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ECOLOGICAL WEED MANAGEMENT FOR ORGANIC FARMING SYSTEMS

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ABSTRACT OF THESIS

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Two field studies examining direct ecological weed control practices were conducted in Lexington, Kentucky. The first evaluated weed control efficacy and influence on yields of several mulches in two organically-managed bell pepper (*Capsicum annum)* production systems for two years. Peppers were planted in double rows in flat, bare ground or on black polyethylene-covered raised beds with drip irrigation, and four mulches (straw, compost, wood chips, and undersown white dutch clover (*Trifolium repens L.*) “living mulch”) were applied to the two production systems. In both years, polyethylene-covered raised beds produced higher yields than the flat, bare ground system. In the second year, the polyethylene-covered bed system coupled with mulching in-between beds with compost or wood chips after cultivation provided excellent weed control and yields.

The second field study evaluated the efficacy of soil solarization and shallow cultivation on the invasive and noxious weed johnsongrass over two years (*Sorghum halapense*). A soil solarization treatment, using clear plastic stretched over soil for eight weeks, and a cultivated bare fallow treatment, utilizing a tractor pulled cultivator implement equipped with sweep blades, were randomly applied during the summers of 2003 and 2004 to a field infested with johnsongrass. Solarized and cultivated plots in both years were lightly tilled 8 months after completion of the initial treatment period. At the conclusion of the experiment the johnsongrass population was significantly reduced in all treatments and in the control plots compared to the original infestation.

These two experiments testing direct weed control practices (mulching, cultivation, solarization) were undertaken in the context of an ecological weed management plan that includes long term strategies to reduce weed infestations such as crop rotation, cover cropping, and fertility management that are essential for organic farmers.

Keywords: ecological weed control, mulching, solarization, cultivation, organic

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THESIS

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ECOLOGICAL WEED MANAGEMENT FOR ORGANIC FARMING SYSTEMS

THESIS

A thesis submitted in partial fulfillment of the
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Introduction

Farmers in Kentucky are at a difficult crossroads. The loss of the quota system and price support for the major cash crop tobacco coupled with an aging farmer demographic will have long-term impacts on the rural character of the state. Faced with these challenges, the US Department of Agriculture has instituted a series of grant opportunities designed to identify alternative agricultural crops that can allow existing farmers to continue farming and encourage younger people to start agriculturally-based businesses. These New Crops Opportunities grants are an important element of Kentucky's response to the changing agricultural landscape of the state, and are being used to encourage farmers to explore alternatives to tobacco such as vegetable and nursery crops as well as alternative production practices such as organic systems management.

There has been a rapid increase in organic acreage nationally, although farmers in the southeast have not adopted organic production systems as rapidly as other parts of the country. Consumer demand for organically-produced foods rose during the 1990s by 20% or more annually, and organic products are available in nearly 20,000 natural food stores and 73% of conventional grocery stores; however these sales account for only 2% of total food sales in the U.S. (Dimitri and Green, 2002; Organic Trade Association, 2004). Because of consumer demand, organic farming remains one of the fastest growing segments of American agriculture, with the number of organic farms rising by about 12% annually (Dimitri and Greene, 2002). While still a minor component of the total agriculture sector, the amount of land under organic production has increased by over 1 million acres since 1997, with a total of over 2.3 million acres in organic production nationally.

In Kentucky, the organic vegetable acreage doubled between 2000 and 2002, climbing from 71 to 140 acres (Ernst, 2002). In 2003, there were approximately 100 certified organic farmers and many more growing organically, but not choosing to certify (Bhavsar, 2003). Kentucky's comparatively few organic acres have yielded high returns, with organic products valued at $3 million in 2002 (USDA, 2002). Although there is growing interest in organic production in the state, a major constraint is the lack of research-based information on organic production practices. The two experiments presented here were funded by New Crops Opportunities grants in an effort to address both a major production challenge in organic management systems and to present organically-managed systems to Kentucky farmers as an alternative means of crop production.

Production losses from weed competition are among the most important crop management concerns for organic growers, and the ability to control weeds is considered a major limiting factor for farmers wishing to transition to organic production systems (Bond and Grundy, 2001; Walz, 2004). There are many weed management techniques used by organic farmers such as mechanical cultivation and the use of polyethylene and organic mulches. The most effective and economically sustainable organic production systems integrate a combination of practices into a whole-farm management approach. Cover crops, crop rotations, and balanced nutrient availability are all important elements in an organic farm's weed management plan, and when combined with well-timed cultural practices, successful non-chemical weed control is possible (Bond and Grundy, 2001; Grubinger, 1999). The two experiments presented here represent efforts to evaluate weed control measures within a larger ecological weed management systems approach.

Chapter One

Review of Literature

The control of weeds in agro-ecosystems has likely troubled humans since the practice of agriculture began. The most negative aspects of weeds is they compete with cash crops for water, light and nutrition, and they can harbor diseases and pests that will further reduce the productivity of cash crops (Liebman, 2001). In the United States, where modern agriculture has reached its highest level of refinement, weeds still cause an overall reduction of approximately 12% in crop yields, while in the worlds' least developed countries crop yield reductions due to weed competition can reach 25% (Pimental et al. 2001; Akobundu 1987). Billions of dollars are spent annually on herbicides, tillage, and cultivation to limit the damage weeds cause worldwide. However, when viewed in an ecological context, weeds may provide many positive elements to an agro-ecosystem such as habitat for beneficial insects and other wildlife, reduction of soil erosion; and many weeds may also serve as secondary sources of food, medicine, and fodder (Liebman, 2001). Weeds, their control, and how they relate to human managed agro-ecosystems are important elements of agriculture today.

Since the 1960's weed management in the US has primarily been focused on the use of herbicides to the extent that 193 million acres of US land had herbicides applied to them in 2002 (Abernathy and Bridges, 1994; USDA, 2002; Aspelin and Grube, 1999). The use of herbicides has been shown to improve crop productivity and increase farm labor productivity in the short term, but major questions about the long-term sustainability of herbicide use have arisen in recent years. Herbicide applications are responsible for widespread contamination of surface and ground water throughout North America, and public concern has driven increased government regulation to minimize this contamination (Barbash et al. 1999; Gassman, 1993; Gutfield, 1993). Other major problems associated with reliance on herbicides for weed control include pesticide poisonings (increasingly common in less developed nations that import herbicides), and herbicide resistance among weed species (Liebman and Gallandt, 1997). Herbicides are a convenient short term fix for weed control, but as knowledge of their drawbacks grows it is obvious that other, more ecologically balanced, means of weed control must be developed.

Ecological weed management is a holistic approach to weed control combining scientifically deduced information about weed biology and ecosystem dynamics with site-specific knowledge from individual farms to produce long term weed management plans. Direct and indirect weed control measures are utilized with tactical (single year) and strategic (multi-year) goals in mind (Kristiansen, 2003). The key to this approach is that it is knowledge based; the biology and ecology of weed species must first be understood. Weed species morphology, phenology, reproduction strategies, competitive ability, spatial distribution, and response to control measures all are elements that form the foundation of an ecological weed management system. This information then allows both farmers and researchers to choose from the suite of weed control measures available that can favor a crop relative to a weed. Using biological knowledge and cultural solutions to combat the problem posed by weeds is the foundation of ecological weed control.

Organic farmers stand at the front lines when it comes to the practice of ecological weed control. Numerous surveys of organic producers reveal that weed control remains a major concern for practicing farmers and is a barrier to converting to organic management by transitioning farmers (Bond and Grundy, 2001; Kristiansen, 2003; Walz, 2004). Yet demand for organically produced foods continues to rise, with sales growing at a rate of 20% per year (OTA, 2004), and a market share that is expected to pass $30 billion in the United States by 2007 (Haumann, 2004). Because of this ever-increasing demand, organic farming remains the fastest growing segment of American agriculture, with the number of organic farms rising by about 12% annually (Dimitri and Greene, 2002). The lure of producing crops for this growing market is great, and despite the inherent challenges of organic weed control, many farmers are turning to this management system.

The foundation of ecological weed management is already an essential element in every certified organic farm plan. Starting with crop rotation and cover cropping, organic farmers utilize the cultural and physical methods available to them to reduce weed pressure over the long term and they must detail their methods and plans as part of the organic certification process. The long-term strategic weed management required in an organic farm plan are then melded with the daily operational decisions that should shift the crop-weed interaction toward favoring the crop (Rasmussen, 1998). Liebman and Gallandt (1997) used the phrase "many little hammers" to illustrate how an ecological weed management plan differs from a conventional plan that might utilize one large hammer such as an herbicide. The utilization of numerous weed management methods that can be chosen based on site-specific qualities allows producers to be creative and their weed management plans to potentially develop synergistic effects that may be lacking in less complex systems.

Kristiansen (2003) summarized many of the direct and indirect weed control practices often utilized in organic crop production. Direct or physical methods are listed as tillage, hand weeding, mulching, slashing (machine or hand mowing), grazing, biological control, solarization, and thermal methods. Indirect or cultural methods include crop rotation, cover crops, prevention, timing, planting density, intercropping, crop and cultivar selection, precision placement, and soil management. The research described in Chapters 2-3 incorporate many of these direct and indirect practices and each method will be briefly reviewed here.

Hand weeding is a common weed control method used by organic growers and farmers in both developed and developing countries (Walz, 1999; Akobundu, 1991). Pulling weeds by hand, rougeing them out with a hand-held hoe, or cutting them at the soil surface with a wheel hoe are all considered hand weeding (Marshall, 1992). With hand weeding, selectively killing weeds in relation to the crop is easy, but the time and labor required is a limitation (Pratley, 2000; Melander and Rasmussen 2001). Research aimed at improving hand weeding is uncommon, but efforts to improve its effectiveness would be of great value, especially to farmers in developing countries (Chatizwa, 1997; Women in Development Service (FAO), 2001). Though hand weeding is an important weed control method for certified organic farmers in the U.S., it is often used as informal measurement of the effectiveness of all other weed control measures practiced on the farm. As experience and skill in the application of other direct and indirect weed control measures increases, time and labor necessary for hand weeding should be reduced.

Tillage for weed control can be differentiated between primary and secondary tillage. Primary tillage is conducted as an initial step in crop production and, depending on the tool utilized, can have a number of drawbacks. In relation to weed control, use of a moldboard plow buries existing weeds and weed seeds to prevent reproduction and germination. However, weed seeds will reside in the soil horizon, sometimes for decades, waiting to germinate as part of the weed seedbank. In addition, the energy cost of using a moldboard plow is considered high and higher rates of soil erosion are associated with its use (Forcella and Burnside, 1994). Some farmers have adapted the moldboard plow for use within a soil conservation tillage regimen by using the tool as a "skim plow". Instead of allowing the plow to penetrate deeply into the soil it is set to invert only the top 2 inches of soil, thus eliminating the negative drawbacks that deep inversion plowing can have (Nordell and Nordell, 1998). There are other primary tillage implements such as the chisel plow or the spading machine which do not invert soil layers. Some annual weed species densities have been found to be influenced by tillage type in the short term, but over the long term the elimination of deep soil inversion will favor a reduction in the surface weed seedbank as well as having lower energy costs and associated rates of soil erosion (Buhler and Oplinger, 1990; Coolman and Hoyt, 1993).

Secondary tillage is any tillage operation that occurs after primary tillage has been completed, and usually involves using a type of harrow to prepare a fine seed bed for crops. Using a secondary tillage operation to destroy weed seedlings that germinate in the time between primary tillage and the planting or emergence of a crop is called stale seed bed. This practice is commonly used by organic vegetable growers, and two main methods, shallow cultivation with either tine or basket type cultivators, or flaming with propane flame are applied once the first flush of weed seedlings emerges from freshly-tilled soil (Grubinger and Else, 1996; Bowman, 1997). Research conducted by Balsari et al. (1994) found that flaming just prior to transplanting reduced weed densities by 62% in lettuce beds. Caldwell and Mohler (2001) compared tine weeder, rotary tiller, spring tooth weeder, flaming, and application of the herbicide glyphosate, and found flaming and glyphosate were most effective. They noted that the choice of cultivating tool in relation to the soil type and the depth at which tool operated both played a role in the effectiveness of the cultivation treatments in relation to the control. Forcella et al. (1993) applied the stale seed bed technique to plantings of corn and soybeans prior to emergence, and killed a high percentage of weed seedlings thus reducing season-long weed competition. A stale seed bed can be an effective component within a larger ecologically- based weed control program.

Once a crop is planted mechanical control of weeds becomes more difficult and in genera,l these direct physical methods are less effective when compared to herbicide application (Barberi, 2002). Mechanical cultivation that causes soil disturbance brings new weed seeds to the soil surface, and may increase soil N mineralization, both of which can increase weed competition with a crop (Walz, 1999). Compared to herbicides, which may persist in soil for weeks or months, mechanical cultivation is effective for a shorter time, and depending on soil moisture, environmental conditions, and growth stage of the crop, may be impossible to conduct at the most opportune time for maximum weed control (Kurstjens and Bleeker, 2000). Still the quantity and variety of tools designed for mechanical weed control has never been greater. Chain harrows, rigid or spring-tine weeders, torsion weeders, finger weeders, basket weeders, brush weeders, tractor steerage hoes, powered rotary hoes, and high-residue knife cultivators are examples of new implements that have been developed for mechanical weed cultivation (Eadie et al., 1992; Merfield, 2002; Tillett and Home, 2002).

The importance of site-specific soil characteristics (i.e. tilth, drainage, etc.) cannot be underestimated when considering which mechanical cultivation tool would be most effective. In addition, the skill and experience of the operator is very important when accurately judging the speed, depth, and timing that will make a cultivation event successful (Oriade and Forcella, 1999; Welsh et al. 1999). Mechanical weed control will be one of the most common elements in an organic weed management system, but it must not be relied upon as the sole means of control. Only when cultivation is combined tactically with other cultural crop production practices, within a strategic weed management program, will it effectiveness be most evident. Bastiaans and Drenth (1999) relate that the higher risk of incomplete weed control when relying solely on cultivation for weed control can doom the long-term effectiveness of an ecological weed control plan if surviving weeds can go to seed, thus increasing the weed seedbank.

The use of biodegradable mulches is a widespread and common practice for weed control on organic farms, though it is usually considered to be economical only for high value or perennial crops or on small acreages (Runham and Town, 1995). Biodegradable mulches such as straw, leaves, wood chips or compost have been documented to offer advantages such as conservation of soil moisture, reduced soil erosion, weed and disease suppression, and no removal requirement from the field (Singh, 1992). These mulches have also been shown to improve soil quality and stimulate soil microbial communities due to the addition of organic matter (Lalande, 1998; Ozores-Hampton, 1998; Olsen and Gounder, 2001). Disadvantages from the use of mulches can include ineffective season long weed suppression, nitrogen tie-up, and cooling of soil temperatures to sub-optimum levels (Hill et al., 1982). The difficulty and expense of application prevents biodegradable mulches from seeing more widespread use on a large commercial scale; however, they can be an effective and valuable part of an ecological weed management program in particular because of their contribution to soil health.

Plastic mulches or films are commonly used for vegetable production, and though the use of plastic mulch is allowed in organic vegetable production in the US, the identification of alternatives is important to organic producers (Wittwer, 1993; Lamont, 1993; Schonbeck, 1998). Research has shown that plastic mulches, despite offering the advantages of fewer weed problems, earlier and higher yields, and reduced evaporation, have important disadvantages including initial equipment cost, difficulty of removal, increased soil erosion, and increased agricultural chemical runoff (Lamont, 1993; Hochmuth, 1998; Rice et al., 2001). Many types of plastic mulch are available with different reflective properties and colors, and some of these have shown to enhance crop growth or limit insect predation (Majek and Neary, 1991). The use of plastic mulch is often debated by organic farmers given its drawbacks, and although it is a convenient and effective method of weed control, many growers feel that its use should be minimized within an ecological weed management system.

When a dense stand of low-growing plants planted in the same area as a crop is managed in a way to exclude weeds, it is known as living mulch. Living mulches are common in perennial crop plantings such as orchards and they are effective at competing with weed species when carefully managed. However a major drawback is that living mulches can also compete with the crop for water and nutrients, thus lowering yields. Additionally, if used in an annual cropping system, the establishment of the living mulch is often difficult (Rajalahti and Bellinder, 1996; Muller-Schaerer and Potts, 1991). Living mulches have other benefits besides potential weed control, including reducing soil erosion, adding fertility, improving soil structure, influencing crop-pest dynamics, and once established, they require little more than timely mowing for maintainence (Bond and Grundy, 2001). While living mulches are an essential element in an ecological weed control program for perennial crops, they are less suited for annual crops. One way growers try to get the benefits of the living mulch in an annual cropping system without the major drawbacks of crop competition or slow establishment is to delay planting the mulch crop until the cash crop is well established (Coleman, 1989).

Modern no-till agriculture is usually associated with genetically engineered crops designed for resistence to herbicides, and cover crops are rarely incorporated into the most common conventional corn/soybean no-till rotations. Vegetable producers, however, have explored means for using no-till procedures in their crop production systems for decades and recent work that incorporates winter cover cropping has been successful (Morse, 1999; Adbul-Baki et al., 1996). Killing a thick planting of winter/spring grown rye and hairy vetch with either herbicides, or a tool designed to undercut, crimp, or crush the cover crop, produces a thick mat of dead plant material through which vegetable crop seedlings can be transplanted (Groff, 2000; Adbul-baki and Teasdale, 1997; Creamer et al., 1996). The in-situ mulch provides weed control, nutrition to the crop, has no transportation cost, and has been shown to produce high yields, though crop maturity is often delayed compared to conventionally transplanted vegetable crops. The cooling effect that the no-till mulch has on soil temperatures has prevented this system from being successfully used for early season plantings, but both warm and fall planted cool season crops can achieve high yields when incorporating cover crops into a no-till system (Morse, 1999). Conventional no-till operations often exhibit a shift in weed pressure from annual to perennial species and herbicide resistance is a growing problem, but when used as part of an ecological weed control rotation, no-till vegetable production has the potential to become a valuable system for growers.

Flame weeders are another tool used by innovative growers pursuing an ecological weed control system (Ascard, 1995). Flame weeding involves burning or scorching weeds with a flame, and can be used in the stale seed bed technique, total vegetation control, or for selective weed control (Bond and Grundy, 2001). Equipment is usually powered by propane fuel and ranges in size from backpack sized tanks with hand-held burners to large tractor-pulled tanks with multiple burners (Ascard, 1990). The major benefit of flame weeding is that no soil disturbance is required, thus reducing weed pressure later in the season. However, flaming can not be relied upon as the sole weed control measure, as its effects usually do not provide complete season-long weed control, particularly of grasses (Mohler, 2001a). As with cultivation, timing is important to destroy the highest number of weeds while protecting the crop, therefore bed flame shields must be used and aligned correctly for crop protection (Ascard, 1997).

Growers and homeowners who wish to prevent the spread of weeds within their management areas commonly practice mowing or slashing for weed control. Cutting weeds at the soil surface prevents flowering and seed set and when practiced diligently, can lower weed seedbank pressure over time (Nawroth and Estler, 1996). Commonly used power mowers include hand held weed whackers and flail, rotary, or reciprocating knife mowers while hand mowing or slashing is often accomplished using a machete or scythe. Rotary mowers leave weed debris scattered, while flail and reciprocating mowers leave debris in place, usually lying in one general direction. Mowing to prevent weeds from going to seed must be done often during the growing season, and any failure to maintain a rigorous schedule will result in increased weed problems in the future if weeds are allowed to go to seed (Bond and Lennartsson, 1999).

Domesticated herbivores can make weed problems worse in pasture environments because they disperse weed seeds, they may not graze unpalatable weed species, and they can contribute to soil compaction in certain areas. However, when managed within an ecological weed control plan, herbivores can reduce overall weed pressure (Staver, 2001). The key for the grower is to know the weed species present on his/her farm, and whether those weeds might be susceptible to changes of timing or population pressure through herbivore management. Managing animals with high stocking rates at certain times of the year has been shown to reduce some weed problems, and growers using a rotational grazing program often report fewer weed control problems (Scifres, 1991). Using geese as weed grazers has proven effective in a number of crops including cotton, onion, and potato, but just as with large herbivores in a pasture setting, careful and timely management is essential (Wurtz, 1995). Incorporating animals into an ecological weed control program is both possible and desirable, and can be an important part of a whole farm plan.

The use of biological control agents to control weeds can also be part of an ecological weed control program, though it has been difficult to include in many agricultural settings (Muller-Schaerer et al., 2000). Classical biological control consists of identifying insects or pathogens that have kept invasive weed species in check in their native environments. After extensive testing to ensure that the control agent would not become a pest in and of itself, the agent is released to attack or infect the invasive weed species in its new environment. Andow, Ragsdale, and Nyvall (1997) identify three strategies to promote biological control efforts, by either native or introduced control agents. Conservation management attempts to retain and bolster the weed control effects of native control agents on introduced/invasive weeds, inoculation involves the importation of a non-native control agent that is well adapted to its new environment to control a target weed, and inundation is when both native and non-native weed predators are introduced in high numbers in an attempt to control an invasive weed quickly. Biological control is controversial primarily because it advocates the introduction of new non-native species that might become invasive themselves regardless of how much testing is conducted to ensure this does not occur (Simberloff and Sterling, 1996). However, managing soils and farmscapes to encourage and conserve native weed control agents is part of any good organic farm plan.

Beyond classical biological control, researchers are finding that numerous varieties of fungi and bacteria can have weed control properties. Mycoherbicides and deleterious rhizobacteria (DRB) have been developed that can kill weeds, often with single weed species accuracy (Liebman, 2001). The process for development of these products include identification of a diseased weed species, collection and isolation of the plant pathogen, and eventual mass production of a virulent strain of the pathogen for use as an herbicide (Boyethchko, 1997). Literally hundreds of fungi and bacteria have been identified as pathogenic to particular weed species, and effective marketable products are slowly appearing for use by farmers. It must not be expected that such naturally derived products will become the sole answer to invasive weed infestations because they are rarely as effective as conventional herbicides. Additionally, there exists few reasons for multi-national corporations conducting the majority of herbicide research to focus their efforts on developing such products for the organic farming community. However, such products fit well into an ecological weed control program as they can be used to introduce another level of environmental stress to an invasive weed species (Liebman and Janke, 1990). Much work is still to be done in understanding how to use and manage microorganisms to combat weeds. Researchers continue to study the biology of weed/pathogen interactions, and some are looking to find how these products might be produced on the farm outside of the corporate marketplace.

Yet another direct weed control measure that can be used to combat weeds within an ecological weed control program is solarization (Standifer, 1984). Solarization is described as a hydrothermal soil disinfestation technique that has been tested for its ability to combat many soil pathogens and weed species (Stapleton, 2000; Katan, 1981; Egley, 1990). The technique uses clear plastic sheets stretched over an area of bare soil during the summer months, allowing solar radiation to heat the soil beneath while leaving soil structure undisturbed (Katan, 1991). Though most often used in arid climates, this technique offers promise as an alternative to herbicides, and is allowed for use by organic farmers.

The direct or physical methods of ecological weed control such as tillage, hand weeding, mulching, slashing, grazing, biological control, and solarization offer a wide range of choices for individual farmers from which to choose farm-specific weed control options. However, none of these methods are as effective at controlling weeds as herbicides are for conventional farmers, so more than one method, within the context of a larger long-term weed control plan, is essential. In addition, while certain physical weed control methods may become preferred for an individual farmer on a specific farm, it is important to rotate weed control methods. Utilizing different cultivating implements from year to year, or using biodegradable mulch one year rather than plastic, are examples of weed control rotations. Constant experimentation and change of weed control methodologies ensures weeds will not adapt and escape from an ecological weed control management plan.

Just as direct and physical methods of weed control should be rotated regularly, the long term strategic planning that is the bedrock of an ecological weed control plan relies of the same concepts of change and rotation. Before the widespread use of agricultural chemicals, crop rotation was essentially the most important weed control measure available to farmers (Lee, 1995). The goal in adapting crop rotations or crop sequences for weed control is the maintenance of an unstable environment in which weed species are severely limited in their potential to grow, reproduce, and proliferate (Bond and Grundy, 2001; Liebman and Staver, 2001; Mohler, 2001c). Thus planting crops with different planting and harvesting dates, root structures and physiological properties, management requirements, and competitive niches from year to year will encourage such an unstable environment from the weed species perspective (Liebman and Ohno, 1998). Even very simple rotations like corn/soybean or corn/wheat exhibit decreases in weed pressure compared to continuous corn (Forcella and Lindstrom, 1988; Coravelli and Tei, 1988). More diverse crop rotations, particularly those including a pasture element, reduce long-term weed pressure even further (Entz et al. 1995, Wilson and Phipps, 1985).

In ecological terms, it is important to remember that crop agro-ecosystems are early successional environments, and weeds are plants that have evolved and adapted over time to be very successful at colonizing such habitats (Alteri and Liebman, 1998). The phrase “nature abhors a vacuum” is especially relevant because, based on a myriad of environmental factors, particular weed species will be adapted to colonizing and proliferating on bare soil; this ability is known as a weeds’ regenerative niche (Grubb, 1977). Crop plants valued by farmers and consumers have undergone centuries of artificial selection for traits such as good taste, pleasant appearance, and high yields. Weeds associated with agro-ecosystems have also undergone selection, both artificial and natural, and they have evolved traits such as the ability to scavenge nutrients more completely or produce more seeds faster in a competitive environment (Mohler, 2001b). Crop plants, because of human selection practices, aren’t very competitive in the environments in which we place them compared to weeds; however, utilizing crop rotation can help maintain an unstable environment in which weeds cannot become problematic. The goal is not to eliminate weeds, but to shift the competitive balance of the agro-ecosystem toward the crop (Gallandt et al., 1999). The inclusion of a diverse crop rotation is the first step toward that goal.

Cover cropping is the second most powerful strategic tool available to ecological weed control practitioners (Bowman et al., 1998). Cover crops aid in weed suppression primarily by competing with them for nutrients, water, and light, which disrupts a weeds’ ability to carve out a regenerative niche (Liebman and Davis, 2000). If a planted cover crop is present there is no space for weeds to establish (Creamer et al., 1997). For cover crops to successfully compete with weeds they must be sown heavily, establish and grow quickly, and be highly competitive (Schonbeck et al., 1991; Barberi e.al., 1998a; Creamer and Dabney, 2002). Beyond weed suppression, cover crops can improve soil physical characteristics, reduce soil erosion and nutrient leaching, be a residual surface mulch in a no-till crop production system, and provide nitrogen if leguminous species are used (Creamer and Baldwin, 2000). Some cover crops such as grain rye (*Secale cereal*) produce phytotoxic chemicals that can suppress weeds, via allelopathy (Grundy et al., 1999). Within an ecological weed control plan, cover crops play essential roles as soils should have some kind of growing plant community covering them whenever possible. With no management, weeds will fill this role, but farmers and land managers can choose a cover crop plant community that will both compete with weeds and improve soil health.

Once an ecological weed control program is started for a certain area, preventing additional weed seeds from entering the weed seedbank is crucial. It has been reported that there is a weed control threshold beyond which crop yields do not increase even as more weeds are eliminated from the growing area; however, the potential troubles that can occur in future seasons from allowing weeds to reproduce shifts the threshold to require weed control later in the season regardless of the lack of yield benefits (Rasmussen and Svenningsen, 1995; Bond et al., 1998). Avoiding weed reproduction is essential for the long-term management focus that is required of an ecological weed control program (Buhler et al., 1998). Other elements that are important in preventing new weed seeds from entering the seedbank include efficient harvesting practices that ensure crop propagules or seeds do not become weeds themselves, and limiting importation to the management area of materials that might include weed seeds, such as uncomposted manure or hay (Bond and Lennartsson, 1999; Barberi and LoCascio, 2001).

Prevention, combined with the other long-term elements of an ecological weed control plan, should result in an overall reduction in total number of weed seeds over time.

Compared to most crop plants, weeds are much more adapted to capturing nutrients in the soil and it has been found that the form in which a nutrient is applied may influence the weed/crop interaction (DiTomaso, 1995; Liebman and Mohler, 2001). Rapidly soluble chemical fertilizers are equally available to both crops and weeds, yet weeds have evolved in a way that allows them to absorb more fertilizer and grow faster compared to crop plants (Liebman and Mohler, 2001). Fertilizer application placement and timing can swing the weed/crop interaction away from the crop. Banded fertilizer applications and delayed fertilizer treatments have both been found to favor crops over weeds when compared to broadcast treatments and single point fertilizer applications (DiTomaso, 1995; Rasmussen et al., 1996). Weeds may react differently to organic fertilizer sources as they are much less soluble than conventional fertilizers and will provide nutrients over a longer time period, thus buffering their initial availability. Cropping systems that tend to rely on cover cropping and crop rotations with fewer external inputs will have much different patterns of nutrient availability throughout the growing season than systems that restrict nutrient application to the growing period of the crop (Gallandt et al., 1998; Liebman and Davis, 2000). By increasing soil biological health and providing well-placed and well-timed fertilizer applications that require movement through the microbially-mediated soil nitrogen cycle before becoming available to plants, farmers can reduce weed competition to their crops. This is particularly true when these techniques are practiced along with other elements of an ecological weed control plan.

The final important elements of an ecological weed control program are found within the cultural practices used to grow a crop. Timing the best moment to seed or transplant a crop so that it has the competitive advantage over weeds is essential. Using vigorous crop seed that germinates quickly and healthy transplants that have been properly hardened-off both can give the crop an advantage (Rasmussen and Rasmussen, 2000). Certain crop cultivars are better able to compete with weeds if they have larger seed size, faster seedling emergence, higher early growth rate, or more rapid canopy closure (Mohler, 2001b). The density and arrangement in which many crops are planted play a role in the growth rate of the crop and therefore relates to its ability to compete with weeds. However, crop densities that are too great will have negative impacts on the yield and disease susceptibility of many crops (Barberi and Mazzoncini, 2001). Crop spatial arrangement within a rotation from year to year has also been shown to play a role in weed/crop competitiveness as crops planted into rows that were kept weed free the previous year had much lower weed competition (Melander and Rasmussen, 2000; Mohler, 2001c). Planting date, crop density, crop cultivar and crop spatial arrangement all can play a large role in helping reduce weed competition, but much depends on local environmental and soil characteristics and the benefits from close attention to cultural weed control measures is often site specific. Though general recommendations exist for all of these farmer-controlled factors, the heart of the cultural management strategies within an ecological weed control context is the fine-tuning of these strategies that is accomplished over years of experience on an individual farm.

In conclusion, ecological weed management is a holistic approach to weed control, combining scientifically deduced information about weed biology and ecosystem dynamics with site-specific knowledge from individual farms to produce long-term weed management plans. The many direct tactical weed control options available to farmers combined with the essential underlying elements of the indirect strategic plan for whole farm weed control have been outlined in this literature review. In Chapters Two and Three, experiments testing two direct weed control measures, mulching and solarization, within the framework of an ecological weed control plan, are presented.

Chapter Two

Weed Control Efficacy of Organic Mulches in Two Organically-Managed Bell Pepper Production Systems

Introduction

Production losses from weed competition are among the most important crop management concerns for organic growers, and the ability to control weeds is considered a major limiting factor for farmers wishing to transition to organic production systems (Bond and Grundy, 2001; Walz, 2004). As farmers in Kentucky and other states move away from tobacco as a result of the federal government's ending of the tobacco price-stabilization program, production of alternative crops such as vegetables has increased. In this region, as in many parts of the country, growers have expressed interest in organic vegetable production in response to the ever-increasing demand for organic products (Organic Trade Association, 2004). A major constraint for these growers is the lack of research-based information on organic production practices, particularly regarding weed management. There are many weed management techniques used by organic farmers such as mechanical cultivation and the use of polyethylene and organic mulches; the most effective and economically sustainable organic production systems integrate a combination of practices into a whole-farm management approach. Cover crops, crop rotations, and balanced nutrient availability are all important elements in an organic farm's weed management plan, and when combined with well-timed cultural practices, successful non-chemical weed control is possible (Bond and Grundy, 2001; Grubinger, 1999).

The use of polyethylene mulch with drip irrigation is an important and widespread practice in commercial vegetable production systems, and although polyethylene mulch is allowed in organic vegetable production, the identification of alternatives is important to many organic producers (Lamont, 1993; Schonbeck and Evanylo, 1998; Wittwer, 1993). Despite advantages such as increased weed control, earlier and higher yields, reduction of nutrient leaching, and increased soil moisture retention, polyethylene mulch has disadvantages such as difficulty of removal, cost of disposal, increased soil erosion, and increased agricultural chemical runoff (Brown and Channel-Butcher, 2001; Hochmuth, 1998; Lamont, 1993; Rice et al., 2001). Organic mulches such as straw, wood chips or compost can conserve soil moisture, reduce soil erosion, suppress weeds, and may also have advantages of low cost, with no removal requirement (Aparbal-Singh et al., 1992; Davis, 1994; Feldman et al., 2000; Isenberg and Odland, 1950; Roe et al., 1992; Singh, 1992). Organic mulches have also been shown to improve soil quality and stimulate soil microbial communities due to the addition of organic matter (Lalande et al., 1998; Olsen and Gounder, 2001; Ozores-Hampton, 1998). Disadvantages of organic mulches include nutrient tie-up and lowering of soil temperatures to sub-optimum levels (Hill et al., 1982; Schonbeck and Evanylo, 1998). Living mulches planted during the growth of the cash crop have been shown in some cases to compete well with weeds and provide soil cover (Paine and Harrison, 1993). In addition to organic mulches, there are a limited number of organically-approved products such as corn gluten meal that have been shown to exhibit herbicidal properties (McDade and Christians, 2000).

Although research on the benefit and use of mulches is extensive, little is known about how to optimize their use in organically-managed systems. Applications of straw, compost, wood chips, living mulch, and corn gluten are all allowed under USDA organic certification standards. Many farmers in Kentucky converting from tobacco to vegetable production have adopted the polyethylene mulched raised bed (plasticulture) system with drip irrigation for bell pepper (*Capsicum annuum*) production. As a result, bell peppers have become one of the most popular and profitable vegetable crops grown in the state. In this study, four organic mulches (wood chips, straw, compost, and undersown clover "living mulch") and the organically-approved herbicide corn gluten were evaluated for weed suppression and effects on yield when incorporated into organically-managed flat, bare ground and plasticulture production systems. This was the first experiment conducted at the newly established University of Kentucky Organic Farming Research and Education Unit in Lexington. Our objective was to determine which treatments could be effectively used for weed management in two organically-managed bell pepper production systems.

Materials and Methods

2003 EXPERIMENT. Five weed control treatments in two bell pepper production systems were compared for their weed control efficacy and influence on yields. The treatments were straw mulch, wood chip mulch, compost mulch, corn gluten, a "living mulch" of undersown Dutch clover (*Trifolium repens*), and an untreated control. The bell pepper variety 'Aristotle' (Seminis, Oxnard, Calif.) was chosen for its high yields, high quality, and resistance to bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*). Seeds were sown in Sunshine Organic Gro-mix (Sun Gro Horticulture, Bellevue, Wash.) on 23 Mar. and transferred on 14 Apr. to individual cells (Styrofoam, 72 cell count, Speedling, Sun City, Fla.) containing the same media. While in the greenhouse, plants were fertigated nine times with Omega 6-6-6 (6N-2.6P-5K), (Peaceful Valley Farm Supply, Grass Valley, Calif.) at a rate of 25 fl oz/gal of water. The experimental field had been planted in a winter wheat (*Triticum aestivum*) cover crop (80 lb/acre, Southern States, Lexington, Ky.) prior to the experiment. Following plowing and disking, but prior to transplanting, a pelleted organic fertilizer, Nature Safe Fine 10-2-8 (10N-0.9P-6.6K) (Griffin Industries, Cold Spring, Ky.), was spread and incorporated at a rate of 60 lb/acre of N. An additional total of 55 lb/acre of N was fertigated in six weekly doses through drip irrigation using liquid Phytamin 7-0-0 (7N-0P-0K) (California Organic Fertilizers, Fresno, Calif.). *Trichogramma ostriniae* wasps (IPM Laboratories, Locke, N.Y.) were released for European corn borer (*Ostrinia nubilalis*) control on 18 and 25 July, and 1 Aug., at a rate of 150,000/acre per release (Friley et al., 2003).

The experimental design was a randomized complete block with four replications with a split plot arrangement of treatments. Main plots were the production systems: 1) flat, bare ground and 2) raised beds covered with black polyethylene mulch. Both systems are commonly used in Kentucky. Main plots consisted of two double rows 75 ft long. Peppers were spaced 12 inches apart within rows with 18 inches between the double rows. Double rows were spaced on 6 ft centers. Subplots were 12 ft long and 12 ft wide and consisted of five weed control treatments and an untreated control in two double-row beds. Mulch treatments were applied to bare ground in both production systems. For the flat, bare ground system, mulches were spread evenly within 1 inch of the transplants. For the polyethylene-covered raised bed system, mulch treatments were applied only to exposed soil between beds (row middles). Drip irrigation was used on all plots. Tensiometers were placed in black polyethylene and flat ground main plots and water was applied when readings of 30 centibars were reached.

Mulch treatments were applied at transplanting on 5 June, except for the living mulch treatment. Wood chips and compost were applied to a depth of 3 inches while the wheat straw was spread to a depth of 6 inches. Compost (0.01N-0.006P-0.35K) was obtained from Creech Compost Company, Lexington, Ky., a local producer of compost derived from horse muck. Baled wheat straw was obtained from a local farm supply store and wood chips were obtained without charge from a regional tree trimming businesses. Corn gluten meal (Bioscape, Petaluma, Calif.) was applied at a rate of 50 lb/1000 ft^2 four times at approximately two-week intervals during July and Aug. All mulch treatments and the corn gluten were applied by hand. The living mulch treatment consisted of white Dutch clover, (Southern States, Lexington, Ky.) sown on newly cultivated soil at a rate of 20 lb/acre, 11 d after pepper transplanting (after transplant recovery). Following mulch applications, weeds were not managed in any other way for the remainder of the season. Weed control was rated on 10 July and 4 Aug. using visual analysis on a 0 to 100% scale with 0% equaling no observable control and 100% equaling complete weed control. Weed ratings for the flat, bare ground system included the entire subplot covered by organic mulch, while only the row middles in between the black polyethylene-covered raised beds were evaluated in the plasticulture system. The polyethylene-covered beds were not included in the ratings. Areas immediately adjacent to the experimental plots were also rated for weed growth and used as a 0% control for comparison. These areas were plowed and disced like the experimental plot, but were otherwise undisturbed for the entire season. Weed species were identified throughout the season and an inventory was compiled. Peppers were harvested on 4 and 24 Aug., and after grading into marketable fruits or culls, were counted and weighed.

2004 EXPERIMENT. Because none of the treatments in 2003 resulted in acceptable weed control, all plots in 2004 were shallow cultivated (< 1 inch deep) by hand hoeing three times at two week intervals after transplanting but prior to mulch application. These cultivations were intended to simulate mechanical cultivation and were included to reduce early weed pressure and potentially shift the period of weed control provided by the mulch treatments to later in the growing season. The corn gluten treatment was eliminated due to ineffective weed control and low marketable yields in 2003. The “living mulch” Dutch clover was also eliminated because of its slow germination and growth, which substantially reduced its ability to compete with weeds. In addition to the untreated (weedy check) control, a treatment utilizing shallow cultivation at approximately two week intervals throughout the season was included.

Bell peppers ‘Red Knight’ (Seminis, Oxnard, Calif.) were sown 29 Mar. and transferred to individual cells (Styrofoam, 253 cells per tray Speedling, Sun City, Fla.) containing organic potting media on 16 Apr. ‘Red Knight” was chosen for its high yields, resistance to bacterial spot, and because untreated seed of ‘Aristotle’ was unavailable. Fish emulsion (Maxicrop Liquid Fish Fertilizer 5-1-1 (5N-0.4P-0.8K), Elk Grove Village, Ill.) was used as the primary nitrogen source for the transplants; however, repeated use of this product resulted in a crust on the media surface that limited water penetration and delivery of nutrients to the roots. Threatened with the loss of these transplants and the entire 2004 field trial, conventional 20-10-20 (20N-10P-20K) (150 ppm) soluble fertilizer was applied twice as a rescue treatment. Although synthetic fertilizers are unacceptable for certified organic production, it was necessary in this case to ensure transplant survival. All other production practices in this study were consistent with organic certification guidelines.

Peppers were transplanted in a field that had been cover cropped with two consecutive plantings. During the preceding summer, plots had been planted with sorghum-sudangrass (*Sorghum bicolor* x *S. bicolor* var. *sudanese*), (60 lb/acre, NC+ Organics, Grand Junction, Ia.) and cowpeas (*Vigna unguiculata*), (20 lb/acre, Southern States, Lexington, Ky.) that was plowed in the fall. That cover crop was followed by rye (*Secale cereale*), (80 lb/acre, NC+ Organics, Grand Junction, Ia.) and hairy vetch (*Vicia villosa*), (40 lb/acre, NC+ Organics, Grand Junction, Ia.) as a winter cover crop. This was plowed on 23 May and was estimated to provide at least 40-50 lb/acre of total N (Bowman et al., 1998). On 7 June an additional 45 lb/acre of N in the form of Nature Safe Fine fertilizer was surface-applied and incorporated with a shallow cultivation. An additional total of 30 lb/acre of N was fertigated in two doses at mid-season through the drip irrigation system using Phytamin as in 2003. *Trichograma ostriniae* wasps were released on 16 July and 14 Aug., at a rate of 150,000/acre per release for European corn borer control.

As in 2003, the experimental design was a randomized complete block with four replications with a split plot arrangement of treatments. Main plots were the same while subplots consisted of three mulch treatments from 2003 (compost, wood chips and straw), a control (weedy check), and a cultivated control. The main and subplot dimensions, as well as pepper spacings, were as in 2003. Mulch treatments were applied after shallow cultivation (described previously). Drip irrigation was used on all plots. Tensiometers were used to determine water application as in 2003.

Mulches were obtained from the same sources as in 2003 and were applied by hand on 20 July. After 20 July, cultivated control plots were shallow cultivated (< 1 inch deep) by hand hoeing five times at approximately two-week intervals. For the control plots (weedy checks) cultivation ceased after 20 July. Wood chips and compost were applied as in 2003. Weed control was evaluated on 30 Aug. and 8 Oct. using the visual scale as in 2003. A weed inventory was also compiled. Peppers were harvested on 5, 16, and 30 Aug., 16 Sep., and 11 Oct. Fruits were graded and weighed as in 2003. To determine the mid-harvest date as a measure of earliness, yields for each date were multiplied by the serial value of the harvest date (days after 1 Jan.

1900). These products were summed, and then divided by total weight harvested. The resulting quotients were then converted to Julian dates.

Analysis of variance of all data was conducted using the PROC GLM procedure of the Statistical Analysis System (SAS Institute, 1999). Main effect means (production systems) were separated by a single degree of freedom F-tests, while subplot means (weed control treatments) were separated by Waller-Duncan K-ratio t-tests. When the F-test for the interaction between production system and weed control treatment was significant, means were separated by t-test, using the LSMeans options of PROC GLM. Weed control data for the three mulch treatments that were common to both years were combined and analyzed. Year was assumed to be a random variable in the analysis conducted by use of PROC GLM.

ECONOMIC ANALYSIS. A partial budget analysis was used to compare costs and returns among organic weed control treatments for the two production systems (polyethylene/raised beds and flat, bare ground) in 2004. The partial budget itemizes only costs and returns that are directly affected by changes in treatments; it includes (but does not show) all itemized costs as in a complete crop budget. Production costs not affected by treatments were based on estimates published by the University of Kentucky (Isaacs et al., 2004). Costs associated with organic mulch and other treatments were determined as follows.

The "mulch application charge" was calculated for hand application. An average of 15 min was required for one worker to apply mulch to one plot (≈ 20 min for 144 sq ft plots on flat ground, ≈ 10 min for 72 sq ft in the polyethylene mulched plots). An hourly labor rate of $8 was used. Mulch transportation costs were not included.

"Cultivation costs" were estimated using the same fuel and lube costs from the University of Kentucky conventional bell pepper crop budget ($2.55/hr). It was estimated that it would take approximately two hours to cultivate one acre of peppers resulting in a cost of $5.10/ cultivation. Repair costs in the conventional pepper budget were $30/acre; since there was additional use of the equipment for cultivation in the organic system, we added $15/acre for repairs for three cultivations and $45/acre for six cultivations.

"Total production costs" included production inputs, some of which are not itemized in the partial budgets. Total production costs included seed, flats, organic potting media, lime, pre-plant fertilizer, soluble fertilizer, black polyethylene mulch, drip tape, *Trichogramma* wasps, mulch, mulch application charges, cultivation, lube and fuel, repairs, transplanting labor, and irrigation labor.

"Total harvesting and marketing costs" included boxes, polyethylene mulch disposal labor, a polyethylene mulch disposal fee, marketing costs, fuel and lube, and labor for harvest, packing and grading. All except the disposal labor and fee, and fuel/lube were dependent on yield.

"Total variable costs" were the sum of total production costs and total harvesting and marketing costs. In addition, an interest charge was included that took into account the opportunity cost for money spent rather than saved. The following formula was used to calculate interest: Interest = ((A*B*(4/12)) + ((C*D*(2/12)) where A = total production cost, B = 0.06%, 4 months/12 months = portion of a year that money was unavailable, C = total harvesting and marketing cost, D = 0.06%, and 2 months/12 months = portion of a year that money was unavailable.

Total fixed costs (not shown in the partial budgets) were the same for all treatments and included depreciation on machinery, depreciation on irrigation equipment, taxes and insurance. "Total expenses" are the sum of all variable and fixed costs.

Results

WEED CONTROL. For the 10 July 2003 weed control rating, the mean square for weed control treatments was highly significant while the mean squares for production systems and interaction of production systems with weed control treatments were not significant. The lack of significant interaction between production systems and weed control treatments was not surprising because weed control ratings were made only on the areas covered by the treatments, and did not include the weed control provided by the polyethylene mulch. With regard to differences among weed control treatments, only the straw and wood chip mulch treatments gave acceptable levels (>70%) of control, while corn gluten and the untreated control gave the worst (Table 1.1).

The 4 Aug. 2003 weed control rating was consistent with the 10 July rating in that the only significant source of variance was the weed control treatments. As the season progressed, weeds grew in all treatments, overwhelming the crop by harvest time. In the polyethylene mulched system, weeds grew in between the beds to the point that they substantially shaded the pepper plants. Straw mulch gave the highest level of weed control, followed by wood chips, but their respective ratings of 34% and 20% control were not adequate for commercial production (Table 1.1). Although the compost mulch also failed to give adequate weed control, it was slightly higher than the weed control from the clover treatment. These results indicated that a single mulch application at planting did not provide effective season-long weed control.

In 2004, when weed control was first assessed on 20 Aug., the mean square for weed control treatments was again significant, while that for production system was not. The three mulch treatments provided weed control similar to that in the cultivated control and considerably better than the weedy check (Table 1.2). At this date, there also was a significant interaction

Table 1.1. Efficacy of weed control treatments averaged over flat ground and polyethylene-mulched raised bed organic bell pepper production systems on two assessment dates in 2003.

Weed Control Treatment	**July 10th 2003**	**August 4th 2003**
	--------------------% Control[z]	--------------------
Straw	83 a	34 a
Wood chips	73 b	20 b
Compost	54 c	9 c
Clover	54 c	8 c
Corn gluten	13 d	3 c
Untreated control	13 d	3 c

[z]Means in a column and year followed by the same letter(s) are not significantly different (Waller-Duncan K-ratio t-test *P*=0.05).

Table 1.2. Efficacy of weed control treatments averaged over flat ground and polyethylene-mulched raised bed organic bell pepper production systems on two assessment dates in 2004.

Weed Control Treatment	**Aug 20th 2004**	**October 4th 2004**
	--------------------% Control^{z}	---------------------
Compost	95 a	92 a
Cultivated control	93 a	90 a
Wood chips	92 a	77 b
Straw	95 a	63 c
Control	55 b	17 d

^{z}Means in a column and year followed by the same letter(s) are not significantly different (Waller-Duncan K-ratio t-test *P*=0.05).

between production systems and treatments, mainly caused by the weedy checks, which had an average of 50% weed control on flat, bare ground but 60% in the plasticulture system (data not shown).

For the 4 Oct. 2004 assessment date, the mean square for weed control treatments was again significant while that for production systems was not. Also, there was a significant interaction between production systems and weed control treatments, mainly caused by the straw mulch which inexplainably performed poorly in the plasticulture system (45% control) compared to the flat, bare ground system (83% control). Differences in weed control efficacy were apparent among the treatments, with compost being the most effective weed suppressor, followed by wood chips and straw (Table 1.2). The cultivation treatment provided effective weed control, although by the end of the season there was no significant difference between this labor intensive technique and the compost treatment.

Three treatments (compost, wood chips, straw) were common to both years of the study. When the data for the two years were combined and analyzed, there was a highly significant year effect (P<0.0001), with an average weed control rating of 45% in 2003 and 86% in 2004, indicating that the cultivations in 2004 improved overall weed control.

Weed diversity in both years of the study was essentially the same, and included many horticulturally significant species such as velvetleaf (*Abutilon theophrasti*), lambsquarters (*Chenopodium album*), common ragweed (*Ambrosia artemisiifolia*), ivy leaf morning glory (*Ipomea hederacea*), field bindweed (*Ipomea purpurea*), pigweed (*Amaranthus retroflexus*), Pennsylvania smartweed (*Persicaria pensylvanica*), galinsoga (*Galinsoga parviflora*), prickly sida (*Sida spinosa*), foxtail (*Setaria glauca, Setaria viridis*), johnsongrass (*Sorghum halapense*), yellow nutsedge (*Cyperus esculentus*), and crabgrass (*Digitaria* spp.). The weed distribution was consistent with that on the rest of the research farm and individual species appeared throughout the plots with no treatment providing better control of a particular species.

MARKETABLE YIELD. For the 2003 marketable yield, the mean squares for weed control treatments, production systems, and the interaction of production systems with weed control treatments were significant. The overall average marketable yield for the plasticulture system (8310 lb/acre) was considerably greater than the average yield for the flat, bare ground system (1012 lb/acre). On average, corn gluten resulted in the poorest yield. The yields for the straw, compost and woodchips were significantly greater than that for the control. The significant interaction between production system and treatments ($P<0.001$) resulted from a difference in magnitude of response among the weed control treatments in the two production systems (Table 1.3). For example, yields from the compost treatment in the plasticulture system were 2.6 times that of the same treatment in the bare ground system. In addition, the yield difference was infinite for the two systems treated with corn gluten because the bare ground system treated with gluten had no marketable yield.

For the 2004 marketable yield, the mean square for weed control treatments was nearly significant, which reflects the overall increase in weed control in 2004. As in 2003, the mean square for production systems was significant, while the interaction of production systems with weed control treatments was not significant. The average marketable yield from the plasticulture system was more than 42,900 lb/acre and from the bare, flat ground system, more than 29,700 lb/acre. Among treatments, compost resulted in the highest yield, while the lowest yields resulted from the straw mulch and uncultivated control (Table 1.4).

Production systems and mulches, but not their interaction, had a significant impact on earliness in 2004 (2003 data were not analyzed because of extensive weed

Table 1.3. Effect of weed control treatments on yields of marketable[z] bell peppers on flat, bare ground or polyethylene-mulched raised beds, 2003-2004. All data are means from four replications.

Production System	**Weed Control Treatment**	**Marketable Yield[u] (lb/acre)**	
		2003	**2004**
Polyethylene Mulch			
	Straw	12424 a	38511
	Wood Chips	10162 ab	42516
	Clover	8387 b	-
	Compost	8300 bc	46345
	Control	6938 c	40949
	Corn Gluten	3648 d	-
	Cultivated	-	46258
Flat, Bare Ground			
	Compost	3192 de	34062
	Wood Chips	933 ef	31375
	Control	453 f	25562
	Straw	322 f	28249
	Clover	158 f	-
	Corn Gluten	0 f	-
	Cultivated	-	29278
Interaction[v]			
	FG[y] x PM[x]	***[w]	ns

[z] Marketable yields included X-Large, Large, Medium and Choppers in 2003; X-large, Large and Medium in 2004
[y] FG = Flat Ground
[x] PM = Polyethylene-Mulched Raised Beds
[w] *** significant at $P < 0.001$
[v] Interaction refers to the comparison of total pepper yields produced from the flat ground systems and the plasticulture system
[u] Means followed by the same letter are not significantly different ($P<0.05$)

Table 1.4. Effect of weed control treatments on marketable pepper yields from both flat ground and polyethylene-mulched raised bed organic bell pepper production systems in 2003 and 2004. Data are means of four replications.

Weed Control Treatment	**Marketable Yield**[z] (lb/acre)	
	2003	**2004**
Straw	6373 a	33380 b
Wood chips	5548 ab	36946 ab
Compost	5746 ab	40204 a
Clover	4273 bc	--
Control	3696 c	33256 b
Corn gluten	1824 d	--
Cultivated	--	37768 ab

[z]Means in a column followed by the same letter(s) are not significantly different (Waller-Duncan K-ratio t-test $P<0.05$).

pressure and low yields). The average 2004 harvest midpoint date was 28 Aug. for raised beds and black polyethylene mulch, and Sept. 5 for flat, bare ground plots. This 8 d difference in midpoint harvest dates was highly significant ($P < 0.01$). Among treatments, use of any mulch tended to delay harvest midpoint by 4-7 d (Table 1.5). The longest delay was associated with compost, which was significantly different than the cultivated and control treatments (Table 1.5).

ECONOMIC ANALYSIS. Yield data from 2004 reflect a drastic improvement in weed control and other management practices over 2003. The 2004 data were considered more typical of an optimized organic production system and were therefore used in the partial budget analysis (Table 1.6). Due to hand application (labor) costs, use of any additional mulch treatment in either the bare ground or plasticulture system increased weed control costs substantially ($300-600/acre) over the control and cultivated treatments, even if the mulch material could be obtained without cost. Purchase of mulch as an off-farm input dramatically drove up costs, and in the case of purchased compost, resulted in a net loss in both systems (Table 1. 6). Using a relatively low wholesale price of $8/box, which is not unusual for growers in Kentucky, and without any premium for organic produce, net returns were low to moderate for wood chip mulch and cultivated treatments on bare ground. Net returns were roughly doubled in all but the compost and straw mulch treatments when the plasticulture system was used; the highest returns were obtained from the cultivated plasticulture treatment ($6575/acre, Table 1.6). If a theoretical (but realistic) 15% price premium was received for organic bell peppers, moderate profits were possible even on bare ground from wood chip and cultivated treatments although the highest net returns were obtained from the cultivated treatment on raised beds with black polyethylene (Table 1.6). The analysis indicated no *economic* benefit from straw mulch or wood chip treatments compared to the control in the plasticulture system.

Table 1.5. Predicted dates at which 50% of the total pepper harvest was completed for five weed control treatments on flat ground and polyethylene-mulched raised bed organic bell pepper production systems in 2004.

Weed Control Treatment	**Harvest Mid-Point**
Straw	6 Sep
Wood chips	6 Sep
Compost	9 Sep
Cultivated	2 Sep
Control	2-Sep

Table 1.6. Partial budget analyses for four weed control treatments used in two organic bell pepper production systems (bare, flat ground and polyethylene mulch/raised beds), 2004. All data except yields are $/acre.

	Flat, Bare Ground					Polyethylene Mulch/Raised Beds				
Associated Expenses/Returns	**Compost Mulch**	**Straw Mulch**	**Wood Chip Mulch**	**Cultivated**	**Control**	**Compost Mulch**	**Straw Mulch**	**Wood Chip Mulch**	**Cultivated**	**Control**
Black polyethylene mulch/drip	--	--	--	--	--	300	300	300	300	300
Organic mulch	10830	1513	0	--	--	5041	756	0	--	--
Organic mulch application charge	600	600	600	--	--	300	300	300	--	--
Cultivation costs	15	15	15	31	15	15	15	15	31	15
Machinery repairs	45	45	45	75	45	45	45	45	75	45
Weed control, total costs	**11516**	**2198**	**686**	**131**	**86**	**5727**	**1442**	**686**	**431**	**386**
Total production cost	13028	3711	2198	1644	1598	7239	2955	2198	1944	1898
Total harvesting and marketing cost	4546	3772	4189	3910	3415	6269	5227	5759	6258	5555
Total variable cost	17880	7595	6473	5625	5079	13716	8293	8059	8303	7546
Total expenses	18200	7915	6793	5945	5399	14036	8613	8379	8623	7866
Yield (no. boxes harvested) [z]	1216	1008	1120	1045	912	1655	1375	1518	1652	1463
Gross returns[y]	9728	8064	8960	8360	7296	13240	11000	12144	13216	11704
Gross returns (with premium)[x]	11187	9274	10304	9614	8390	15226	12650	13966	15198	13460
Net Return (loss)[w]	**(-8472)**	**149**	**2167**	**2415**	**1897**	**(-796)**	**2387**	**3765**	**4593**	**3838**
Net Return (loss) with premium[v]	**(-7013)**	**1359**	**3511**	**3669**	**2991**	**1190**	**4037**	**5587**	**6575**	**5594**

[z]One 1 bushel box = 28 lb.
[y] Wholesale price used = \$8.00/ box.
[x] Wholesale price used = \$8.00/box plus a theoretical 15% premium for organic = \$9.20/box.
[w] Return to operator labor, land, capital, and management @ \$8.00/box
[v] Return to operator labor, land, capital, and management @ \$9.20/box (includes 15% premium for organic).

Although this study was not designed to compare conventional and organic production systems, returns from the compost mulch and cultivated treatments in the plasticulture system with the organic premium were only slightly lower than those for the same cultivar grown in a conventional bell pepper variety trial on the same farm approximately 1500 ft from the organically-managed plots with no price premium applied (data not shown). This cultivar was one of the two highest yielding varieties in that trial (Rowell et al., 2004).

Discussion

The primary goal of this research was to determine if surface-applied organic mulches would effectively suppress weeds in a commercial organic production system for bell peppers. While weed control was the main focus of this study, it is only one component of a system that relies on the integration of many important parts, each contributing to the overall enhancement of the crop. These include the use of mixed leguminous and grass cover crops as nitrogen and carbon sources, planting disease-resistant varieties, releasing bio-control agents as part of an insect management program, and using shallow cultivation for early weed control. Although each of these components was incorporated into the experimental design, the focus was on evaluating how mulches fit into this system to provide economical and effective weed control.

In 2003, the straw and wood chip mulch treatments provided the best weed control and highest yields (Table 1.1, Table 1.3). Although the compost treatment failed to give adequate weed control in 2003, it was tested again in the second year due to its documented positive effects as surface-applied mulch in bell peppers (Roe et al., 1992). In 2004, cultivation was integrated with the straw, wood chip, and compost mulches in a way that maximized weed control and yields. Most of the mulches provided very good to excellent weed control in 2004 from the time they were applied until final harvest (Table 1.2); however, for reasons unknown, straw mulch was less effective in row middles in the plasticulture system by the end of the season and therefore its control rating was lower than the other treatments when averaged over the two systems.

Marketable pepper yields from the organic plasticulture production system were higher than those on flat, bare ground system in both years of the study (Table 1.3). This is consistent with other studies showing that polyethylene mulch increases bell pepper yield (Abdul-Baki et al., 1999; Roe and Stoffella, 1994; VanDerwerken and Wilcox-Lee, 1988) compared to bare ground systems. Simply using black polyethylene and raised beds ensured higher yields; the addition of organic mulches to control weeds in between beds did not significantly enhance yields. Polyethylene mulch has been shown to increase soil temperatures (Janick, 1986) and it is possible that this accounted for some of the increased yield in 2004, however; the reduction of weed competition directly around the plants provided by the polyethylene mulch probably had a greater impact on yield. In the flat, bare ground production system there were some differences in marketable yields among mulch treatments with compost appearing to outperform the others; however, none of these differences were statistically significant (Table 1.3).

Consistent with the level of weed control provided by each treatment (Table 1.1), straw, compost and wood chip mulches resulted in the highest overall total yields in 2003 (Table 1.4). In 2004, when these treatments were applied after three shallow cultivations, compost gave the highest marketable pepper yields, although these were not significantly different from yields in the cultivated control and wood chip treatments (Table 1.4). Although adequate nitrogen was provided, it is possible, that the slightly higher yields observed with compost mulch resulted from a trace amount of additional nitrogen and other nutrients provided to the crop by the compost. Additionally, the compost may have had a higher water holding capacity than the other mulches which could have contributed to the increased yield. In general, yields were consistent with the level of weed control provided by the individual treatments; that is, treatments with the highest weed control ratings were the highest yielding.

Any of the organic mulches (compost, straw, or wood chips) could be incorporated in a large field production operation via mechanical application; however, given the increased yields in 2004 (Table 1.4), it is clear that post-transplanting cultivation is required to ensure good yields. Soil tests from both years indicated that potassium and phosphorous levels were adequate. Although nitrogen sources differed between the two years, similar rates were applied (115 lb/acre N in 2003 and 115-125 lb/acre N in 2004), based on recommended rates for pepper production in Kentucky. Therefore, the overall increase in marketable yield in 2004 was likely caused by the increased level of weed control resulting from the addition of the shallow cultivations. While the three cultivations in this experiment were necessary to provide acceptable weed control for the treatments applied to the flat ground system, it seems likely only two would be sufficient in between raised beds in the plasticulture system because of the weed control provided by the plastic mulch.

The combination of shallow cultivation following transplanting coupled with midseason mulch application was capable of producing good yields in two organically-managed bell pepper production systems. Excellent economic returns were possible, particularly with the use of polyethylene mulch and raised beds; however, profits in both systems were reduced substantially if organic mulch was purchased (Table 1.6). In addition, application costs should be considered and mechanization used where possible, to lower the amount of time ─ and associated costs ─ required for mulch application. As reduction of off-farm inputs is highly desirable on organic farms, applying purchased mulching material solely for weed control should be limited. However, other benefits that organic mulches provide, such as the addition of organic matter and reduced erosion/runoff, which were not factored into the economic analysis, could help justify the mulch and application costs on a site-specific, case-by-case basis. If organic mulches can be acquired at no charge, as with the wood chips in this study, the justification for their use would be substantially increased.

In conclusion, integrating early-season shallow cultivation with mid-season mulch applications could provide organic growers with a sustainable way to minimize yield losses from weed competition. Additionally, growers using polyethylene mulch-covered raised beds could use these techniques to increase soil organic matter while optimizing the production of organically-grown bell peppers

Chapter Three

Evaluating Solarization and Cultivated Fallow for Johnsongrass (*Sorghum halepense*) Control on an Organic Farm

Introduction

Surveys of organic farmers and farmers wishing to transition to certified organic crop production consistently report that weed control is a very important concern (Bond and Grundy, 2001; Walz, 2004). Numerous tools and techniques that destroy germinating weeds and reduce weed populations over time are available to organic farmers, but the efficacy of some newer weed control strategies have yet to be tested against more time-honored techniques, particularly when confronted with a troublesome perennial weed species.

Johnsongrass (*Sorghum halepense*) is listed as an invasive and noxious weed by many states in the U.S.A., and while control of this weed on conventionally managed farms is usually achieved with repeated herbicide applications, these chemicals are not available for use by organic or transitioning-to-organic farmers (USDA, 2005). Prior to the use of herbicides, johnsongrass control was accomplished primarily by a combination of mowing and tillage (Cates, 1907). A technique recommended early in the 20th century was to plant pasture grasses in the infested area; these grasses were then repeatedly mowed or grazed for hay throughout the first season, forcing shallow rooting of johnsongrass (McWhorter, 1989). The pasture system was maintained for at least a year, then shallow cultivation in association with a cash crop or a bare fallow were used to kill the weakened perennial weeds. Multiple passes of a cultivator equipped with sweeps brought rhizomes to the soil surface during the summer months, allowing them to desiccate and die (Hunt, 1915; Talbot, 1928). Although it took up to two years to pass through the cycle of mowing and cultivation, this method was considered effective.

A newer method of weed control, solarization, is a hydrothermal soil disinfestation technique that has proven useful for combating many soil pathogens and weed species (Stapleton, 2000). The technique uses clear plastic sheets stretched over bare soil during the summer months, allowing solar radiation to heat the soil while leaving soil structure undisturbed (Katan, 1981). Johnsongrass has been documented as being susceptible to solarization in California, and other perennial, difficult to control weeds such as purple nutsedge (*Cyperus rotundus)* and bermuda grass (*Cynodon dactylon*) have been controlled using solarization (Elmore, 1993; Ricci et al., 1999). Though most often used in arid climates, solarization offers promise as an herbicide alternative that is applicable to many climates and suitable for use by organic farmers.

Although solarization is commonly used for pathogen suppression, very little is known about the influence of solarization on soil microbial processes. One potentially negative aspect of solarization is that it may reduce soil microbial community functioning and nutrient cycling (Ristaino, 2003). Additionally, solarization has been found to result in levels of NO_3-N and NH_4-N that were elevated up to 6 times those of non-solarized soils (Stapleton et al.,1985). This effect did not last beyond 9 months after solarization ceased.

This study compared the traditional mechanical method of johnsongrass control, consisting of a cultivated bare fallow, with the newer technique of soil solarization. A second objective was to investigate the influence of solarization on key soil nitrogen (N) and carbon (C) cycling processes to evaluate potentially negative aspects of using this technique as an organic weed management tool.

Materials and methods

2003-2004

A field measuring 300 ft. by 125 ft. at the Organic Farming Systems Research Unit of the University of Kentucky Horticulture Research Farm in Lexington Kentucky was selected for this trial based on its uniform and heavy infestation of johnsongrass. The entire area was homogeneously infested with johnsongrass and about 40-50% of the area was occupied by the weed. Prior to the start of the experiment the area had been planted in a winter wheat cover crop (80 lb/acre, Southern States, Lexington, Kentucky) in the fall of 2002. The field was plowed in mid-May 2003, and the soil (Maury silt loam) was disked twice before the start of the experiment on 15 July 2003. The area was divided into 12 identical 25 ft. by 125 ft plots and the three treatments were randomly assigned to these plots resulting in a completely random design with four replications.

The solarization treatment consisted of stretching a 25 ft. by 125 ft. piece of 6 ML (150 micron) clear plastic over a plot and burying the edges. Researchers in California determined that solarization works best as a weed control technique when applied to well-moistened soil during the hottest period of the summer so irrigation drip tape was laid underneath the plastic at approximately 4 ft. intervals and the soil was irrigated until thoroughly moistened (Elmore, 1993). The plastic and drip tape were applied on 15 July 2003 and removed 16 Sept. 2003.

The cultivated bare fallow treatment plots were cultivated weekly, weather permitting, using a field cultivator equipped with S-tine shanks and cultivating sweeps. Cultivation began 15 July 2003 and ended 16 Sept. 2003.

The check treatment plots were left undisturbed during the season except for two passes with a rotary mower on 26 July 2003 and 20 Sept 2003, which prevented johnsongrass from going to seed. Following the second mowing in September, all four check plots were disked and planted with a winter wheat cover crop (80 lb/acre, Southern States, Lexington, Kentucky).

During the fall and winter of 2003, all solarization and cultivated bare fallow treatments were left untouched. On 14 May 2004 one-half of each solarization and cultivated bare fallow treatment plot was randomly selected and then shallowly disked to a depth of 3-4 inches. The shallowly disked area was designated as tilled, and the undisked area, untilled. Check plots planted with winter wheat were left undisturbed until 1 June 2004 when they were plowed and disked twice.

Weed data from all treatments were collected on 15 July 2004. Data collected included a visual estimate of percent johnsongrass soil coverage, and a count of all johnsongrass plants present on a 30 ft. transect in each plot. All johnsongrass plants counted on the transect were then classified as having been derived from seed or rhizome. In addition, all johnsongrass plants were counted in a randomly placed one meter square section of each treatment.

2004-2005

The four check plots established in 2003 were used for the experimental plots in 2004. Each 25 ft. by 125 ft. area was divided into three 25 ft. by 40 ft. areas and the same three treatments as used in 2003 (cultivated bare fallow, solarization and check) were randomly assigned to one of the three position within each plot. This subdivision was necessary as no other areas at the research farm possessed a similar infestation of johnsongrass.

For the second year of experiments, all treatments were applied on 16 July 2004 using the same methodology as that used in 2003. Bare fallow cultivation ended 17 Sept. 2004 and solarization plastic was removed on 22 Sept. 2004. Check plots were mowed twice on 29 July and 25 Sept. All plots were then left undisturbed until the following spring. On 28 May 2005 half of each plot was randomly chosen and then lightly tilled as had been done in 2004. On 14 July 2005 weed data were collected from all plots using the same procedures as those used in 2004.

Analysis of variance of all data was conducted using the PROC GLM procedure of the Statistical Analysis System and means were separated by Waller-Duncan K-Ratio t-tests (SAS Institute, 1999). Since data for density, transect, rhizome and seed were small whole numbers, they were transformed by adding 0.5 to each value and then calculating the square root, following the recommendations of Steel and Torrie (1960).

Soil sampling and analysis

Soil samples were first collected 21 May 2004. This sampling provided information on residual treatment effects from 2003. Twenty-four cores per plot, 1 inch diameter, 0-1 inch and 1-2 inch depth, were obtained by random sampling. Samples were homogenized in the field, placed on ice for transport, and stored at 39.2° F until analyzed. Samplings in 2004 and 2005 occurred only on former control plots that were converted to treatment plots in 2004, as described above. For 2004 and 2005 two 10.76 square foot subplots were sampled within each treatment plot at each sampling date. Twelve cores were taken from each subplot and treated as described above. To sample solarized plots, plastic was cut on three sides of each subplot to expose the soil, and was taped back into place when sampling was complete. New subplots were used for every sampling event. Soil temperatures at 1 inch and 2 inch depths were taken in all subplots with a mercury thermometer. Gravimetric water content was measured at every date, and all soil data were calculated and are expressed on a dry weight basis. Samples were collected 26 July, 16 August, 31 August, 21 September, and 18 November 2004, and 9 March and 12 May 2005. Sampling was completed before plots were split into tilled and untilled on 28 May 2005; only the main effects of the solarization and cultivated fallow treatments were measured in the soil analysis.

To measure mineral N content, 5 g field-moist soil was extracted with 20 mL 2M KCl. Nitrate-N in filtered extracts was measured by the cadmium reduction method (Keeney and Nelson, 1982). The Berthelot (indophenol-blue) reaction (Bundy and Meisinger, 1994) was used to measure NH_4-N in filtered extracts.

Arginine deaminase activity was measured by NH_4^+-N accumulation following treatment with L-arginine (Kandeler, 1995). Potentially mineralizable N (PMN) was measured by NH_4^+-N accumulation following a 7-day anaerobic incubation, as described by Kandeler (1995b).

Substrate-induced respiration (SIR) was measured by incubating soils with added glucose as described by Horwath and Paul (1994). Carbon dioxide evolution was measured on a Shimadzu GC 8A gas chromatograph equipped with a thermal conductivity detector (TCD). Injector temperature was 30°C, column temperature was 25°C, and the carrier gas was helium (He), at 100 kPA.

Labile C content was measured by the $KMnO_4$ oxidation method described by Weil *et al.* (2003). Five g field-moist soil was oxidized with 15 mL 0.02M $KMnO_4$. Samples were shaken for 2 min on a reciprocating shaker at 160 shakes min^{-1}, centrifuged briefly, and filtered. Absorbance was measured at 550 nm and moles of C oxidized were calculated based on color disappearance.

Total soil C and N were measured at the University of Kentucky Regulatory Services Soil Testing Laboratory. One-half gram of dried, sieved soil was injected into a LECO combustion instrument. Organic matter was calculated as % C ÷1.72 = % organic matter. Total N was reported based on total N_2 generated from combustion.

All soil data were analyzed by analysis of variance. For each sampling date analysis of variance was accomplished by use of the GLM Procedure of SAS (SAS Institute, 1999). Least-square estimates of the means were separated by t-test.

Results

2003-2004

Analysis of 2003-2004 data indicated significant differences among treatments for all five measurements of johnsongrass populations (Table 2.1). Coverage, the percent of the ground covered by johnsongrass, was significantly lower in tilled and untilled solarization treatments and in the cultivated-untilled treatment compared to the check treatment, indicating that these treatments were more effective (Table 2.1). The coverage in the cultivated-tilled treatments was not statistically different from the check. This trend was also present for johnsongrass density, as both solarized treatments and the cultivated-untilled treatment had significantly lower johnsongrass populations than the cultivated-tilled or check treatments. The transect data reflected the same trend. When plants on the transect line in the solarized-tilled treatment were excavated fewer of those plants had grown from rhizomes compared to all other treatments, although this difference was not statistically different. Of the plants identified as coming from seed, the solarized-untilled and check plots had the lowest percentage, although not statistically different from the other treatments (Table 2.1).

In 2003-2004 there were no significant differences between the tilled and the untilled sections of the solarized treatment (Table 2.1). However, significant differences were found between the tilled and untilled portions of the cultivated treatment with johnsongrass density and the number of plants on the transect substantially higher in the tilled sections.

Table 2.1. 2004 johnsongrass population data from plots treated in 2003 with cultivation or solarization.

Treatment[z]	Coverage[a] (%)	Density[b] (No./m^2)	Transect[c] (No.plants/9.1m)	Rhizomes[d] (%)	Seed[e] (%)
Cultivated-Tilled	27.5ab	35.0a	15.5a	45a	55a
Cultivated-Untilled	11.8b	7.8b	4.3b	43a	57a
Solarization-Tilled	11.3b	4.8b	3.3b	39a	61a
Solarization-Untilled	13.0b	6.3b	4.8b	64a	36a
Check	42.5a	18.0ab	14.8a	65a	35ab

a. Mean percent ground covered by johnsongrass.
b. Mean number of johnsongrass plants found in 1 m^2.
c. Mean number of johnsongrass plants found on a 9.1m transect.
d. Mean percent of johnsongrass plants derived from rhizomes present on the transect.
e. Mean percent of johnsongrass plants derived from seed present on the transect.
z. Mean separation based on transformed data ($\sqrt{X} + 0.5$). Means followed by the same letter are not significantly different ($P<0.05$).

The check treatment retained, on average, the overall level (40% coverage) of the johnsongrass infestation that had prompted this study (Table 2.1). Johnsongrass population data from the check treatment were not significantly different from those from the cultivated-tilled treatment.

2004-2005

As in 2003-2004, analysis of 2004-2005 data indicated significant differences among the treatments for all five measurements of johnsongrass populations (Table 2.2). The percent johnsongrass coverage was lower in solarized-untilled and cultivated-untilled treatments than the check treatment, while the cultivated-tilled treatment was slightly higher than the check. The percent johnsongrass coverage was lowest in the solarized-untilled treatment; however, this was not significantly different from the low johnsongrass populations present in the cultivated-untilled treatment. This trend among treatments left untilled having the lowest johnsongrass population mirrored a similar trend in 2003-2004.

Johnsongrass density was lowest in the solarized-untilled treatment, which was significantly less than densities present in solarized-tilled, cultivated-tilled, or check treatments (Table 2.2). As with percent of ground covered by johnsongrass, the zero johnsongrass population found in the solarized-untilled treatment was not significantly different from the low johnsongrass densities found in the cultivated-untilled treatment.

Of the number of plants found on the transect, the solarized-untilled treatment with zero johnsongrass was significantly less than check plots, which were highest (Table 2.2). The inclusion of a spring tillage event influenced johnsongrass populations significantly with lower overall control and higher numbers of plants on the transect in both the cultivated-tilled and the solarized-tilled plots. The percentages of johnsongrass plants found on the 2005 transect from

Table 2.2. 2005 johnsongrass population data from plots treated in 2004 with cultivation or solarization.

Treatment[z]	Coverage[a] (%)	Density[b] (No./m^2)	Transect[c] (No.plants/9.1m)	Rhizomes[d] (%)	Seed[e] (%)
Cultivated-Tilled	10.0a	5.0a	4.5ab	63a	37a
Cultivated-Untilled	3.8cd	1.5ab	1.5cd	67a	33a
Solarization-Tilled	5.8bc	4.3a	2.3bc	81a	19a
Solarization-Untilled	0.0d	0.0b	0.0d	--	--
Check	8.8ab	4.3a	6.0a	63a	37a

a. Mean percent ground covered by johnsongrass.
b. Mean number of johnsongrass plants found in 1 m^2.
c. Mean number of johnsongrass plants found on a 9.1m transect.
d. Mean percent of johnsongrass plants derived from rhizomes present on the transect.
e. Mean percent of johnsongrass plants derived from seed present on the transect.
z. Mean separation based on transformed data ($\sqrt{X} + 0.5$). Means followed by the same letter are not significantly different ($P<0.05$)

rhizomatous growth were higher than those derived from seed, but this difference was not significant.

Check plots in 2004-2005 had a 9% ground coverage by johnsongrass which was dramatically lower than the 40%-50% coverage rating in 2003 and which was retained in check plots over the first year of experimentation. Johnsongrass populations were significantly lower in the solarization and cultivated fallow treatments by the end of the experiment.

All aspects of soil microbial activity differed by date in 2004-2005, a common result in soil microbial investigations due to temperature and moisture fluctuations (see for example Carpenter-Boggs *et al.,* (2000). Analysis by date is therefore not shown; the more interesting information was the difference among treatments at each date, and between shallow and deep sample depths in each treatment.

Solarized soil had significantly higher temperature at both 0-1inch and 1-2 inch depths than either cultivated or undisturbed soil at dates when plastic was in place (Table 2.3). Temperature was not elevated in solarized plots at any date after plastic was removed on 22 September 2004. Cultivated and check treatments did not differ in soil temperature at any time except 12 May 2005, when undisturbed (check) soil was 1^{o}C warmer ($P<0.05$) than cultivated soil. Soil depth affected soil temperature in all treatments at all dates ($P<0.05$) in the expected manner, with 0-1 inch warmer than 1-2 inch depths. Treatment x depth interactions occurred on 6 July, 16 August, 31 August, and 21 September 2004; plastic was in place at these dates. The interactions were due to the much greater elevation in temperature between the 0-1 and 1-2 inch depth of solarized soil, compared to the temperature difference between shallow and deep soil in the other treatments. Tables 2.4 and 2.5 present mineral N content in soils at different dates.

Table 2.3. Least squares estimates of mean temperature (^{o}C) in soils treated with cultivation or solarization.

		Date[c]						
		6	16	31	21	17	9	12
	Depth[b]	Jul	Aug	Aug	Sept	Nov	Mar	May
Treatment[a]	(cm)	2004	2004	2004	2004	2004	2005	2005
Cultivated	0-2	25.8	27.1	27.0	22.3	15.6	1.3	26.7
	2-5	24.9	23.8	24.8	19.6	13.9	1.1	23.3
Solarization	0-2	37.3	36.3	36.1	30.0	15.1	2.9	25.6
	2-5	34.8	32.3	33.4	27.6	14.5	1.9	22.8
Check	0-2	25.9	27.8	28.8	22.6	14.9	2.6	27.6
	2-5	24.6	24.1	26.1	20.0	13.8	2.2	24.2

[a]In the analysis of variance treatment as a source of variance was significant for every date except 17 Nov. 2004. Temperature in solarized soils was significantly higher than the other treatments ($P<0.05$) for 6 July, 16 August, 31 August, and 21 September 2004; plastic was in place at these dates.

[b]Soil sample depth was significant at every date. The treatment x depth interaction was significant for 6 July, 16 August, 31 August, and 21 September 2004; plastic was in place at these dates.

[c]Data from 26 July 2004 was lost.

Table 2.4. Least squares estimates of mean nitrate content (mg NO_3^--N kg soil^{-1}) in soils treated with cultivation or solarization.

	Date							
	6	26	16	31	21	17	9	12
	Jul	Jul	Aug	Aug	Sept	Nov	Mar	May
Treatment[a]	2004	2004	2004	2004	2004	2004	2005	2005
Cultivated	4.3ab	11.5b	17.2b	17.5b	5.8b	1.8b	1.6b	0.3a
Solarization	5.4a	19.5a	46.9a	73.3a	70.1a	8.8a	2.8a	0.1a
Check	3.7b	11.5b	6.9b	6.0b	2.5b	4.2b	3.2a	0.5a

[a]Soil depth was significant ($P<0.05$) on 16 Aug, 31 Aug 2004, and 21 Sept 2004. Depth x treatment interactions were signficant ($P<0.05$) on 26 July, 16 Aug, 31 Aug, and 21 Sept 2004; and 9 Mar 2005.

Table 2.5. Least squares estimates of mean ammonium content (mg NH_4^+-N kg soil^{-1}) in soils treated with cultivation or solarization.

		Date								
		11	6	26	16	31	21	17	9	12
	Depth	May	Jul	Jul	Aug	Aug	Sept	Nov	Mar	May
Treatment[a]	(cm)	2004	2004	2004	2004	2004	2004	2004	2005	2005
Cultivated		1.8	0.1	0.2	ND	0.8	0.7	1.3	0.4	0.9
Solarization[2]	0-2	0.2	ND	21.5	44.0	45.3	23.6	1.4	0.6	1.0
	2-5	0.8	ND	5.9	6.2	1.9	1.4	1.6	0.5	0.8
Check		0.3	0.05	0.2	ND	0.9	1.2	1.3	0.7	1.0

[a]Depth was significant only in solarized soils at any date ($P<0.05$). Depth was significant in solarized soils on 26 July, 16 Aug, 31 Aug, and 21 Sept 2004, and 9 March 2005.
[2]Averaged over depth, ammonium in solarized soils was higher ($P<0.05$) than in other soils on 26 July, 16 Aug, 31 Aug, and 21 Sept. There were no differences between cultivated and check soils at any date.
ND = not detectable

There was no clear pattern of depth or depth x treatment influence, although these factors were significant (P<0.05) at several dates. The overall treatment effect was more consistent. While plastic was in place from July to September 2004, the solarized soil had higher nitrate content, as found by Stapleton *et al*. (1985) (Table 2.4). However, this pattern did not last for up to nine months as Stapleton had found; by March 2005, the solarization effect on nitrate had disappeared. Ammonium followed a pattern similar to that of nitrate, except that depth was clearly significant in solarized soils (Table 2.5); the 0-1inch depth consistently had more ammonium than the 1-2 inch depth while plastic was in place. Similar to nitrate results, the elevated ammonium in solarized soils did not persist for as long as indicated by Stapleton (1985). It is not known from these data exactly when solarization ceased to affect nitrate and ammonium levels after the removal of plastic, but clearly solarization did not have a long residual effect on mineral N levels in this soil during this experiment.

Table 2.6 presents L-arginine deaminase activity in cultivated, solarized, and control soils. L-arginine deaminase is sensitive to soil disturbance (Bandick and Dick, 1999). There was no difference between solarization and the other treatments in May 2004, reflecting the 2003 solarization season (data not shown). At all dates in 2004 while plastic was in place, solarized soils had significantly less (P<0.05) arginine deaminase activity than the other treatments. The 0-1 inch depth in solarized soil had significantly less activity than the 1-2 inch depth on several dates, possibly indicating that the high temperatures close to the plastic-covered surface negatively affected the activity of this enzyme. The 2004 solarization effect on arginine deaminase activity persisted through May 2005. On 17 Nov. 2004, 9 March 2005, and 12 May 2005, cultivation negatively affected this enzyme compared to undisturbed soil. Table 2.7 presents potentially mineralizable nitrogen (PMN). This soil characteristic followed a similar

Table 2.6. Least squares estimates of mean L-arginine deaminase activity (mg NH_4^+ kg^{-1} soil hr^{-1}) in soils treated with cultivation or solarization.

	Date						
	6	26	16	21	17	9	12
	Jul	Jul	Aug	Sept	Nov	Mar	May
Treatment[a]	2004	2004	2004	2004	2004	2005	2005
Cultivated	4.7ab	4.2a	3.9a	4.7a	3.5b	3.6b	3.4b
Solarization[b]	5.1a	3.2b	2.6b	2.7b	1.8c	2.1c	2.5c
Check	4.4b	3.8a	3.8a	4.1a	4.4a	4.2a	3.8a

[a]Means in the same date with different letters differ (P<0.05).
[b]Solarization differed by depth on 26 Jul 2004, 17 Nov 2004, and 9 Mar 2005. The 2-5 cm depth had significantly (P<0.05) more arginine deaminase activity at each date than the 0-2 cm depth.

Table 2.7. Least squares estimates of mean potentially mineralizable nitrogen (mg NH_4-N kg^{-1} soil d^{-1}) in soils treated with cultivation or solarization.

	Date					
	6	26	16	17	9	12
	Jul	Jul	Aug	Nov	Mar	May
Treatment[a]	2004	2004	2004	2004	2005	2005
Cultivated	1.2a	1.2a	0.7a	0.7b	1.6a	0.8b
Solarization	1.1a	0.1c	ND	0.4c	0.6c	0.6c
Check	0.7b	0.7b	0.5a	1.4a	1.3b	1.3a

[a]Means in the same date with different letters differ ($P<0.05$). For all dates except 26 July, potentially mineralizable nitrogen was significantly higher in the 0-2 cm depth than the 2-5 cm depth in every soil treatment. A depth x treatment interaction was significant on 17 November 2004, and 9 March and 12 May 2005, with difference in magnitude of depth effect between treatments responsible for the interaction.
ND = not detectable

pattern to that of arginine deaminase, with solarization negatively affecting PMN at every date while plastic was in place. Table 2.8 presents substrate-induced respiration (SIR) values.

Solarized soil had a lower SIR than cultivated or check soil in May 2004 ($P<0.05$), possibly reflecting a residual effect from the 2003 solarization season. There was a clear pattern of reducedSIR in solarized soil when plastic was in place, especially in the latter part of the summer; this may reflect gradual die-off of active microbial biomass. The reduction in SIR persisted through 17 November 2004, but not after that date. It is not known from this data exactly when solarization ceased to affect SIR after the removal of plastic, but solarization did not have a long residual effect on SIR in this soil during the 2004-2005 experimental season.

Table 2.9 presents labile C. There was no clear pattern in labile C related to soil treatment or depth over the dates surveyed, except that solarization did not reduce labile C compared to cultivation or non-disturbance.

Discussion

Our major objective was to compare two practical methods of johnsongrass control: cultivated bare fallow and solarization. Cultivated bare fallow did not appear quite as effective as solarization for long-term johnsongrass control in this experiment (Tables 2.1 and 2.2). Initial populations in the cultivated bare fallow treatment were reduced in both years to essentially the same levels as found in the solarized treatment; however, spring tillage of these treatments appeared to reduce their effectiveness. Johnsongrass eradication was of great interest in the early part of the 20th century and cultivation during mid-summer was considered an effective control. This experiment confirmed that cultivated bare fallow is an effective technique; however, one year of this treatment may not be sufficient to eradicate dense johnsongrass populations similar

Table 2.8. Least squares estimates of mean substrate-induced respiration activity (μg C g^{-1} soil min^{-1}) in soils treated with cultivation or solarization.

	Date								
	11	6	26	16	31	21	17	9	12
	May	Jul	Jul	Aug	Aug	Sept	Nov	Mar	May
Treatment[a]	2004	2004	2004	2004	2004	2004	2004	2005	2005
Cultivated	52a	95ab	49a	39a	32a	86a	89b	65a	162a
Solarization	26b	115a	36b	21c	17b	47b	63c	70a	153a
Check	51a	82b	39ab	33b	29a	111a	134a	59a	172a

[a]Means in the same date with different letters differ (P<0.05). Depth was significant (P<0.05) only on 9 Mar and 12 May 2005, with the 0-2 cm depth greater than the 2-5 cm depth on both dates.

Table 2.9. Least squares estimates of mean labile C (mg labile C kg $soil^{-1}$) in soils treated with cultivation or solarization.

	Date							
	11	6	26	16	21	17	9	12
	May	Jul	Jul	Aug	Sept	Nov	Mar	May
Treatment[a]	2004	2004	2004	2004	2004	2004	2005	2005
Cultivated	467a	514a	558a	583a	420a	340a	343a	401a
Solarization	433b	511a	571a	599a	417a	337a	356a	408a
Check	483a	476b	521b	543b	401a	330a	418a	395a

[a]Means for the same date with different letters differ ($P<0.05$).

those present at the beginning of this study. The additional plowing, disking, and cover cropping of the check plots from 2003-2004 (which became treatment plots in 2004-2005) probably played a large role in the overall reduction of johnsongrass by the end of the experiment in those treatment plots.

From our results it appears that solarization effectively controlled johnsongrass as populations were greatly reduced in both years in solarized treatments. Even when solarized plots were tilled, (a treatment that tended to allow greater johnsongrass survival in cultivated bare fallow treatment plots), johnsongrass populations remained much lower than the 40-50% infestation present at the start of the experiment. These results corroborate findings of Elmore (1993), Standifer *et al*. (1984), and Ricci *et al*. (1999), who reported that solarization effectively controlled perennial weed species having extensive rhizomatous growth.

The majority of solarization research has been conducted in warm temperate and tropical areas with the major focus on soil-borne pathogen control. Weather would be a critical factor influencing the effectiveness of solarization and cultivated bare fallow in Kentucky for weed control and both total precipitation and average ambient air temperature play a role in the success of these techniques. Weather data from the Lexington airport, located near the site of these experiments, for the months of July through September of 2003 showed that the mean ambient temperature was 72° F tying it for the 16th coolest summer period since 1896. Mean ambient temperature data from July to September for 2004 was 70° F which ranked it as the 5th coolest summer period recorded since 1896 (MRCC, 2005). Precipitation for the months of July to September in 2003 was 14.68 inches which ranked it as the 14th wettest year, and was 15.96 inches in 2004 which ranked it as the 12th wettest year since 1896 (MRCC, 2005). Additional weather data show that total solar radiation in the region was within the normal range expected during both summers of this study (Table 2.10). As solarization seemed to be the somewhat more effective of the two treatments for the control of johnsongrass, it is interesting to note that the two years of this study were both cooler and wetter than average years in Kentucky. In years closer to average it can be expected that solarization could perform even better than found in this study.

One potential consideration when using soil solarization for weed control is the negative effect that solarization has on soil microbial activity. Solarization is often used to reduce pathogen loads in soil, and some farmers have used solarization to elevate mineral N levels before planting a crop (Stapleton *et al*., 1985). Elevated mineral N levels along with lowered levels of microbial activity indicators such as arginine deaminase and SIR demonstrate reduced N-recycling in solarized soils. In other words, N that is mineralized remains mineral in solarized soil because the microbial biomass is either not active enough or not large enough to recycle released mineral N into biomass. If the subsequent crop did not use all mineral N, net loss of mineral N from solarized soils could result, probably in the form of nitrate leaching. Planting a grass cover crop or other heavy N-using crop immediately after removing solarization plastic could address this issue. Most cash crops for which solarization would be used are spring or summer crops in Kentucky. Because the influence of solarization on the nutrient cycling microbial biomass seems to be transient, such cash crops would not be affected by solarization (assuming that the solarization's effect on a pathogen of interest was *not* transient). Therefore, the short-lived effect of solarization on nutrient cycling should not be of great concern to growers wanting to use solarization for pathogen or weed control. We did not test the influence of compost or other soil amendment to reinvigorate the microbial population immediately after

Table 2.10. Daily Average of Solar Radiation at UK Spindletop Farm in Lexington Kentucky during 2003, 2004, and averaged from 1989-2005.

Date (range)	**Solar Radiation Total ($kJ \cdot m^{-2}$)[a]**		
	Average[b]	2004	2003
July 15th-31st	20166	19266	19677
August 1st - 31st	18870	19172	19642
Sept 1st - 18th	16290	15227	17545

a – kilo-joules per square meter
b – based on solar radiation data from University of Kentucky weather station at Spindletop Farm (1989 -2005).

solarization. It is possible that some normal organic farming techniques would mitigate even the transient influence of solarization on the nutrient cycling microbial population. Organic farmers often depend on cultural and mechanical means to control weeds and farmers transitioning to organic production techniques must learn and master these strategies to achieve profitability. Yet, when confronted with land infested with a troublesome perennial weed such as johnsongrass, growers are understandably interested in faster alternatives for eliminating such weeds. Solarization has been used by limited resource and organic growers in California as an alternative to methyl bromide and for weed control, and from this research it appears to be to be an equally effective weed control tool as cultivated bare fallow for small farmers in temperate climates such as Kentucky (Stapleton et al., 2005).

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Vita

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I. <u>Education</u>

Berea College, Berea KY

Bachelor of Science in Agriculture emphasis in Sustainable Systems, 2000

Harry Lundeberg School of Seamanship, Piney Pt. MD

Attended Jan. 1993 - Mar. 1993

Awarded Able Seaman Certification

Attended May 1991 - Sept. 1991

Awarded Coast Guard "Z" Card Certification

"B" Seniority ranking in Seafarers Int'l Union

Flagstaff High School, Flagstaff AZ

Awarded Diploma May 1990

II. <u>Professional Employment and Career Related Experience</u>

University of Kentucky Graduate Research Analyst: 9-2005 to present

University of Kentucky Graduate Research Assistant: 6-2003 to 9-2005

University of Tennessee Graduate Research Assistant: 8-2002 to 12-2002

Berea College Work Program

9-1998 to 12-2000: Berea College CSA Farmer and Greenhouse Manager.

9-1997 to 5-1998: Farm Worker

5-1997 to 9-1997: Campus Gardeners

Howell Living History Farm: May 1998- Sept 1998

III. Honors

Thomas J. Watson Fellowship: 7-2001 to 7-2002:

Morris K. Udall Scholarship in National Environmental Policy
Morris K Udall Foundation, 1999

Henry W. and Edna Austin Scholarship for academic excellence
Berea College, 1998

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IV. Publications

Derek Law, Victoria Bhavsar, John Synder, Mike Mullen, and Mark Williams. 2006. Evaluating Solarization and Cultivated Fallow for Johnsongrass (Sorghum halepense) Control on an Organic Farm. (submitted to Biological Agriculture and Horticulture 7/2006)

Derek Law, John Synder, Brent Rowell, and Mark A. Williams. 2006. Weed Control Efficacy of Organic Mulches in Two Organically-Managed Bell Pepper Production Systems. HortTechnology. 16(2): 225-232.

Sean Clark and Derek Law. 2000. Multipurpose program at Berea College. *BioCycle* 41(9): 69-70.

V. <u>Research Reports</u>

Derek Law, John Synder, and Mark Williams. 2005. Solarization and Cultivated Fallow for Weed Control on a Transitioning Organic Farm. University of Kentucky Fruit and Vegetable Report.P.R. 521

Derek Law, Brent Rowell, and Mark A. Williams. 2004. Evaluation of Weed Control Practices in an Organic Bell Pepper Production System. University of Kentucky Fruit and Vegetable Research Report. P.R. 504.

VI. <u>Abstracts Presented Before Professional Societies</u>

Derek Law, Brent Rowell, and Mark A. Williams. Weed Control Efficacy of Organic Mulches in Two Organically-Managed Bell Pepper Production Systems. American Society of Horticultural Science Meeting. Las Vegas, NV. July 18-21, 2005.

VII. <u>Professional Meetings Attended</u>

Southern SAWG's Practical Tools and Solutions for Sustaining Family Farms Conference. Louisville, KY. January 19-22, 2006.

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VIII. <u>References</u>

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