the first and second plantings, respectively. Plants were harvested when they reached an appropriate size, or left to be harvested on subsequent dates (29 Oct., 2 Nov. and 6 Nov. for planting I, and 26 Nov. and 30 Nov. for planting II). Appropriate size varied by cultivars: Tania was harvested when the head was firm (with a diameter of approximately 20 cm), while the other cultivars were harvested when the plant height reached approximately 25 cm. Fresh weight was recorded individually for heads harvested from 10 plants from the center bed of each subplot.

Mixed models for average yield were fitted by the restricted maximum likelihood method and used to perform analysis of variance, orthogonal contrasts and mean separation tests. A primary model with plantings and blocks as random factors was fit without including treatment T3. The form of the model was:

$$Y_{ijkl} = \mu_{ij} + \alpha_k + \beta_l + \gamma_{kl} + \delta_{ikl} + \varepsilon_{ijkl}$$

where Y is average lettuce head weight ($n = 10$), μ is the population mean for treatment i and cultivar j , α is the effect of field k , β is the effect of block l , γ is the field by block effect, δ is the whole plot effect and ε is the residual error. Due to the difference in soil pesticides between

plantings, hypotheses tests involving treatment T3 were tested with additional models fitted for each planting. Such models did not include the α and γ terms. Under standard assumptions, statistics for all the models follow exactly the t and F distributions, and standard errors are exact.

3.2.3. Weed Pressure

Weed pressure on the beds was assessed after the final harvest by counting the number of individuals in a 0.18-m² area on the center of the record row of each subplot. Mulch was removed, and separate counts were conducted for grass, sedge (*Cyperus spp.*) and broad leaf weeds. Data pooled from the two plantings was analyzed by non-parametric methods. Goodness of fit chi-square tests were performed to determine if weed counts were distributed following the proportions of experimental units (subplots) associated with treatments or groups of treatments. Proportions of experimental units were 12⁻¹ for T3/MEF and T3/TC-35, and 6⁻¹ for the rest of the treatments. Groups of treatments were the same as those in the contrasts tested for yield data.

Average weed density was compared between groups of treatments by means of ratios. These values were calculated as ratios of weed counts weighed by the reciprocals of the corresponding proportions of experimental units:

$$r = \frac{n_1 \cdot \left(\frac{m_1}{m_1 + m_2} \right)^{-1}}{n_2 \cdot \left(\frac{m_2}{m_1 + m_2} \right)^{-1}}$$

where n is the weed count from m subplots for treatment groups 1 and 2. These ratios are equal to one only if weed counts are distributed following the same proportions of the experimental units. Therefore, null hypotheses for the chi-square tests were of the following form:

$$H_0: r = 1$$

$$H_0: \frac{n_1}{n_2} = \frac{m_1}{m_2}$$

Additionally, homogeneity chi-square tests were performed on contingency tables to determine if the composition of the weed community differed between treatments (3×7) and groups of treatments (3×2). For both goodness of fit and homogeneity analyses, treatments were grouped the same as for the contrasts tested for yield data. All statistical analyses were performed using SAS/STAT v. 8e (SAS Institute, 2000) and R v. 1.4.1 (Ihaka and Gentleman, 1996).

3.2.4. Economics

Cost budgets were estimated for each treatment based on projected costs for Louisiana vegetable crops (Hinson and Boudreaux, 2002). Budgets were tailored for small operations with a high technological level, and included costs for soil preparation, pest management and cultural practices. Costs associated with soil solarization, fall-mulching and supplemental pest-control were added as required by each treatment. Land rent costs, which are usually not considered in production budgets, were included to account for the opportunity cost associated with keeping the field unproductive during the solarization period.

Lettuce yields required to cover production costs (breakeven yields) were calculated for each treatment, assuming a price of US\$ 5.45 per box of 24 heads (Takele, 2001). Relative increases in breakeven yields required to cover the differences in costs between T1, T2 and the rest of the treatments were also calculated.

3.3. Results and Discussion

3.3.1. Soil Temperature

Frequency distributions of minimum hourly temperatures (Figure 3.1) showed differences in the soil temperature regime under solarization. High values for minimum temperatures increased by over 10°C, while low values remained stable but less frequent.

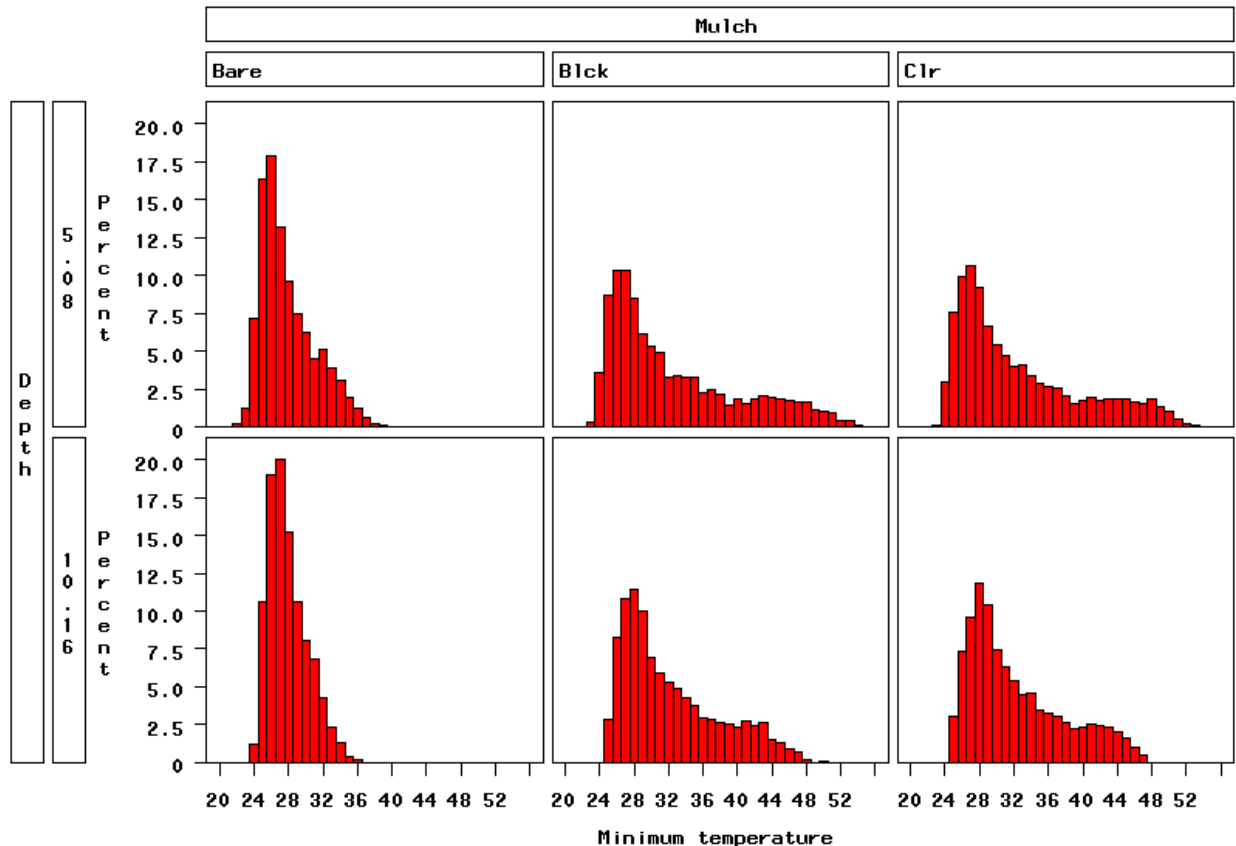


Figure 3.1. Frequency distributions of minimum hourly soil temperatures at 5 and 10-cm depth for bare ground, and black and clear mulches. Distributions were calculated from data from solarization periods of 1272 and 816 hours beginning on 26 June and 24 July, respectively.

Evolution of hourly minimum temperatures (Figure 3.2) shows that solarization increased temperatures primarily between 8:00 and 24:00. This increase coincided with the asymmetric expansion of the temperature range observed on the histograms.

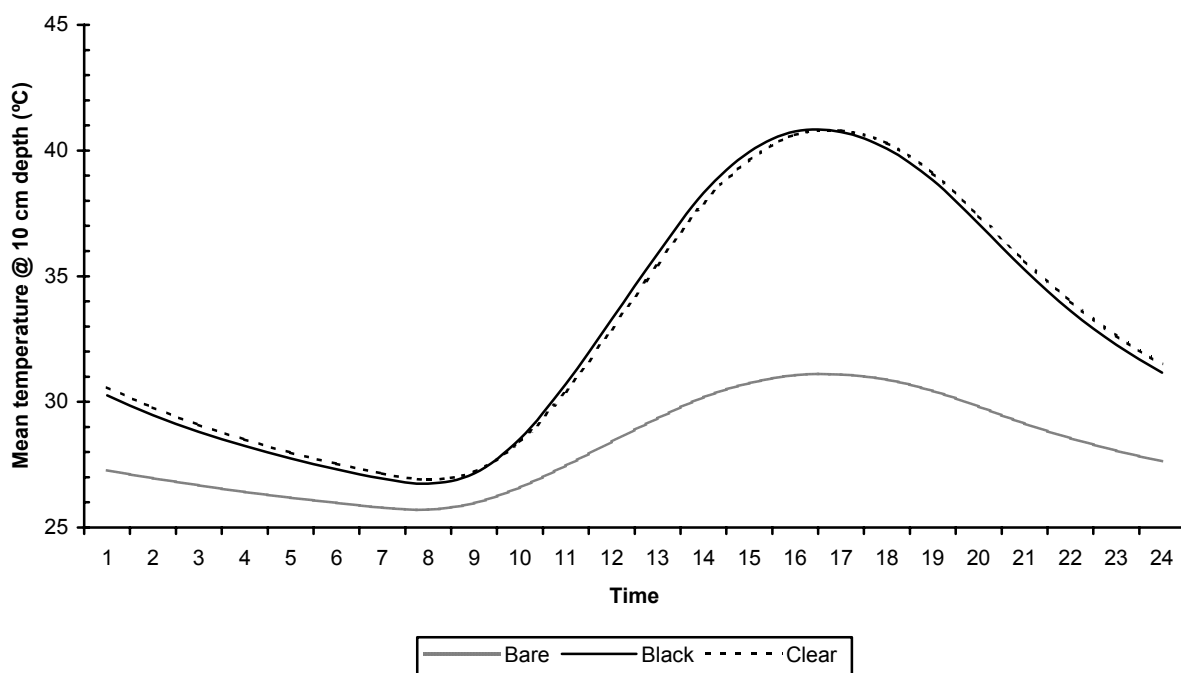


Figure 3.2. Mean hourly soil temperatures recorded under bare ground, and black and transparent mulches (depth = 10 cm). Means were calculated from data from solarization periods of 1272 and 816 hours beginning on 26 June and 24 July, respectively.

Both the distribution and evolution of minimum temperatures were similar for clear and black mulches. Mean times with continuous minimum temperatures were higher for the transparent mulch (Table 3.2), suggesting that clear films may have a higher potential for pathogen control.

Table 3.2. Mean times (h) with a continuous minimum temperature above 37°C (depth = 10 cm) under bare ground, and black and transparent mulches, calculated from data from solarization periods of 1272 and 816 hours beginning on 26 June and 24 July, respectively.

Mulch	Continuous minimum soil temperature (°C) at 10 cm depth											
	37	38	39	40	41	42	43	44	45	46	47	48
Bare ground	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Clear film	6.5	6.1	5.7	5.2	4.8	3.9	3.1	2.7	1.9	1.6	1.3	0.0
Black film	6.0	5.4	5.2	4.5	3.9	3.0	2.4	1.9	1.7	1.0	0.0	0.0

Mean temperature models (Table 3.3) were highly significant ($P < 0.0001$) and accounted for 96% of the variability observed in temperatures at both depths. Solarization significantly increased thermal degree hours by $114 \text{ h} \cdot \text{°C} \cdot \text{d}^{-1}$ and $99 \text{ h} \cdot \text{°C} \cdot \text{d}^{-1}$ at the 5 and 10 cm depths, respectively, with no differences between black and clear films. For both depths, the predicted peaks in average soil temperatures for black mulch occur approximately 20 minutes earlier than those for clear film.

Table 3.3. Cubic polynomial models for mean soil temperature between 8:00 and 24:00 for 5 and 10-cm depths. Models had an excellent fit ($R^2 = 0.96$) and were highly significant ($P < 0.0001$). Estimates of model parameters, area and peak temperature are shown, along with their standard errors (SE). Estimates of time of occurrence of peak temperatures are also shown. Models were estimated from averaged data from solarization periods of 1272 and 816 hours beginning on 26 June and 24 July, respectively ($n = 17$).

	Parameter estimates ^z				Area ^y ($\text{h} \cdot \text{°C} \cdot \text{d}^{-1}$)	Peak temperature		
	β_0	β_1	β_2	β_3		Max (°C)	SE (°C)	Time
Depth = 5 cm								
Clear mulch	-49.877	13.388	-0.585	0.007	588.3 ^a	42.3	0.54	15:45
Black mulch	-61.775	15.915	-0.742	0.010	593.1 ^a	43.0	0.53	15:25
Bare ground	-13.734	7.218	-0.352	0.005	476.3 ^b	32.2	0.53	15:09
SE	13.799	2.859	0.187	0.004	5.7			
Depth = 10 cm								
Clear mulch	4.999	2.153	0.090	-0.006	563.8 ^a	39.7	0.44	17:40
Black mulch	-1.977	3.612	-0.002	-0.004	563.7 ^a	39.7	0.44	17:22
Bare ground	13.824	1.618	-0.018	-0.001	465.2 ^b	30.7	0.45	17:21
SE	10.835	2.425	0.147	0.003	4.4			

^z β_0 = intercept, β_1 = linear, β_2 = quadratic and β_3 = cubic.

^yAreas with the same letters within each depth were not significantly different (t -test, $P \leq 0.01$).

3.3.2. Yield

Plant stand was not significantly affected by treatment or cultivar (data not shown). Less than 0.5% of the plants in record rows were lost during the experiments and no plants showed

disease symptoms. Both treatment and cultivar affected head weight, however, and consequently total yield (Table 3.4). There was no interaction between the two factors. The use of plastic mulch increased head weight by 70 g regardless of solarization treatment. In plasticulture treatments, solarization increased head weight by 23 g. This increase can be attributed to factors other than control of soil-borne pathogens, as no obvious disease symptoms were detected. Gamliel and Stapleton (1993) reported increases in lettuce plant stand and head weight as a result of solarization in non-plasticulture cropping systems. Palumbo et al. (1997) and Campiglia et al. (1998) also documented increases in lettuce yield due to solarization, although such increases were inconsistent. Film color (black or clear) during solarization and fall mulching did not affect head weight. Campiglia et al. (1998) compared the yields of lettuce from soils solarized with transparent and black films, reporting significantly higher yields for clear mulch in one of two growing seasons. It is likely that the effect of film opacity depends on other factors such as separation, or air layer, between mulch and the soil. Mefenoxam (MEF) did not affect head weight in the first planting. This result suggests that populations of Oomycete fungi pathogenic to lettuce were not large enough to cause disease. In the second planting, TC-35 significantly reduced head weight by 35 g, likely due to phytotoxicity caused by residues of the fumigant in the soil. A longer ventilation period is required between fumigation and crop planting. Effects for both pesticide treatments were calculated in comparison to mulch-only treatments.

Lettuce heads of compact-type cultivars (Buttercrunch and Tania) were significantly heavier than those of loose cultivars (Two Star and Waldmanns Dark Green). However, mean separation tests indicate that head weights for Buttercrunch and Two Star (compact and loose, respectively) were not significantly different. It is likely that phenotypic characteristics other than compactness affected head weight.

Table 3.4. Effects of treatments and cultivars on head weight of lettuce.

	Weight (g/head)	SE (g/head)	P-value (F-test)
Solarization treatments			< 0.01
<u>Treatment (summer + fall)</u>	<u>Mean^z</u>		
T1: Bare ground	275.8 ^b		
T2: Bare ground + black mulch	329.0 ^a		
T3: Bare ground + black mulch/MEF ^y	344.0		
T3: Bare ground + black mulch/TC-35 ^y	270.8		
T4: Solarization + mulch w/clear film	355.8 ^a		
T5: Solarization w/clear film + black paint	347.5 ^a		
T6: Solarization + mulch w/black film	353.4 ^a		
<u>Contrast</u>	<u>Difference</u>		
Plastic mulch vs. bare ground	70.6	10.8	< 0.01
^L MEF vs. fall mulch ^y	-8.5	16.0	0.60
^L TC-35 vs. fall mulch ^y	-34.6	14.2	0.03
^L Solarized vs. non solarized	23.3	11.1	0.05
^L Clear vs. black	-1.8	11.8	0.88
^L Painted vs. non painted	-8.2	13.6	0.55
Cultivars			< 0.01
<u>Cultivar</u>	<u>Mean^z</u>		
Tania	368.4 ^a		
Buttercrunch	336.1 ^b		
Two Star	336.0 ^b		
Waldmanns	288.7 ^c		
<u>Contrast</u>	<u>Difference</u>		
Compact vs. loose	39.9	8.6	< 0.01
^L Buttercrunch vs. Tania	-32.3	12.2	0.01
^L Two Star vs. Waldmanns	47.4	12.2	< 0.01
Treatments by cultivars			0.98

^zMeans with the same letters within columns were not significantly different at $P \leq 0.05$ (Tukey-Kramer procedure).

^yStatistics were calculated based only on data from one planting (MEF = Mefenoxam, TC-35 = 1,3-Dichloropropene + Chloropicrin). Data were omitted from analysis using main model.

3.3.3. Weed Pressure

Soil solarization significantly reduced weed pressure in plasticulture treatments (Tables 3.5 and 3.6). Weed density on non-solarized mulched plots was over four times higher than weed density for solarized plots. Al-Masoom et al. (1993) and Campiglia et al. (1998) reported that solarization significantly reduced weed pressure while increasing head lettuce yields.

Table 3.5. Density and composition of weed populations on experimental treatments and cultivars. Weed pressure on the beds was assessed after the final harvest by counting the number of individuals in a 0.18-m² area on the center of the record row of each subplot. Mulch was removed prior to counting.

Factor / Level	Density (u/m ²)	Broadleaf <i>Cyperus spp.</i> Grass		
		------(%)-----		
Solarization treatments (summer + fall)				
T1: Bare ground	533.3	73.3	0.3	26.4
T1: Bare ground + black mulch	173.4	29.7	1.1	69.2
T3: Bare ground + black mulch/MEF ^z	199.3	45.3	1.0	53.7
T3: Bare ground + black mulch/TC-35 ^z	13.5	69.2	7.7	23.1
T4: Solarization + mulch w/clear film	60.6	46.4	0.9	52.7
T5: Solarization w/clear film + black paint	20.5	52.5	19.5	28.0
T6: Solarization + mulch w/black film	21.7	59.2	2.4	38.4
Cultivars				
Tania	137.5	57.2	0.5	42.3
Buttercrunch	171.5	62.3	1.1	36.5
Two Star	157.3	58.0	2.1	39.9
Waldmanns	169.6	58.8	0.5	40.7

^zStatistics were calculated based only on data from one planting (MEF = Mefenoxam, TC-35 = 1,3-Dichloropropene + Chloropicrin).

The color of the solarization mulch also affected weed density: weed counts were 86% higher for clear films than for black mulches (Tables 3.5 and 3.6). However, this result is

opposite to observations by Campiglia et al. (1998), who reported that densities and dry weight yields of weeds on solarized soils were lower for transparent film than for black mulch.

Table 3.6. Ratios of average total weed density between groups of treatments, and tests for homogeneity of proportions across weed types. Tests of hypothesis were based on the chi-square statistic. Weed pressure on the beds was assessed after the final harvest by counting the number of individuals in a 0.18-m² area on the center of the record row of each subplot. Mulch was removed prior to counting.

Categories	Density comparison		Homogeneity			
	(H ₀ : r _{total} = 1)		(H ₀ : r _{BL} = r _C = r _G) ^z			
	Ratio	P-value	Ratio by type			P-value
	(r _{total})		r _{BL}	r _C	r _G	
Solarization treatments						
Plastic mulch ÷ bare ground	0.14	< 0.001	0.08	1.09	0.31	< 0.001
↳MEF ÷ fall mulch ^y	1.15	0.008	1.75	1.09	0.89	< 0.001
↳TC-35 ÷ fall mulch ^y	0.08	< 0.001	0.18	0.55	0.03	< 0.001 ^x
↳Solarized ÷ non solarized	0.24	< 0.001	0.34	0.97	0.18	< 0.001
↳Clear ÷ black	1.86	< 0.001	1.51	4.33	2.26	0.052
↳Painted ÷ non painted	0.33	< 0.001	0.38	7.67	0.18	< 0.001
Cultivars						
Compact ÷ loose	0.95	0.038	0.97	0.62	0.92	0.156
↳Buttercrunch ÷ Tania	1.25	< 0.001	1.36	2.83	1.08	0.003
↳Two Star ÷ Waldmanns	0.92	0.046	0.92	3.63	0.91	< 0.001

^zBL = broadleaf, C = *Cyperus spp.* and G = grass.

^yStatistics were calculated based only on data from one planting (MEF = Mefenoxam, TC-35 = 1,3-Dichloropropene + Chloropicrin).

^xOne cell (17%) had an expected frequency of less than 5.

Post-solarization mulch painting reduced weed pressure to a third of that for non-painted transparent film (Tables 3.5 and 3.6). These results suggest that film opacity contributed to weed suppression both during the solarization treatment and crop development. Since temperatures for

clear and black mulches were similar during solarization, and assuming that the photometric properties of black-painted clear film are equivalent to those of black plastic, the reduction in weed pressure under black films can be attributed to the lack of light. In the first planting, MEF significantly increased weed pressure by 15% compared to the standard fall-mulch treatment. Weed survival could have been enhanced by suppression of diseases of weeds caused by Oomycete fungi. In the second planting, TC-35 reduced weed density by 96% compared to non-solarized plastic mulch. This reduction was expected due to the herbicidal activity of TC-35.

The composition of weed communities was significantly affected by treatments and groups of treatments (Tables 3.5 and 3.6). The utilization of plastic mulches for solarization or fall mulching resulted in a reduction of the density of broad-leaf and grass weeds, while slightly increasing the density of *Cyperus spp.* as previously observed (Elmore, 1991). MEF reduced grass populations but increased the density of broadleaf and *Cyperus spp.* compared to fall-mulch. It is possible that the fungicide altered the balance of pathogenic and beneficial fungi in the soil, causing differences in emergence between weed types.

Soil treatment with either TC-35 or solarization reduced the densities of all weed types compared to fall-mulch. However, the density of *Cyperus spp.* in solarized plots was similar to that of non-solarized plots. The effectiveness of both treatments for controlling weeds varied among weed types, decreasing in the following order: grass, broadleaf and *Cyperus spp.*

The suppressive effect of the opacity of the solarization mulch on weed emergence also varied among weed types. Maximum and minimum suppressions were observed for *Cyperus spp.* and broad leaves, respectively. However, post-solarization painting of the mulch increased *Cyperus spp.* populations, while reducing the densities of other weed types.

3.3.4. Economics

Production costs by treatment were estimated by adding together the costs of individual operations or inputs (Table 3.7) as required by each treatment. All treatments but T1 included costs for mulch installation and removal (mulch layer, pickup truck and plastic film, and labor, respectively). The costs of soil pesticides MEF and TC-35 were included only for treatment T3. Post-solarization mulch painting was included only in treatment T5 (boom sprayer, paint and solvent). Finally, supplementary weed control costs were considered only for treatment T1. All the remaining costs were included for all the treatments.

Production costs of solarization treatments (T4 and T6) were \$1235 and \$490 higher than bare ground (T1) and fall-mulch (T2) cropping systems, respectively (Table 3.8). The additional expenses translate into increases in break-even yields of 15.1% for bare ground and 5.4% for fall-mulch. Bell (1998) reported that an increase of 4.8% in the yields of crisphead lettuce was required in order to cover solarization costs in conventional production in California, with a price of \$7.79 per carton of 24 heads. In this study, solarization expenses comprised the cost of plastic film, its application and its removal, and were estimated as \$750 per hectare. Previous research suggest that the increases in lettuce yield required to cover additional expenses can be attained with soil solarization. Palumbo et al. (1997) reported increases of 7 to 29% in lettuce yields due to soil solarization, while Campiglia et al. (1998) reported higher increases of 90-113%.

Results showed that substantial yield increases of 39.5 and 27.8% for bare ground and fall-mulch systems, respectively, are required to cover the additional cost of mulch painting. Since these increases are approximately twice as high as the increase required for switching from bare ground to a solarization system, it may be more convenient to install plastic mulch twice than to paint the mulch before planting the crop.

Table 3.7. Production costs of lettuce (1 ha) with drip irrigation, plastic mulch and soil fumigation. Prices and costs are in U.S. dollars.

Operation / input	Size/ unit	Performance rate (h-ha ⁻¹)	Times over	Tractor cost		Equipment cost		Allocated labor		Operating input		Total cost
				Direct	Fixed	Direct	Fixed	Hours	Cost	Amount	Price	
<u>Soil preparation</u>												
Lime (spread)	kg	-	1	-	-	-	-	-	-	747.6	0.1	54.4
Disc and herbicide applicator - 2 rows	1.8 m	1.46	2	5.8	4.6	2.1	2.9	3.2	24.1	-	-	39.4
Hipper and fertilizer applicator - 1 row	0.9 m	3.83	1	7.6	6.1	4.5	6.4	4.2	31.6	-	-	56.1
8-24-24	kg	-	-	-	-	-	-	-	-	631.0	0.2	139.1
Hipper - 1 row	0.9 m	3.78	1	7.5	6.0	1.7	2.4	4.2	31.2	-	-	48.7
Ditcher	0.5 m	0.12	1	0.2	0.2	0.3	0.4	0.1	1.0	-	-	2.1
Row shaper - 1 row		7.09	1	14.0	11.2	4.1	6.0	7.8	58.5	-	-	93.8
<u>Mulch/irrigation/fumigation</u>												
Mulch layer	1.5 m	3.71	1	7.3	5.9	5.9	12.3	11.5	86.2	-	-	117.6
Pickup truck	0.45 t	2.47	-	-	-	13.7	11.6	2.5	18.5	-	-	43.9
Plastic film	roll	-	-	-	-	-	-	-	-	12.4	64.0	790.7
Telone C-35	L	-	-	-	-	-	-	-	-	187.1	4.8	889.6
Other labor	h	-	-	-	-	-	-	-	-	32.1	7.5	240.9
T-tape, drip irrigation	roll	-	-	-	-	-	-	-	-	7.4	111.0	822.8
Hose, lay flat	roll	-	-	-	-	-	-	-	-	2.5	90.0	222.4
Trailer utility	3 m	2.47	1	4.9	3.9	2.3	2.3	2.7	20.4	-	-	33.9
Other labor	h	-	-	-	-	-	-	-	-	29.7	7.5	222.4
Sprayer, boom	3.7 m	0.47	1	0.9	0.7	3.7	0.7	0.5	3.9	-	-	9.9
Paint	L	-	-	-	-	-	-	-	-	212.9	8.5	1817.3
Solvent	L	-	-	-	-	-	-	-	-	282.2	0.7	186.3
<u>Weed control</u>												
Sprayer, boom	3.7 m	0.47	1	0.9	0.7	3.7	0.7	0.5	3.9	-	-	9.9
Kerb	kg	-	-	-	-	-	-	-	-	1.5	72.8	107.6
Gramoxone	L	-	-	-	-	-	-	-	-	5.8	8.1	47.2
Surfactant	L	-	-	-	-	-	-	-	-	1.2	4.2	4.9
Buffer	L	-	-	-	-	-	-	-	-	1.2	4.2	4.9

(Table 3.7. continued)

Operation / input	Size/ unit	Performance rate (h-ha ⁻¹)	Times over	Tractor cost		Equipment cost		Allocated labor		Operating input		Total cost
				Direct	Fixed	Direct	Fixed	Hours	Cost	Amount	Price	
<u>Cultural practices</u>												
Trailer small	2.4 m	2.47	1	4.9	3.9	2.1	2.1	2.7	20.4	-	-	33.4
Pickup truck	0.45 t	2.47	-	-	-	13.7	11.6	2.5	18.5	-	-	43.9
Lettuce seedlings	Tray	-	-	-	-	-	-	-	-	827.8	4.8	3971.2
Contract planting	1000 u	-	-	-	-	-	-	-	-	37.1	18.8	695.0
Irrigation w/fert, drip	ha-mm	-	10	-	-	27.8	148.3	2.5	18.5	25.4	0.0	194.6
Ammonium nitrate	kg	-	-	-	-	-	-	-	-	302.6	0.5	146.8
<u>Supplementary weed control</u>												
Sprayer, boom	3.7 m	0.47	1	0.9	0.7	3.7	0.7	0.5	3.9	-	-	9.9
Kerb	kg	-	-	-	-	-	-	-	-	3.4	72.8	244.6
Gramoxone	L	-	-	-	-	-	-	-	-	5.8	8.1	47.2
Surfactant	L	-	-	-	-	-	-	-	-	1.2	4.2	4.9
Buffer	L	-	-	-	-	-	-	-	-	1.2	4.2	4.9
<u>Pest control</u>												
Sprayer, boom	3.7 m	0.47	5	4.6	3.7	3.7	0.7	2.6	19.4	-	-	32.1
Ambush	L	-	-	-	-	-	-	-	-	0.7	30.3	21.3
Thiodan	L	-	-	-	-	-	-	-	-	2.7	8.1	22.1
Sevin	kg	-	-	-	-	-	-	-	-	2.1	11.2	23.6
Ridomil Gold	L	-	-	-	-	-	-	-	-	2.3	178.1	416.5
Rovral	L	-	-	-	-	-	-	-	-	2.0	41.5	85.0
Surfactant	L	-	-	-	-	-	-	-	-	5.8	4.2	24.7
Buffer	L	-	-	-	-	-	-	-	-	5.8	4.2	24.7
<u>Mulch removal</u>												
Labor	h	-	-	-	-	-	-	-	-	9.1	7.5	68.6

Adapted from Hinson and Boudreaux (2002).

Table 3.8. Production costs (US\$/ha) of experimental treatments and yield increases required to cover additional costs over bare-ground and fall-mulch treatments. Budgets were based on projected costs for Louisiana vegetable crops (Hinson and Boudreaux, 2002) and adjusted for small operations with a high technological level.

Operation / input	Experimental treatment										
	T1	T2	T3	T3	T3	T4	T5	T6			
	Bare ground	Fall mulch	Fall mulch + MEF ^z	Fall mulch + TC-35 ^z	Fall mulch clear	Solarized: clear	Solarized: clear + paint	Solarized: black			
Soil preparation ^y	433.6	433.6	433.6	433.6	433.6	433.6	433.6	433.6	433.6	433.6	433.6
Mulch/irrigation/fumigation ^y	1542.4	2494.6	2494.6	3384.1	2494.6	2494.6	4508.1	2494.6	4508.1	2494.6	2494.6
Cultural practices ^y	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8	5084.8
Weed control ^y	486.2	174.6	174.6	174.6	174.6	174.6	174.6	174.6	174.6	174.6	174.6
Pest control ^y	233.5	233.5	650.0	233.5	233.5	233.5	233.5	233.5	233.5	233.5	233.5
Mulch removal ^x	0.0	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6
Land rent ^w	429.8	465.9	465.9	646.3	465.9	646.3	955.9	955.9	955.9	955.9	955.9
Total cost	8210.4	8955.6	9372.1	10025.5	9445.5	9445.5	11459.1	9445.5	11459.1	9445.5	9445.5
Breakeven yield (cartons) ^y	1507.0	1644.0	1720.0	1840.0	1734.0	1734.0	2103.0	1734.0	2103.0	1734.0	1734.0
Increase over bare-ground (T1)	0.0%	9.2%	14.1%	22.1%	15.1%	15.1%	39.5%	15.1%	39.5%	15.1%	15.1%
Increase over fall-mulch (T2)	-8.4%	0.0%	4.5%	11.9%	5.4%	5.4%	27.8%	5.4%	27.8%	5.4%	5.4%

^zMEF = Mefenoxam, TC-35 = 1,3-Dichloropropene + Chloropicrin.

^yAdapted from Hinson and Boudreaux (2002).

^xAdapted from Parish et al. (2000).

^wAdapted from USDA (2001).

^vCalculated at \$5.45 per carton of 24 heads. Adapted from Takele (2001).

The cost of applying MEF was \$73 per ha lower than the cost of implementing soil solarization. MEF may be a better option when yields are reduced mainly because of diseases caused by Oomycete fungi. However, continuous exposure of soil-borne pathogens to MEF may eventually lead to resistance problems that can negatively affect economic returns. On the other hand, fumigation with TC-35 was more expensive than solarization by \$580 per ha. Solarization could be a better option, unless yields from soil fumigated with TC-35 are increased by over 6% in comparison to yields from solarized soil. Additionally, the logistics of soil fumigation with TC-35 are complicated, since specialized equipment and trained applicators are required.

Since a relatively low, wholesale price of \$0.23 per head was utilized for the economic analysis, increases in breakeven yield are likely to be overestimated. Lettuce has been sold at prices as high as \$1.50 per head in local farmers' markets (Carl Motsenbocker, personal communication), one of the outlets available to small growers for whom the experimental budgets are representative. Other potential markets for such growers include produce stores and restaurants, also likely to pay prices above wholesale for small volumes of product.

3.4. Conclusions

Soil solarization increased the yield of lettuce by enhancing plant growth as evidenced by higher head weight. Since lettuce is marketed by units and not by weight, this increase does not have a direct short-term economic impact. However, solarization has shown to have long-term effects such as pest suppression that can be reflected as cost reductions in the long run (Davis, 1991). Results from this investigation show that soil solarization significantly reduced weed populations, especially those of grasses. Solarization has the potential to modify the composition of the weed community over time, eventually affecting the requirements of weed management strategies.

The choice of transparent or black mulch has been previously investigated with mixed results (Abu-Gharbieh et al., 1991; Chase et al., 1999^b; Campiglia et al., 1998; Campiglia et al., 2000; Ham et al., 1993; Rieger et al., 2001). In this investigation, mulch opacity did not directly affect yield. However, temperature data suggest that clear mulch has a slightly greater potential for controlling soil-borne pests. On the other hand, weed pressure was higher in soils solarized with clear mulch. Painting transparent mulch after the solarization period increased the populations of *Cyperus spp.*

The short-term economic returns of solarization treatments are conditioned by pest pressure on agroecosystems. In this experiment, solarization did not exert an effect on marketable yield due to the lack of pest pressure. However, previous research suggests that increases in yield required to cover solarization costs are attainable.

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CHAPTER 4

CONCLUSIONS

Plastic mulches significantly modified the temperature regime of the soil during solarization, increasing both the magnitude and frequency of high temperatures. Black and clear mulches generated equivalent time/temperature combinations, although the transparent film consistently showed longer periods of sustained high temperatures.

Soil solarization enhanced the growth of lettuce, increasing final head weight and yield. This enhancement can be attributed to factors other than control of soil-borne pathogens, as no disease symptoms were detected. In addition, yield was not affected by the application of chemical agents commonly used to control soil-borne pathogens. The opacity of the plastic mulch did not affect the yield of the crop.

Treatment effects on yield were consistent for all the cultivars. Differences in yield observed between cultivars were expected due to the different types of plant material utilized.

All the factors considered in the experimental treatments (solarization, fall-mulching, mulch color and pesticides) affected weed pressure. The magnitude of such effects differed for different types of weeds. In general, solarization reduced weed pressure, and this effect was more pronounced for grasses than for other types of weeds. Black mulch was more efficient in reducing weed pressure than clear film, during both solarization and crop growth. However, the best weed control was achieved by fumigation.

The economic benefits of soil solarization in lettuce production could not be estimated due to the nature of the crop and the lack of substantial pest pressure. Since lettuce is marketed by unit and not by weight, economic returns are a function of price and plant stand: therefore, additional investments in production costs are justified only for improving either plant stand or

quality of the produce. In this study, neither plant stand nor quality was affected by the treatments. However, cost comparisons between treatments indicate that the increases in lettuce yield required to cover solarization expenses are generally lower than the increases reported by other researchers. This suggests that given the appropriate conditions, solarization may be not only viable but also profitable, as previously reported by some authors. Future research should address the ecologic and economic conditions determining the success of soil solarization in lettuce and other high-value vegetable crops.

VITA

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