EVALUATION OF THE LONG TERM SUSTAINABILITY OF METHYL BROMIDE ALTERNATIVES IN TOMATO (*Solanum lycopersicum* Mill.) AND PEPPER (*Capsicum annuum* L.)

By

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To my parents

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LIST OF ABBREVIATIONS

CUE	Critical use exemption
DAT	Days after treatment
DATP	Days after treatment
DMDS	Dimethyl disulfide
EC	Emulsified concentrate
FOL	*Fusarium oxysporum* f.sp. lycopersici
FORL	*Fusarium oxysporum* f.sp. radicis-lycopersici
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
MeBr	Methyl bromide
MeI	Methyl iodide
Metam	Metam potassium
MNa	Metam sodium
ODP	Ozone depleting potential
Pic	Chloropicrin
TIF	Totally impermeable film
VIF	Virtually impermeable film
WAT	Weeks after treatment
WATP	Weeks after transplant
1,3-D	1,3-dichloropropene

Abstract of Thesis Presented to the Graduate School
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Florida produces the majority of domestically grown tomatoes and bell peppers during the winter months. In 2010, Florida ranked first in value of production of fresh market tomatoes at $631 million and first in value of production of bell peppers at $296 million. A three year trial was initiated in August of 2008 at the Gulf Coast Research and Educational Center in Balm, FL to determine the long-term sustainability of four methyl bromide alternative programs, in comparison to a non-treated control and methyl bromide plus chloropicrin standard in a Florida tomato and bell pepper production system. The methyl bromide alternatives were methyl iodide in combination with chloropicrin, dimethyl disulfide in combination with chloropicrin, 1,3-dichloropropene in combination with chloropicrin followed by metam potassium, and 1,3-dichloropropene in combination with chloropicrin. The fumigant systems were applied with and without a pre-emergence herbicide program. In general, the addition of an herbicide to the fumigant systems provided better control of yellow and purple nutsedge (*Cyperus esculentus* and *Cyperus rotundus*). The fumigant systems in combination with herbicides showed a better potential for sustainability in tomato than bell pepper.

CHAPTER 1
INTRODUCTION

In 2010, Florida tomato (*Solanum lycopersicum* Mill.) totaled 13,000 ha with a value of more than $600 million. Bell Pepper (*Capsicum annuum* L.) is also an important winter crop for Florida with 7,600 ha grown in 2010 worth almost $300 million. To maintain economical production levels, growers have relied on methyl bromide (MeBr) for fumigation. Methyl bromide was classified as an ozone depleting chemical in 1993 under the Montreal Protocol. Methyl bromide production in the U.S. was to be phased out by 1 Jan. 2005 and following 2005, it was allowed only for quarantine use or through a critical use exemption (CUE). The amount nominated for CUE use in 2012 is 4.6% of the 1999 baseline of 25,500,000 kg. This reduction in supply of MeBr has led to a need for alternative fumigants that are economical and provide acceptable control of soilborne pest which includes weeds, diseases, and nematodes. These pests cause production losses as a result of lower crop yields, poorer crop quality, and higher production costs. Purple and yellow nutsedge (*Cyperus rotundus* L. and *Cyperus esculentus* L.) are two economically important pests in tomato and bell pepper production.

Growers must be able to determine the fumigant or combination of fumigants and herbicides that provides the same yield and control levels as MeBr. Methyl bromide has the ability to eradicate weeds, diseases, and pests over a broad range of environmental conditions. Some research trials have shown MeBr alternatives to be equally effective as MeBr, but others have shown to lack in pest control and have shown reduced yields. The inconsistency of these MeBr alternatives leads to concern of their sustainability as replacements for MeBr. Sustainability as it relates to a fumigant, is the capacity for a fumigant or fumigant system to maintain soilborne pest pressure at a level equal to or less than the previous cropping cycle without any negative impact on yield while still being economically viable. To determine a fumigant's sustainability, it must be applied to the same piece of land over several cropping seasons. Successful systems will allow vegetable growers to use the same fields year after year for crop production. Research on fumigant sustainability must be completed in order to implement these systems at the commercial production level. This research was conducted on the same site each season in order to evaluate and determine the influence each MeBr alternative system has on pest populations across growing season.

This research included a methyl bromide plus chloripicrin standard (MeBr:Pic), three full fumigant systems: methyl iodide in combination with chloropicrin (MeI:Pic), dimethyl disulfide plus chloropicrin (DMDS:Pic), 1,3-dichloropropene in combination with chloropicrin followed by metam potassium (1,3-D:Pic:Metam), and a reduced fumigant system: 1,3-dichloropropene in combination with chloropicrin (1,3-D:Pic).

The hypotheses were that all fumigant systems tested will provide better crop yields than the non-treated control; the reduced fumigant system of 1,3-D:Pic will not be sustainable as it relates to nutsedge populations; and the addition of herbicides will improve the sustainability of the fumigant systems. The objective of this study was to determine the sustainability of economically effective methyl bromide alternative fumigant systems for the control of weeds in tomato and bell pepper.

CHAPTER 2
LITERATURE REVIEW

Tomato

Florida produces the majority of domestically grown tomatoes (*Solanum lycopersicum* Mill.) during the winter months. In 2010, Florida ranked first in value of production of fresh market tomatoes at $631 million harvested from 13,000 ha, accounting for 45% of the total U.S. value (USDA-NASS, 2010).

Tomato, native to the Andean region (Sims, 1980) on the west coast of South America, is a dicotyledonous angiosperm in the family Solanaceae that is typically grown as an annual in temperate regions. Within this family, tomato belongs to the Solanoideae subfamily and the tribe Solaneae. The tomato was introduced into Europe by the Spanish in the early 16th century (Harvey et al., 2002). Initially, they were grown only as ornamentals. The Europeans brought the tomato to China and South Asia in the 17th century. It was subsequently brought to the US and Japan in the 18th century (Siemonsma and Piluek, 1993). Tomatoes are popular because they can be eaten fresh in salads, used for grilling, baking, and frying or in many different processed forms.

The tomato fruit is known as a berry and consists of seeds inside a fleshy pericarp (walls and skin) which was developed from an ovary (Heuvelink, 2005). Round tomatoes contain two to three locules with a mean fruit weight of 70-100 g and diameter of 4.7-6.7 cm. Fruit maturation from pollination requires about 60 days (Heuvelink, 2005). Fresh-market tomatoes are known to have six ripeness stages which are based on the external color change of the fruit as it turns from green to red. This color change is due to the destruction of chlorophyll and the synthesis of lycopene. The six stages are as follows starting from green and ending in red: 1) mature green, 2) breaker, 3) turning, 4) pink, 5) light-red, and 6) red-ripe. Tomatoes are harvested at different stages depending on harvest type (i.e. mechanically or by hand), use, and shipping distance. Plant breeders have made many genetic improvements to tomatoes that include higher soluble solids, higher lycopene content, concentrated fruit set, firmer fruit, uniform ripening, prolonged storability, disease resistance, drought resistance, and insect resistance. Ripe tomatoes are good sources of vitamins A and C, and lycopene (Heuvelink, 2005).

Tomatoes require 90-120 days of frost-free weather with a mean temperature above 16°C. Soil fumigation for tomatoes in Florida begins in early July and continues through February of each year. Transplants are commonly used in fresh market production systems. Varieties grown in the field are often of the determinate type. Tomatoes are able to root as deep as 2 m but about 60% of the root system is located in the top 0.3 m of soil (Rendon-Poblete, 1980). Tomato plants grown for fresh market harvest are supported by driving wooden stakes into the soil between the plants 1-3 weeks after transplanting. A tightly stretched twine running horizontally along the plant row supports the actively growing plants. Staking and tying serves the purpose of holding the plants off the ground in order to achieve optimal pesticide spray coverage as well as keeping the fruits clean and ease of harvest. This also allows more air movement through the plant which reduces the duration of foliage wetness (occurring from dew or rainfall), thus lowering the potential for diseases requiring high humidity (Stanley and Geraldson, 1991). The first tying occurs when the plants are between 30-40 cm tall or just before they fall over. The twine is tied about 25 cm above the plastic.

The plants should be tied a minimum of three times over the course of the season and each tying is about 25 cm above the previous tying (Heuvelink, 2005).

Many disease resistant varieties of tomato are commercially available and include resistance to Fusarium wilt (*Fusarium oxysporum* f.sp. lycopersici; race 1,2 and 3), Fusarium crown rot (*Fusarium oxysporum* f.sp. radicis-lycopersici), Verticillium wilt (*Verticillium albo-atrum* and *Verticillium dahliae*; race 1), bacterial wilt (*Ralstonia solanacearum*), gray leaf spot (*Stemphylium solani*), tomato spotted wilt (TSWV), Alternaria stem canker (*Alternaria alternata* f.sp. *lycopersici)*, tomato yellow leaf curl (TYLC) and tomato mosaic (ToM).

Pepper

Bell pepper (*Capsicum annuum*) is also an important winter crop for Florida. In 2010, Florida ranked first in value of production of bell peppers at $296 million, harvested from 7,600 ha, accounting for 46% of the total U.S. value (USDA-NASS, 2010). The principal destination for bell peppers in the U.S. is fresh market. Bell peppers are grown throughout the entire year in the U.S.

Bell pepper is a dicotyledonous angiosperm in the family Solanaceae and the order Solanales. Pepper is native to Mexico and Central America. Christopher Columbus was given the credit for introducing pepper to Europe followed by Africa and Asia (Bosland and Votava, 2007). He came across the plant on his voyage and named it ‘pepper’.

Bell pepper is used in a range of food products that includes meats, baked goods, snack foods, breading and batters, ethnic foods, salad dressings, dairy products, beverages, salsas, and hot sauces (Bosland and Votava, 2007). Extracts of pepper are also used in cosmetic and pharmaceutical products. They can also be grown as ornamentals. High amounts of vitamins A, C and E are present in pepper (Bosland and Votava, 2007).

The pepper plant has a deep taproot (36-48 cm) with the majority of the roots located near the soil surface. The roots are able to spread horizontally to a length of 30-50 cm. The stems are angular when young but become circular as they mature. Most cultivars develop a single stem possessing 8-15 leaves before the first flower appears, with most leaves being simple, entire and symmetrical. Pepper flowers are complete and most species of pepper are self-compatible (Bosland and Votava, 2007).

Peppers are a warm season crop requiring almost the same conditions as tomatoes, being highly susceptible to frost. Florida has a long duration of possible growing seasons. Planting usually begins in the middle of July and continues all the way through to the middle of March, depending on the region. Harvest typically begins in the middle of October and ends the following June. The ideal soil for pepper production is a deep, well-drained, medium-textured sandy loam or loam soil with some organic matter and capable of holding moisture (Bosland and Votava, 2007). Bell peppers are usually transplanted as 5 to 6 week old seedlings as opposed to direct seeding in the field.

Many disease resistant varieties of bell pepper are commercially available and include resistance to bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*; race 1,2,3 and 5), potato virus Y (PVY), tobacco etch virus (TEV), cucumber mosaic virus (CMV), pepper mottle virus (PeMoV), and tobacco mosaic virus (TMV).

Irrigation

Irrigation is a necessity to ensure desired production levels. Selection of an irrigation system depends on availability of water, soil conditions, climate, and economics (Stanley and Geraldson, 1991).

Seepage Irrigation

Seepage irrigation involves pumping water into open lateral ditches that were previously made with a tractor mounted ditch plow. The water in these ditches moves horizontally by subsurface flow and forms a crowned water table on an existing hardpan. The water reaches the root zone by capillary action. The spacing of the ditches depends on the soil type. On a light sand soil the horizontal movement of water is limited. This irrigation system has the lowest initial cost and low application efficiency. The efficiency of this irrigation system strongly depends on depth to the natural water table and characteristics of the soil. These open ditches can also be used for drainage. Under dry climatic conditions, soil fumigation usually requires irrigation prior to forming beds in order to maximize the efficiency of the fumigant. This irrigation practice, usually done by seepage irrigation in Florida, will also encourage the germination of weed seeds and the sprouting of nutsedge tubers, therefore increasing fumigant efficacy (Noling, 2005).

Drip Irrigation

Another irrigation system widely used in Florida vegetable production is drip irrigation. In Florida, an estimate of over 24,000 ha of vegetables are produced with drip irrigation annually (Simonne and Hochmuth, 2009). This system is expensive to install but also has the highest application efficiency when compared to other irrigation systems with the ability to apply water uniformly and precisely to the soil. This allows for reductions in water loss, fertilizer, and cultural costs. Drip tape selection should be made using the following considerations: crop water requirements, plant spacing, bed width, soil type, emitter spacing, and flow rate (Nakayama and Bucks, 1986). Drip irrigation can also deliver fumigants, pesticides and plant nutrients throughout the growing season. Fumigants are applied to preformed beds covered with polyethylene mulch to improve efficacy and worker safety. Even fumigant distribution throughout the field may be attained with proper calibration. The drip tape spacing on the bed and the flow rate must be considered to get adequate coverage. The goal of drip fumigation is to extend the wetted area to the edge of the bed (Martin, 2003). Not only does the water distributes the fumigant horizontally across the soil but also plays the role of a barrier to prevent rapid volatilization of fumigant into the atmosphere (Ajwa et al., 2002). Most Florida tomato growers use a single drip tape but in sandy soils it is very hard to get the lateral movement needed in order to reach the edge of the bed. At the completion of drip fumigant application, extra water should be ran through the system to flush the fumigant out of the drip tape. However, excessive flushing should be avoided to prevent possible reduction in fumigant efficacy.

Soils

Soil type has a major impact on fumigant selection. Factors such as compaction layers and clay layers affect downward diffusion of soil fumigants as well as drainage. The soil type found in many production regions in Florida is called a spodosol. Spodosols contain a spodic horizon that is the result of the accumulation of black or reddish amorphous materials that have a high cation exchange capacity (Collins, 2009). Cation exchange capacity can be defined as “the sum total of exchangeable cations that a soil can adsorb” (Senseman, 2007). A shallow compacted layer is present at a depth of 15 to 20 cm in Florida's spodosols. This compacted layer has been observed to restrict downward penetration of drip irrigation water, and can also cause flooding of row middles once the soil above the compacted layer becomes saturated.

Soil preparation before fumigation is important and producers have to allow adequate time for the process to ensure optimum pest control. Crop and weed residues must be given an adequate amount of time to decay in the soil. Non-decayed plant material can hinder the formation of a desired bed and interfere with the soil seal, which slows diffusion of the fumigant out of the bed. When present, residue can create natural passage ways that aid the movement of the fumigant through the soil and into the atmosphere, therefore limiting the efficacy of the fumigant. In addition, freshly incorporated plant materials can harbor plant pathogens such as *Pythium* and *Rhizoctonia* at sufficient levels to cause damping off of transplants (Simonne and Hochmuth, 2009).

Weeds

Weeds are a problem in vegetable production because they compete with crops for light, water, nutrients, and space. A "weed" can simply be defined as "a plant growing where it is not desired, or a plant out of place" (Monaco, 2002). Weeds are classified as annuals, biennials or perennials, and consist of sedges and grasses (monocots), and broadleaves (dicots). Factors that influence germination include temperature, moisture, light, oxygen, and seed shape.

Cyperus spp.

The most invasive weeds of fruiting vegetable and cucurbit crops in the southern United States are purple nutsedge (*Cyperus rotundus)* and yellow nutsedge (*Cyperus esculentus)* (Webster, 2006). Purple nutsedge has even been identified as the world's worst weed in the major agricultural production areas, infesting at least 52 different crops, while yellow nutsedge was ranked among the top 15 worst weeds (Holm et al., 1977). Nutsedges are creeping perennials that reproduce asexually by underground tubers and sexually by seeds (Anderson, 1996). These reproductive abilities are what make these weeds so difficult to control. The tubers contain large carbohydrate reserves which allow for hasty emergence and growth which is a major advantage over seeded crops.

Distinguishing the Nutsedge Species apart

These two sedges can be difficult to separate but they each have distinguishing characteristics. Purple nutsedge tubers are cylindrical in shape with a brownish-black color, and are susceptible to desiccation. Yellow nutsedge tubers are cylindrical as well, but are a yellow to beige color. They can be dried and become wrinkly but this has minimal effect on viability. Purple nutsedge tubers form chains that can expand long distances away from the mother plant, while yellow nutsedge tubers will remain close to the mother plant because all rhizomes that end in a tuber will be attached to the mother plant. Purple nutsedge usually has a shorter leaf blade that always comes to an immediate tip that remains flat near the tip of the blade. Yellow nutsedge usually has long leaf blades with a leaf tip that gradually tapers, that also tend to form folded boat-shaped blades near the tips. Purple nutsedge has a reddish-purple inflorescence and yellow nutsedge has a yellow inflorescence. Yellow nutsedge has higher seed production than purple nutsedge producing 2,420 seeds per plant. There is a subspecies of yellow nutsedge known as chufa that is grown as a crop for animal feed.

Cyperus rotundus

Purple nutsedge is a weed that flourishes in cultivated crops. The only limitations of this weed are moisture and low temperatures. Stoller (1973) observed that less than 10% of purple nutsedge tubers survived 2°C for 12 weeks when buried in the soil to a depth of 10 cm. However, 95% of yellow nutsedge tubers survived the same treatment. Neeser et al. (1997) estimated the half-life of purple nutsedge tubers is 16 months. Purple nutsedge has also been documented to produce allelopathic compounds that negatively affect the growth and development of crops (Holm et al., 1977). This sedge has a three-sided stem, dark green leaves, and the ability to grow up to 100 cm tall. The inflorescence is reddish to purplish brown. Most new purple nutsedge plants sprout from tubers (Holm et al., 1977), which may have ten or more buds that are each capable of producing an aerial shoot. Typically, the bud located at the apex of the tuber initiates germination and produces a rhizome. Upon vertical growth, the rhizome becomes enlarged near the soil surface, and this is often called a “basal bulb”. Basal bulbs provide meristems to allow for vegetative growth of rhizomes, roots, leaves, and flower shoots. Additional tubers may develop at the terminal end of the rhizome, and these new tubers can either produce a new basal bulb with aerial shoots, or more rhizomes. When more rhizomes are produced, more tubers will be produced resulting in a tuber chain. Siriwardana and Nishimoto (1987) observed the location of purple nutsedge tubers to be fairly shallow; 45% are found in the top 4 cm of the soil profile and 95% are found within the top 12 cm of the soil profile. Hauser (1962a) elucidates that tuber production begins about 6 to 8 weeks after emergence of foliage, which corresponds to flower initiation. He also demonstrated the proliferation of purple nutsedge when he planted 107,340 tubers$\bullet$ha^{-1} and after one season of growth there were 7,635,400 plants•ha^{-1} and 10,980,000 tubers•ha^{-1}. These numbers show the importance of managing fields between crops.

Nutsedge Competition

Weed control in MeBr alternative production systems is very important due to the increased production cost associated with herbicide applications. The principle of weed control is to reduce weed growth and/or infestation to an acceptable level, while increasing crop competition. Competition occurs between two plants when the factors essential for growth and development are not provided optimally for the demands of both plants (Anderson, 1996). Santos et al. (1997b) discovered that purple nutsedge has a lower light compensation point than yellow nutsedge. This allows it to thrive under polyethylene and crops (Dusky and Stall, 1996). Light compensation point can be defined as "the fluence rate at which the competing processes of photosynthesis and respiration are balanced" (Hopkins and Huner, 2004). One of the main concerns for growers is the affect the nutsedge has on the mulch, especially for those growers who double crop in Florida. It will pierce the polyethylene mulch and decrease the stability and reliability of the mulch.

Nutsedge has the ability to reduce crop yields. The two nutsedge species are noted to reduce bell pepper yields up to 73% (Morales-Payan et al., 1998). Motis et al., (2003) observed that a yellow nutsedge density of approximately 96 plants•m^{-2} can reduce bell pepper yield by 70%. Gilreath et al., (2005c) observed that nutsedge densities of approximately 5 plants•m^{-2} during crop fruit set reduced bell pepper yield by 31%. In a study conducted by Gilreath and Santos (2004c), results showed that tomato yield loss due to season-long purple nutsedge interference could reach 51% at a density of 105 plants•m^{-2}.

In the case of tomato, once established it is able to gain a size advantage and can out-compete emerging weeds by shading. Santos et al. (1997) demonstrated that yellow nutsedge is more competitive than purple nutsedge. Tomato was more competitive than both nutsedge species, while peppers was not nearly so. Increased weed competition, not only causes a direct reduction in yield, but also causes early and non-uniform maturation of the crop. This leads to numerous individual pickings, which increases harvest costs, thus lowering total revenue.

Nutsedge Control

Fallow programs are becoming more critical each year with the phase out of MeBr. Studies conducted by Smith and Mayton (1938) and Smith (1942) demonstrated that tillage every three weeks over a two year period eradicated purple nutsedge from fields which consisted of more than 10 different soil types. Currently in Florida vegetable production systems, glyphosate (herbicide) is applied upon nutsedge emergence between tillage treatments occurring during the fallow program. Glyphosate is very effective against *Cyperus* spp. having the ability to translocate through the plant within three days killing the tuber that is directly attached to the foliage as well as the foliage itself (Rao and Reddy, 1999).

Weeds also have the ability to serve as excellent hosts to nematodes and various soilborne pathogens. Numerous weed species of the Solanaceae family act as hosts to pests that are known to attack pepper and tomato (Anderson, 1996). Some of these pests include whiteflies (*Bemisia* spp.), Colorado potato beetle (*Leptinotarsa decemlineata*), cabbage looper (*Trichoplusia ni*), and some viruses. French-Monar et al. (2006) discovered weeds of major importance *(Solanum nigrum, Solanum* *americanum, Geranium carolinianum,* and *Portulaca oleracea)* to the Florida vegetable industry also served hosts to the soilborne pathogen *Phytopthora capsici.*

Vegetable producers are being forced to manage nutsedge and other weed populations with herbicides (Noling et. al, 2011) due to the phase out of MeBr and reproduction capability of the weed. Once emergence is stimulated, a large portion of the nutsedge would be exposed to the herbicides, thus giving better control of the weed. To successfully manage nutsedge, meticulous control programs will be required before crop planting, during the season, and between crops.

Diseases

It is in inevitable that every Florida vegetable grower will incur problems with many different diseases. These diseases can be a limiting factor in the production of marketable yields, thus fumigation is relied on heavily to ensure fruit yield and quality. Tomato and pepper diseases can be caused by pathogens that include: fungi, bacteria, and viruses (Jones et al., 1991).

Soilborne plant pathogens are not adapted to thrive in the entirety of the soil but the infection area where the pathogen comes in contact with the susceptible host (the plant) to establish a parasitic relationship is the rhizosphere (Raaijmakers et al., 2009). The ‘rhizosphere’ is the region of soil influenced by the roots of the plant. Many soilborne fungal pathogens can survive in the soil for long lengths of time as resistant propagules or in plant roots and crop residues. The propagules could be chlamydospores, sclerotia, mycelium, thick walled conidia, or hyphae. These propagules foster the beginnings of a new infestation upon the presence of a host plant and the correct environmental conditions.

The immediate goal of fumigation for disease control is to eradicate or reduce the level of inoculums before it contacts the plant (Agrios, 2005). Among the currently registered fumigant alternatives, Pic is the most efficacious against soilborne plant pathogens. Fusarium wilt caused by (*Fusarium oxysporum* f.sp. lycopersici; FOL) and Fusarium crown and root rot (*Fusarium oxysporum* f.sp. radicis-lycopersici; FORL) have been shown to be the most frequent soilborne pathogens causing serious disease in Florida tomato transplant production (Gilreath et al., 2004). Other problematic soilborne pathogens include *Sclerotium rolfsii*, *Ralstonia solanacearum*, *Pythium* spp., *Rhizoctonia solani*, and *Phytopthora capsici*.

Fusarium oxysporum f.sp. lycopersici

Fusarium wilt is a vascular disease of tomato, caused by the soilborne fungus FOL that produces spores and chlamydospores that germinate to produce mycelium which penetrates the roots and enter the vascular system. The fungus colonizes the xylem tissues of the tomato plant disrupting water movement that leads to the development of vascular discoloration and wilt (Agrios, 2005). Initial symptoms begin as a yellowing and wilting of lower leaves on infected plants. Symptoms can be seen on one or several branches. As the fungus spreads within the host, wilting and yellowing progresses up the plant. The entire plant eventually dies and can reduce crop yield. The severity of this disease occurs at a soil temperature of 27°C but the fungus can be active between 18 and 35°C. This fungus can colonize the roots of many weeds asymptomatically making it a permanent resident in the soil. At least three races (1,2 and 3) of FOL are recognized based on identified causes of resistance in tomato (Momol et al., 2004).

Fusarium oxysporum f.sp. radicis-lycopersici

Fusarium crown and root rot occurs in all tomato production areas of Florida but is most prevalent in sandy, acidic soils (Zhang et al., 2001). The fungus invades fresh emerging roots through natural openings and wounds. Early symptoms include plant stunting, yellowing, and loss of lower leaves. Hypocotyl lesions, root rot, and death can subsequently occur. Infected plants may also display wilt symptoms. The infected plant may produce less fruit than normal. Unlike Fusarium wilt, temperatures between 10 and 20°C are optimal for disease development (Momol et al., 2004). Chlamydospores aid in the survival of this fungus in the soil for numerous cropping seasons.

Sclerotium rolfsii

Southern blight (caused by the fungus *S. rolfsii*) is favored by moist soil conditions and temperatures above 29°C. The wilting and yellowing of lower leaves are the first above ground symptoms of infected plants. The region of the stem near the soil may appear soft and have a whitish fungal growth. Sudden plant death may soon follow caused by girdling of the stem. This pathogen becomes most severe when plant debris is present around the plant base. Mycelium of *S. rolfsii* can spread more than 91 cm through the soil to nearby plants. Sclerotia are often produced at the crown and surrounding soil of the infected plant, and on decaying crop debris which serve as inoculums for the next crop (Xie and Vallad, 2010).

Ralstonia solanacearum

Bacterial wilt is caused by *R. solanacearum*. The bacterium accumulates in vascular tissues causing a rapid wilt of the plant. The upper leaves will wilt during the hottest part of the day, but will stay green. The most common race (race 1 biovar 1) of this bacteria has a wide host range giving it the ability to be a long term resident in the soil (Momol et al., 2004). This disease is usually found in lower areas in a field associated with water accumulation. Bacterial wilt seldom occurs in soils possessing a high pH. Temperatures between 30 and 35°C and high soil moisture are conducive for this bacterium (Momol et al., 2004).

Rhizoctonia solani

This fungal pathogen mainly attacks seeds, hypocotyls, and roots. The most common symptom of this disease is damping off. Infected seedlings will often have reddish-brown lesions on stems and roots. The fungus can also infect leaf and fruit tissue near or on the soil surface. This pathogen is most active in cool, moist soils, and produces sclerotia and mycelium that aid in the survival of this pathogen in the soil for many years (Zhang, 2005).

Pythium spp.

Pythium is a genera belonging to a group of fungal-like organisms called oomycetes. Several species of Pythium are known to infect roots causing root rots, wilting, damping off, and seedling blight (Pernezny and Momol, 2006). The peak of growth and infection of plants occurs between temperatures of 30°C or higher. This pathogen is most active in warm, wet soils. Lower leaves of plant will show yellowing when affected by Pythium stem and root rots. Pythium produces oospores and zoospores. The zoospores are special spores that have flagella that give the pathogen motility to infect plants quickly when soils are saturated with water. The oospores are specialized structures that can survive in the soil for more than 10 years (Pernezny and Momol, 2006). Chellemi et al., (2000) conducted pathogenicity tests of bell pepper and tomato using several different *Pythium* species to measure root rot severity and reductions in plant growth. Four of the *Pythium* species caused severe root rot, reduction in plant weight, and plant mortality of pepper. Similar plant weight loss and disease ratings occurred on tomato but there was little or no plant mortality.

Phytopthora capsici

Phytopthora blight is one of the most common diseases of bell pepper production causing significant losses, caused by the oomycete *P. capsici*. This pathogen causes rotting and blighting of seedlings (Gevens et al., 2008). All parts of pepper are susceptible but infection usually occurs at the soil line. Stem lesions cause girdling and result in plant death. Contaminated roots turn dark brown and spongy. This pathogen can cause foliar blight, leaf spot and crown infections in tomato transplants. Leaf spots are initially small and water-soaked. The spots increase in size and become a light tan color. Pepper fruit are also susceptible, and become covered with a white mold and rot. *Phytopthora capsici* survives in the soil by means of oospores, and also produces motile zoospores that can infect nearby roots. Phytopthora blight incidence peaks during wet weather and in parts of fields where standing water occurs. Optimal zoospore production and infection occurs at temperatures between 27 and 32°C (Gevens et al., 2008).

Nematodes

Nematodes are among the most numerous animals on the planet (Perry and Moens, 2006). Nematodes are small microscopic roundworms that reside in the soil and parasitize the roots of plants. These pests are known to reduce root volume potential, decrease water and nutrient use efficiency, increase fungal and bacterial infections, and transmit viral diseases (Noling, 2005). The two types of nematodes are ectoparasites and endoparasites. Endoparasites invade the tissue of the plant and spend part of their life cycle secluded from the soil. Ectoparasites generally spend the full duration of their lives in the soil and insert their stylet (specialized feeding structure) into the root to feed (Jones et. al, 1991). Most nematode species life cycle consists of egg, four larval stages and the adult male and female. Development is usually most rapid at a soil temperature range of 21 to 27°C (Noling, 2005). Root-knot (*Meloidogyne* spp.*),* sting *(Belonolaimus* spp.*),* and cyst *(Heterodera* spp.*)* are the most common nematodes that affect tomato and bell pepper production.

Meloidogyne incognita. Root-knot nematodes are endoparasites that become sedentary upon entering plant roots. Following entry into the roots they deposit eggs forming root galls. High root gall severity normally correlates with increased populations. Females can produce approximately 2,000 eggs. Above-ground symptoms include wilting, stunting, and chlorosis. Infestation is usually spotty throughout the field. Root-knot nematodes have an extremely wide host range, and are a common problem in sandy soils.

Allowing previous crop residues to decay before fumigation is of importance again here, since the eggs are deposited into the roots, and the fumigant must be able to reach the eggs. These nematodes can cause a great amount of root damage, resulting in a reduction of yield. However, optimal control of root-knot nematodes with soil fumigation delays the formation of root galls on tomatoes until the later stages of crop growth having little influence on crop yield. This late increase in nematode population is important though when considering future crops (e.g. double crop). Carry-over residual effects must be considered when producing subsequent crops. Nematode resistant varieties of tomato and pepper are commercially available. However, research has shown that this resistance gene is unstable at high temperatures, limiting these varieties to winter and spring production in Florida (Noling, 2011).

Introduction to Fumigation

Most commercially grown vegetables are produced for fresh market sales. Growers aim to harvest their crops during marketing windows in order to receive the optimal price for their product. The high value of these fresh market vegetables and their susceptibility to soilborne pests makes it important to mitigate pest populations prior to planting. Vegetable production may be increased with the selection of an appropriate fumigant. The "ideal" fumigant will possess herbicidal, fungicidal, and nematicidal properties along with the ability to dissipate from the soil rapidly, while not posing any serious long-term impact to the environment.

Fumigants are applied pre-plant in the production of fruits, vegetables, turfgrasses, tree fruits and nursery crops. Commercial tomato and bell pepper production in Florida requires the use of soil fumigation to limit the impact of weed, disease, and nematode pests on production (Noling and Becker, 1994). Soil fumigation involves a pre-plant application of a pesticide into the soil that converts from a liquid into a volatile gas. This gas is able to diffuse through water and open pore space throughout the soil to eliminate soilborne pests. Important factors that influence movement of the gas are moisture, temperature, soil texture, organic matter, and soil profile variability. Also, vapor pressure of the fumigant is important to determine the movement of gases in soil. The vapor pressure is the rate at which a gas leaves the liquid phase (Monaco et. al, 2002). A fumigant with a high vapor pressure moves quickly since the gaseous concentration of the chemical increases rapidly and the movement of the pesticide occurs by mass flow followed by diffusion (Munnecke and Van Gundy, 1979).

Fumigant Application

Shank injection refers to the application of fumigants into the soil via shank mounted tubes that are attached under a tractor mounted bed press or a broadcast application rig. These shanks are pulled through the soil injecting the fumigant at depths between 20 and 45 cm. The Yetter Avenger coulter applicator (Yetter Farm Equipment, Colchester, Illinois, USA) contains deep injectors that apply the fumigant to a depth of up to 45 cm. This fumigant rig has a large coulter that cuts through strings, old plastic, and other hindering residue that would normally hang on to gas knives reducing fumigant efficacy (Gilreath et al.,2005e).

Fumigants travel through the soil profile after injection by way of vapor diffusion. The vapor pressure of a fumigant will determine which application method will work more effectively, shank or drip. For example, metam potassium has a low vapor pressure so it will only move a short distance from the shank injection point. However, applying it with water through a drip irrigation system (chemigation) may provide a more uniform distribution of fumigant throughout the soil (Smelt and Leistra, 1974). Use of emulsified fumigant formulations through drip irrigation systems has been shown to be more effective for fumigants possessing lower vapor pressures.

Mulches

The use of polyethylene mulch was introduced in the early 1950s (Lamont, 1993). Polyethylene mulches are advantageous in Florida vegetable production systems to protect raised beds from erosion, decrease soil moisture evaporation, improve fumigant efficacy, extend weed control, and increase soil temperature in the root zone. Tomatoes and peppers have shown measurable increases in earliness, yield, and quality when produced using polyethylene mulch (Lamont, 1993).

Selection of an appropriate mulch color is crucial. Dark colored mulches absorb light energy while lighter mulches reflect light energy. In southwest Florida, white mulch is normally used for tomato and pepper grown during periods of warmer temperatures (August-October), while black mulch is used during cooler periods (November-March). The optimal temperatures for crop production are often ideal for pests as well.

An appropriate film material and thickness should also be selected. The options for polyethylene film include low-density polyethylene (LDPE), high-density polyethylene (HDPE), metallized, virtually impermeable films (VIF) and totally impermeable films (TIF). VIF mulches are the most widely used in Florida vegetable production systems. These films are called VIF because they are only slightly permeable to fumigant gases, but not totally impermeable. These are normally manufactured as multi-layer films which contain one or two barrier polymers such as polyamide (nylon) or ethylene vinyl alcohol (EVOH) compressed between other layers of polymer that keep the barrier polymers from swelling and bind the polyethylene outer layer to the barrier layer. Thickness, density, and chemical composition of polyethylene mulches are directly related to its permeability to fumigant gas. According to the French standard, in order for a polyethylene mulch to be classified as VIF, its permeability to MeBr should not exceed 0.20 $g \cdot m^{-2} \cdot hr$ (Noling et al., 2011). The majority of VIF mulches in the United States do not meet this standard.

Polyethylene Mulches

Using VIF plastic reduces fumigant emissions into the atmosphere and decreases the effective rate needed for pest control (Martin, 2003). In 2001, Nelson et al. conducted a field shank application study comparing the release of 1,3-dichloropropene (1,3-D) to the atmosphere through VIF and HDPE mulched beds to non-mulched beds.

They observed that maximum release of 1,3-D from all treatments occurred within the first 24 hours after application of the fumigant and that VIF beds had 1,3-D concentrations in the soil double that of polyethylene treated beds and four times that of the non-mulched beds.

Santos et al., (2007) conducted field trials that compared MeBr retention and nutsedge control using 9 different mulches. They observed nutsedge populations ranging from 0 to 26 plants•m^{-2} at 63 days after treatment (DAT) in plots fumigated with 196 kg•ha^{-1} of MeBr plus Pic and covered with either VIF or metalized mulches, compared to plots fumigated at 392 kg•ha^{-1} of MeBr plus Pic covered with HDPE mulch which obtained nutsedge densities of 269 plants•m^{-2} at 28 DAT. The fumigant retention between the plots covered with VIF and metalized mulches was not significantly different. They demonstrated the retention properties of VIF and metalized mulches correlate with the improved nutsedge control shown in the data.

A similar trial was conducted by Santos et al., (2006b) but a 1,3-D plus Pic drip tape application was tested instead of MeBr plus Pic shank injection. The data from this study was consistent with Santos et al., (2007) showing that nutsedge densities decreased as fumigant concentration and retention increased from the use of high-retention mulches (e.g. VIF). When applied at a rate of 1400 ppm, 1,3-D plus Pic in combination with a highly-retentive mulch suppressed purple nutsedge densities to below 53 plants•m^{-2}. Reducing volatilization with barrier mulches thus increasing fumigant retention should always be considered.

Maximizing Fumigant Application

The main factors that affect soil fumigant efficacy include soil moisture, soil temperature, polyethylene mulch selection, bed compaction and bed preparation. Soil temperature and moisture change quickly in response to climatic changes that occur in the top 5 cm of field soil. As soil moisture decreases or temperature increases, a fumigant moves more rapidly (Gamliel et al., 1998). Soil moisture generally increases with soil depth thus reducing gas movement and increases the difficulty to control soil pests at greater soil depths. Gas passes readily through a dry soil, but not through a water-saturated soil. The vaporized molecules of a soil fumigant tend to be dissolved in soil water films. Therefore, water solubility is an important character because the majority of the microorganisms in soil are associated with water films, which shelter them from coming in direct contact with the fumigant in vapor phase (Munnecke and Van Gundy, 1979). The fumigant must be in the soil solution to come in contact with the target pest. Diffusion is unaffected by gravity so a polyethylene mulch at the soil surface is necessary to retain diffusing gases long enough to allow for maximum efficacy against soilborne pests.

The fumigant lethal dose effectiveness is based on the concentration of the fumigant and the duration of exposure time in the raised bed. For maximum efficacy fumigants must be established at a lethal concentration for a sufficient length of time to kill an organism. Increasing the application rate will increase the concentration while using polyethylene mulch with a higher barrier quality will lengthen exposure time. Vapor pressure does not indicate the toxicity level of a fumigant. Some fumigant gases may have a high vapor pressure but low-toxicity while other fumigants may have low vapor pressure but are highly toxic. Compounds having a low vapor pressure may take longer to kill organisms in the soil but will remain in the soil at a lethal concentration for a longer period of time. In contrast, a compound with high vapor pressure may escape the soil before controlling dormant weed seeds. Fumigant placement as it relates to the location of pests within the soil profile is a critical consideration to get adequate retention and efficacy. Also, bed preparation is very important as a moist and tightly compressed bed is more resistant to gas diffusion than a dry and loosely compacted bed.

Methyl Bromide

In September of 1987, leaders of 24 countries came together to sign the Montreal Protocol on Substances that Deplete the Ozone Layer. Methyl bromide was classified as an ozone depleting chemical in 1993 under this international treaty. According to the United States Clean Air Act of 1990, any compound having an ozone depleting potential (ODP) ≥ 0.2 is classified as a Class I ozone depleting substance (Honaganahalli and Seiber, 1996). The ODP is based on the half-life of the compound, the amount emitted into the environment, and its ability to break down ozone (Honaganahalli and Seiber, 1996). Methyl bromide has an ODP of 0.6.

Ozone (O_3) is considered to be an important molecule in the upper atmosphere that screens out biologically harmful solar ultraviolet radiation from the sun, preventing it from reaching earth's surface. Bromine and chlorine are capable of catalytically destructing stratospheric ozone (Wofsy et al., 1975). About 90% of the ozone in the atmosphere is contained in the stratosphere ranging from 10-50 km and the other 10% is contained in the troposphere (area of the atmosphere that extends from the earth's surface to 10 km). The major sources of bromine and chlorine in the stratosphere are MeBr and chlorofluorocarbons (CFCs). Chlorofluorocarbons are a family of chemical compounds that contain chlorine, developed to be a safe, non-flammable, non-toxic alternative to substances like ammonia for use in refrigeration and spray can propellants. Due to the ozone depletion of bromine and chlorine, levels of harmful ultraviolet radiation have increased.

Methyl bromide production in the U.S. was to be phased out by 1 Jan. 2005, mandated by the Clean Air Act of 1990. In 2001, MeBr use was restricted to 50% of the amount used in 1991. By 2003, the available amount of MeBr was restricted to 30% of the 1991 levels. In 2005, approved use was based off the 1999 baseline of 25,500,000 kg. Following 2005, use of MeBr was allowed only for quarantine use or through a critical use exemption (CUE). In 2006, a CUE of 36% of the 1999 baseline was nominated for use but only 31% was approved. In 2010, 13% of the 1999 baseline was nominated for use but only 11% was approved. The amount nominated for 2012 is 4.6% of the 1999 baseline. However, these numbers do not reflect the full economic impact of the MeBr phase out on producers. This continuing reduction in the amount of available MeBr has forced the growers to use an alternative fumigant due to the shortage of supply.

States may request usage of MeBr under the CUE. The CUE is "a process of documenting the need for continued use as described by the collective research efforts of grower organizations (Noling et al., 2009). Decision IX/6 paragraph (a)(1) in the protocol states, "That a use of methyl bromide should qualify as "critical" only if that nominating Party determines that the specific use is critical because the lack of availability of methyl bromide for this use would result in a significant market disruption." Approval only occurs when "no technically or economically feasible alternative to methyl bromide is shown to exist" (Noling et al., 2009). Conditions that would qualify for "critical use" include agriculture land with a presence of Karst topography, or an expectation of high infested areas of nutsedge (*Cyperus rotundus or Cyperus esculentus).* Karst topography is characterized from landscape features that result from the dissolving activity of water in carbonate rock formations (limestone, dolomite, marble). Problems associated with Karst topography include sinkholes, springs, caverns, and sinking streams. Dade county, FL has a Karst topography and vegetable production in this area cannot use products containing 1,3-D. As the amount of MeBr approved has decreased significantly every year, Dade county growers recognize the necessity of implementing an alternative fumigant plan.

Methyl bromide has been used in combination with Pic for soilborne pest control since the 1960's (Noling, 2005). These soilborne pests and pathogens include weeds, seeds, plants, vegetative propagules, fungi, and nematodes. It can also be used for post-harvest control of pests and pathogens on fresh produce and resilient commodities. Furthermore, it can be used to control rodents, arthropods, and termites in buildings. The vapor pressure of MeBr at 20°C is 1,420 mm Hg. The boiling point is 4°C and the half-life in soil is 22 days.

Methyl bromide has both natural and man-made sources. Natural sources include the burning of biomass and the ocean. Man-made sources include automobile emissions, post-harvest and structural fumigation and pre-plant soil fumigation. The four removal mechanisms of MeBr include 1) reaction with OH radicals and chemical species, 2) photodissociation in the stratosphere, 3) uptake by soils and/or plants and, 4) flux into the oceans (Honaganahalli and Seiber, 1996).

In 1990, 4.9 million kg of MeBr was applied to 20,000 ha of tomato in Florida. Production of MeBr peaked in 1992 at 71,500 metric tons with agriculture as the primary consumer (Honaganahalli and Seiber, 1996). In 1994, MeBr was used in the production of at least 21 different crops grown in Florida, Georgia, California, North Carolina and South Carolina (Ferguson, 1994). Methyl bromide popularity among growers was due to its broad spectrum control, high vapor pressure, cost effectiveness and short plant-back intervals (Martin, 2003).

Methyl Bromide Alternatives

The most used and researched alternative fumigants proposed to replace MeBr in Florida include 1,3-dichloropropene (1,3-D), dimethyl disulfide (DMDS), methyl iodide (MeI), chloropicrin (Pic), metam potassium (Metam) and metam sodium (MNa). Although other fumigants exist, the above compounds are leading the way as MeBr replacements. Even though these fumigants have not always provided consistent control of nutsedge in previous studies, when combined in a systems approach that includes herbicides, effective cultural practices, and efficient mulches they have demonstrated to be effective alternatives (Gilreath et al., 2006; Gilreath and Santos, 2005a; Gilreath and Santos, 2004a).

Chloropicrin

Chloropicrin (trichloronitromethane) was first patented in 1908 as an insecticide and introduced as a commercial soil fumigant for Florida in 1937. In the 1950s, it was found to be more effective when combined with MeBr. This compound is commonly added as a warning agent to many fumigant formulations because of its ability to act as a lachrymator. It is currently used in mixtures with MeBr, MeI, DMDS, and 1,3-D. The fumigant has a vapor pressure of 18 mm Hg at 20°C, a boiling point of 112°C and half-life of 1 day (Ajwa et al., 2002). Chloropicrin moves readily by diffusion and undergoes rapid photolysis in the troposphere which makes it non-threatening to the ozone.

Chloropicrin is generally known to be effective on fungi and insects, but not as effective on nematodes and weeds (Hutchinson et al., 2000).

1,3-dichloropropene

1, 3-dichloropropene (Telone II®) was introduced by Dow in 1956, and is known to have a narrow spectrum of toxicological activity. The vapor pressure of this fumigant at 20°C is 34 mm Hg. The boiling point is 104°C and the half-life in soil is 11 days (Ajwa et al., 2002). This fumigant provides significant control of nematodes and some soilborne insects, but the activity against pathogens and weeds is limited (Noling and Becker, 1994). Since this fumigant lacks extensive pathogen activity, it is often formulated with Pic (e.g., Telone C-17® and C-35®, which contain 17 and 35% Pic, respectively) to provide control of pathogens. 1,3-dichloropropene acts upon nematodes in the aqueous phase of the soil. It penetrates into the nematode through its natural orifices and causes paralysis. Toxicity is thought to be due to nucleophilic degradation reactions at the active sites of the nematodes (Dow AgroSciences).

According to the label, Telone II® is a liquid fumigant for pre-plant treatment of soil to control plant parasitic nematodes, symphylans, as well as certain soilborne diseases in cropland (Anonymous, 2007). Telone II® contains 97.5% (4.5 kg) of 1,3-D and weighs 1.2 kg•L^{-1} at 21°C. Due to Karst topography, Telone II® is prohibited in Broward and Dade counties, and has a 24(c) label which is a special local need registration allowing distribution and use only within the state of Florida. Telone II® must only be used on soils that have a relatively shallow hard pan or soil layer that restricts downward water movement (such as a spodic horizon) within six feet of the soil surface and have the capability of supporting seepage irrigation, regardless of irrigation method. Application of this product through any type of irrigation system is prohibited. The minimum and maximum soil temperatures at the depth of injection are 4.4°C and 26.7°C, respectively. This product can be applied in-bed or broadcast, but should not be applied more than once per year. Injection at a minimum of 35 cm below level soil or the finished bed top is recommended. Broadcast application rate for vegetable crops is 84-111 $L \bullet ha^{-1}$. Planting should only occur at least 7 days after fumigant application and if no odor is detected in the treated zone. Generally, for every 94 $L \bullet ha^{-1}$, a period of one week is adequate for soil dissipation.

Metam Potassium

Metam potassium (Potassium N-methyldithiocarbamate) is a water soluble liquid. When applied to the soil, this dithiocarbamate salt converts rapidly in the environment to the toxic compound methyl isothiocyanate (MITC). Metam potassium itself is non-volatile. The vapor pressure of MITC at 20°C is 21 mm Hg. The boiling point is 119°C and the half-life in soil is 7 days (Ajwa et al., 2002). Metam potassium is generally used for its strong herbicidal properties and is commonly combined with other fumigants. This fumigant was first used for agriculture purposes in 1994. There was more than 450,000 kg of Metam used in the U.S. in 2002.

According to the label, Metam can be used for the control or suppression of weeds, diseases, and nematodes (Anonymous, 2010). This fumigant contains 0.7 $kg \bullet L^{-1}$. It can be applied through irrigation systems (drip, center pivot, solid set sprinkler, drench, flood basin) soil injection, or soil bedding equipment. The soil moisture in the top six inches of soil must be between 60% and 80% of soil capacity just before application. The maximum application rate is 404 $kg \bullet ha^{-1}$ (580 $L \bullet ha^{-1}$). Effective application rates range from 282 to 580 $L \bullet ha^{-1}$. A light sandy soil will require a lower application rate than a heavier mineral soil. If the target pests are in the upper part of the soil, a lower application rate is needed, but if the target pests are deeper in the soil, a higher application rate should be used. Metam potassium achieves nematode suppression when the MITC comes in contact with the active pests. Although eggs are susceptible to this fumigant, juveniles are easiest to control. Pre-irrigation is recommended to enhance egg hatching of some species, thus giving better overall control. Actively growing nutsedge may be suppressed with Metam if a high rate is used. However, tubers will remain viable. Lack of control may occur near the soil surface if rain occurs within 24 hours after application of this fumigant. Planting may begin 14 to 21 days after application, depending on recent rain and temperatures in that area.

Metam potassium is registered for use on all food, fiber and feed crops as well as in turf areas. Use in a greenhouse is prohibited. It can be used as a root control agent in drains and sewers and for residual control of antimicrobial pests. Under antimicrobial use, the compound is registered as an agent for pulp and paper production, leather processing, raw cane and beet sugar processing facilities, coatings (protective colloids, emulsion resins, and water-thinned paints), metalworking cutting fluids and oils, petroleum operations, water cooling tower systems, and industrial water purification systems.

Methyl Iodide

Methyl iodide or iodomethane, is formulated under the trade name Midas® as a broad spectrum fumigant. The methylating potential and structure is very similar to MeBr, thus suggesting this chemical to be an effective alternative (Ruzo, 2006). This liquid has a low boiling point (42.5°C), high vapor pressure (406 mm Hg), and a water solubility of 14 g•L^{-1} (Ruzo, 2006). The vapor pressure is higher than the other potential alternatives but still below MeBr at 1420 mm Hg. Methyl iodide's ODP is low because the molecule is broken down by photolysis in the troposphere (Hutchinson et al., 2000), thus stopping its path to the stratosphere. The estimated residence time in the atmosphere is less than 12 days. The estimated ODP for MeI is less than 0.029, well below the level of Class I ozone depleters.

According to the Midas 50:50® label, MeI is used for pre-plant fumigation of commercially produced peppers, tomatoes, strawberries, and field-grown ornamentals to control soilborne pests including weed seeds, nematodes, insects and diseases (Anonymous, 2010). One liter of Midas 50:50® weighs 1.8 kg (0.9 kg MeI and 0.9 kg Pic). Raised bed application rates of MeI can range from 224 to 392 $kg \bullet ha^{-1}$ when using standard tarps (VIF) and 168 to 224 $kg \bullet ha^{-1}$ when using highly retentive tarps (TIF). For infested nutsedge fields, a minimum rate of 336 $kg \bullet ha^{-1}$ should be used with standard polyethylene. The area receiving application must be tilled to a depth of at least 13 to 20 cm. The soil temperature must not be less than 53°C or exceed 32°C at injection depth when application begins. Previous crop residues must be decomposed prior to fumigation. Planting must not occur for at least 14 days after application, and 21 days under conditions of high soil moisture, heavy soils, or rain. There is also a four month plant back restriction from the date of fumigant application for food crops other than tomatoes, peppers, and strawberries.

Dimethyl Disulfide

As of 9 September 2011 Paladin® was registered in 24 states. According to the label, DMDS is a preplant liquid fumigant used for the control or suppression of weeds, soilborne plant pathogens and nematodes (Anonymous, 2010). This fumigant can be applied to soils used for the production of tomatoes, peppers, eggplants, cucumber, squash, melons, strawberries, blueberries, field grown ornamentals, and forestry stock when a polyethylene tarp is used. Application can be performed via raised bed shank injection and broadcast/flat fumigation methods only. One liter of DMDS weighs 1.06 kg at 20°C. Soil moisture must be at least 75% of field capacity starting from 5 cm below the soil surface down to a depth of 23 cm below the surface. Following application of this fumigant the treated area can be irrigated with overhead sprinklers to aid with fumigant retention, as well as reducing odor emissions that could escape from the row middles. This should be done within a few hours of application and again within 12 to 24 hours. Application of this formulation through any type or irrigation system is prohibited. However, there is a formulation that is permitted to be used in irrigation systems. The use of seepage irrigation will reduce DMDS efficacy and increase plant back interval. Planting should occur no sooner than 21 days after treatment. The plant back interval is increased with low soil temperatures, high soil moisture, and heavy soils. This fumigant can be applied at any time of the year as soil and weather conditions allow. This fumigant does emit an odor that is similar to garlic or propane to some people. The maximum application rate for pre-plant soil use is 510 kg•ha^{-1} (576 L•ha^{-1}).

Methyl Bromide Alternatives Research

Locascio et al., (1997) demonstrated low rates of Pic provided poor control of purple and yellow nutsedge. They also observed treatments containing 1,3-D plus Pic to be comparable to the MeBr treatments with suppressing nutsedge, total fungi, and root galling. Gilreath and Santos (2004b) observed a purple nutsedge density of 185 plants•m-2 when Pic was applied at a rate of 350 kg•ha-1 in comparison to the untreated control which obtained 125 plants•m-2.

Csinos et al. (1997) observed some effective control of pepper and tobacco pests similar to MeBr plus Pic with the combination of 1,3-D plus 17% Pic plus MNa under polyethylene mulch. Csinos et al., (2000) conducted a trial similar to Csinos et al. (1997), where they evaluated different combinations of MNa, 1,3-D and Pic as alternatives for MeBr in tomato, pepper, and tobacco transplant production. Within the 79 parameters evaluated, the combination of 1,3-D plus C-17 plus MNa was not significantly different from MeBr plus Pic in 74 of them, and was better in three of them.

McGovern et al. (1998) evaluated different application methods of MNa for control of fusarium crown and root rot and observed no reduction in the disease when drip applied at 701 or 935 L•ha^{-1} and shank injected at 935 L•ha^{-1}. When MNa was rotovated into preformed beds at the same rate, incidence of fusarium crown and root rot was reduced to levels equivalent to the MeBr plus Pic combination.

Webster et al., (2001) conducted a study to evaluate potential MeBr alternatives in a bell pepper-squash cropping sequence. Methyl iodide (MeI:Pic) and a combination of 1,3-D and Pic (35%) suppressed purple nutsedge emergence and growth early in the season, but by the end of the season only MeBr had lower purple nutsedge shoot densities than the non-treated control. Methyl iodide had nearly twice the number of colony forming units of fungi (*Pythium* spp. was the major pathogen isolated) as the other fumigant treatments and non-treated control. Pepper yield differences could not be detected among the non-treated control and MeI:Pic, but they related this to the high populations of *Pythium* spp. Root-gall indices were lower with MeI than the non-treated control.

Gilreath et al. (2005d) conducted a four season trial to look at the long term effect of in-bed Pic applications following a broadcast application of 1,3-D plus Pic (Telone C-35®). In the two spring seasons, broadcast 1,3-D plus Pic did not differ from the non-treated control in *Fusarium* wilt incidence. In two of the seasons broadcast 1,3-D plus Pic failed to improve weed control while all the other treatments were as effective as MeBr plus Pic. In-bed application of 1,3-D plus Pic was as effective as MeBr plus Pic in a different season when the other treatments were equal to the non-treated control. In three of the seasons, broadcast 1,3-D plus Pic failed to improve *Meloidogyne* nematode control when compared to the non-treated control. Broadcast 1,3-D plus Pic obtained about 29% less marketable tomato fruit weight than MeBr plus Pic. In-bed application of 1,3-D plus Pic was similar to MeBr plus Pic in producing the highest fruit weights in all four seasons. Their data concluded that broadcast 1,3-D plus Pic and in-bed 1,3-D plus Pic may provide similar pest control when used continuously over multiple seasons.

Herbicides

A herbicide is simply defined as "a chemical substance or cultured biological organism used to kill or suppress the growth of plants" (Senseman, 2007). A separate application of one or more herbicides under polyethylene mulch is a requirement for effective weed control with any alternative system (A.W. Macrae, personal communication). Weed control options currently available in tomato and bell pepper grown in plasticulture systems are extremely limited. Napropamide and S-metolachlor are currently registered for pre-emergence application in tomato and bell pepper in Florida (S-metolachlor is a third party registration for bell pepper). These herbicides are applied to the soil before emergence of the specified weed or crop to control weeds before or soon after they emerge (Senseman, 2007).

Napropamide

Napropamide (-N,N-diethyl-2-(1-napthalenyloxy) propanamide) is a root inhibitor in the acetamide family with a soil half-life of 70 days and a molecular weight of 271.36 g (Monaco et al., 2002). This compound is formulated as a wettable powder (Devrinol® 50DF) or an emulsified concentrate (Devrinol® 2-EC) (Senseman, 2007). Seedling root growth is inhibited without malformation almost suddenly when exposed to the herbicide. Growth is stopped by the herbicide blocking the progression of dividing cells through the cell cycle into mitosis. The molecule also inhibits alpha-amylase activity and this inhibition can be connected to the inhibition of tuber sprouting and rapid shoot growth of purple nutsedge (Senseman, 2007). Only roots that come in contact with the herbicide are affected. Napropamide has low soil mobility and slow rate of microbial decomposition (Monaco et al., 2002). Tomatoes rapidly metabolize this molecule to water-soluble metabolites.

According to the Devrinol® 2-EC label, this herbicide can be applied pre-plant or incorporated into the soil prior to planting tomato and pepper (Anonymous, 2010). This herbicide controls best annual grasses but will also control certain broadleaf weeds. It does not control established weeds. Fields intended for tomato and pepper must have all weed growth and stubble thoroughly worked into the soil before planting. It is for use on mineral soils only and not for soils with greater than a 10% organic matter (OM). Application of this product through any type of irrigation system is prohibited. A maximum of 2.2 $kg \bullet ha^{-1}$ of napropamide per crop cycle can be applied to the soil surface for tomato and pepper use. The higher rate should be used for heavier soils and areas where heavy weed infestation occurred the previous year. Sprinkler irrigation within 24 hours or rainfall sufficient to wet the soil to a 2.54 cm depth is recommended of this application, unless applied under polyethylene mulch.

Fomesafen

Fomesafen(-5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide) is a membrane disruptor in the diphenyl ether family with a soil half-life of 100 days and a molecular weight of 460.74 g (Monaco et al., 2002). The compound directly inhibits the enzyme protoporphyrinogen oxidase (PPO or Protox). Sold under the trade name Reflex®, fomesafen is formulated as a sodium salt. It controls broadleaf weeds, grasses, and sedges and is persistent and mobile in both water and soil. Fomesafen is currently in the registration process in Florida for use under the polyethylene mulch in tomato and bell pepper.

When used as a pre-emergence application, fomesafen was found to be effective in controlling some of the most troublesome weeds in cotton fields including pigweed (*Amaranthus* spp.) and black nightshade (*Solanum nigrum* L.), two large weeds commonly found in fruiting vegetable fields in Florida (Kleifeld et al., 1988). Fomesafen is used to effectively control morningglory in snap bean fields of Georgia. Morningglory is a weed commonly found in vegetable crops of Florida and could be a problem if not controlled due to its rapid growth, thus causing interference with harvesting operations.

Herbicides Research

Gilreath et al., (2004) observed poor nutsedge control (<50%) in bell pepper at 3 and 6 weeks after transplanting (WATP) with napropamide applied at a rate of 4.50 $kg{\bullet}ha^{-1}$, and fair nutsedge control (>60%) with S-metolachlor and pebulate at rates of 2.25 $kg{\bullet}ha^{-1}$ and 4.50 $kg{\bullet}ha^{-1}$, respectively. Gilreath and Santos (2005a) observed napropamide at a rate of 2.25 $kg{\bullet}ha^{-1}$ reduced nutsedge population by 43% at 14 weeks after treatment (WAT), compared to the non-treated control. However, they observed no difference in yield between the non-treated plot and the napropamide-sprayed treatments. Santos et al., (2006a) observed that pre-plant incorporated napropamide + halosulfuron at 2.25 kg and 71 g•ha^{-1} followed by shank-applied 1,3-D plus Pic at 330 L•ha^{-1} under VIF was as effective as MeBr plus Pic in controlling soilborne pests in tomato.

In order for these alternative systems to work effectively the grower must recognize the target pests in their production area, determine necessary fumigant rates, and use accurate application methods and materials. In addition, the management strategy must prove effective under local soil conditions. Economic viability must also be considered. Herbicides are an absolute necessity for the alternative systems as they can serve as an insurance policy against the weeds. For example, if you obtain 90% weed control with your fumigant application and you also apply a herbicide under the polyethylene that gives you 70% control of the remaining 10%, you will have 97% control of the weed population in the bed which is acceptable with any vegetable production system. Environmental conditions are not always favorable so the fumigant application might not occur at the optimal time, therefore you may only obtain 70% weed control but adding a herbicide to your system that gives you 70% control of the remaining 30% will give you 91% control of the weed population in the bed.

Methyl Bromide Alternatives Systems Research

Another study conducted by Gilreath and Santos (2004a) showed at 16 days after treatment (DAT), Telone C-17® (410 kg•ha^{-1}) combined with napropamide at a rate of 4.50 kg•ha^{-1} incorporated 20 cm deep had purple nutsedge plants at a density of 1 plant•m^{-2} compared to the treatment of Telone C-17® alone which had 13 purple nutsedge plants•m^{-2}. No differences between these two treatments were observed at 50 DAT. They also concluded from the marketable yield data and confirmed other research done by Morales-Payan et al. (1997) that the critical period of purple nutsedge interference occurs sometime between 15 and 50 DAT.

Gilreath and Santos (2004b) conducted a study to compare the efficacy of MeBr alternatives in control of purple nutsedge and Fusarium wilt (*Fusarium oxysporum*) in tomato. At 99 days after transplanting (DATP), MeBr plus Pic (98:2) at a rate of 392 plus 8 kg•ha^{-1} had double the purple nutsedge density in comparison to 1,3-D plus Pic (Telone C-17®) plus pebulate at rates of 392 plus 4.50 kg•ha^{-1}, and 240 plus 4.50 kg•ha^{-1}, respectively. Both rates of C-17 plus pebulate had equal marketable yield as MeBr plus Pic. There were also no differences in fusarium wilt control between these two treatments.

Two application methods (broadcast at 253 L•ha^{-1} and in-bed shank at 327 L•ha^{-1}) of 1,3-D plus Pic were compared at commercial tomato farms (Gilreath et al., 2006). Both methods in combination with pebulate at 3.92 kg•ha^{-1} were as effective as MeBr plus Pic (67:33 at 350 kg•ha^{-1}) in controlling nutsedge. The in-bed method of 1,3-D resulted in nearly three times less nematodes than broadcast 1,3-D plus Pic.

Gilreath et al. (2005b) tested fumigant and herbicide combinations to determine their effectiveness against nematodes and nutsedge in pepper. Drip applied 1,3-D plus Pic (327 L•ha^{-1}) and MNa plus Pic (710 L•ha^{-1}) were more effective than MeBr plus Pic (400 kg•ha^{-1}) at controlling *Meloidogyne* populations. The EC formulation of 1,3-D plus Pic controlled *Meloidogyne* and weed populations more effectively than the gas formulation, and had 18% higher yields. In a different season, shank injected 1,3-D plus

Pic decreased the *Meloidogyne* population by 67% when compared to the EC formulation of 1,3-D plus Pic. Both formulations obtained the same *Cyperus* densities. There was no difference between the two 1,3-D plus Pic formulations for nematode control in the Fall of 2002. Metam sodium was the only fumigant that did not effectively control *Meloidogyne*. The gas formulation of 1,3-D plus Pic had 32% less *Cyperus* plants than the EC formulation at 6 WAT. Throughout the study, both formulations of 1,3-D plus Pic and MNA plus Pic provided equivalent or better *Meloidogyne, Heterodera*, and *Belonolaimus* control than MeBr plus Pic.

Gilreath et al. (2005f) examined the long term residual effects of MeBr alternatives in a tomato-cucumber double-cropped system. Fumigation in the first three years maintained nutsedge populations lower than the control. However, nutsedge populations increased in the fourth year to levels similar to the control. Root galling index in cucumbers consistently increased each year showing no residual effect of first crop fumigants. The combination of 1,3-D plus Pic (374 L•ha^{-1}) and the herbicides napropamide plus pebulate (2.25 and 4.5 kg•ha^{-1}, respectively) provided equivalent cucumber marketable yields to that of MeBr plus Pic (392 kg•ha^{-1}).

Gilreath and Santos (2005a) tested the effect of adding a herbicide to the fumigant 1,3-D (364 kg•ha^{-1}) plus Pic (67 kg•ha^{-1}) (Telone C-17®) on tomato. At 12 WAT, the nutsedge density was at a level unaccepted by tomato growers. At 12 WAT, 1,3-D plus Pic plus metolachlor at a rate of 2.25 kg•ha^{-1} had the lowest nutsedge density when compared to all the other treatments but 1,3-D plus Pic plus pebulate at a rate of 4.50 kg•ha^{-1} incorporated 20 cm deep had considerably higher yields. They reasoned this was due to early season control of the nutsedge population.

Gilreath et al., (2006) compared the combination of broadcast application of 1,3-D plus Pic plus herbicides pebulate and trifluralin with in bed application of MeBr plus Pic (67:33 at 394 kg•ha^{-1}). Plant height and vigor at 4 and 8 WATP were equal in both treatments. Both treatments controlled *Cyperus* effectively with <2 plants•m^{-2} in all plots. At one location of the study, the combination of 1,3-D plus Pic plus pebulate plus trifluralin controlled *Trichodorus* nematode populations more effectively than MeBr plus Pic with 52 juveniles•100 cc and 132 juveniles•100 cc, respectively. However, the other location showed no differences between treatments.

Santos (2009) observed no difference in *Cyperus* densities between treatments of MeBr plus Pic and napropamide plus s-metolachlor sprayed on bed top followed by drip application of Metam. *Cyperus* populations were maintained at or below 14 plants•m^{-2}. Marketable fruit yield at 10 WATP and 12 WATP did not differ when comparing the two previously mentioned treatments. In contrast, Santos and Gilreath (2007) conducted a study that looked at the effects of water delivery volume, concentrations and rates of Metam alone for purple nutsedge control. When looking at water application volumes and flow rates, at 10 WAT they observed no difference in nutsedge control between the non-treated control and Metam treatments (560 L•ha^{-1} with 2.5 cm or 5 cm of water applied per hectare via the drip tape, and flow rates of 1.14, 1.7, 2.27 L per 30 m of row per minute). Their study also showed that Metam applied at a concentration of 6000 ppm resulted in purple nutsedge densities of less than 54 plants•m^{-2} up to 10 WAT, compared to the non-treated control's density of 155 plants•m^{-2}. This concentration can be obtained with a rate of 560 L•ha^{-1} (Metam) if applied with 1.25 cm of water•ha.

Most of the alternatives used in this research have been registered for many years but they must be reevaluated to determine how production practices will need to be modified to accommodate their use. By combining different fumigants as well as herbicides it is possible that an economically viable alternative crop production system can be developed. One must always keep in mind that most vegetable production systems evolved around the use of one fumigant, methyl bromide.

CHAPTER 3
THE SUSTAINABILITY OF METHYL BROMIDE ALTERNATIVE SYSTEMS ON TOMATO PRODUCTION

Introduction

While methyl bromide nears eventual phase out, the development of an acceptable economic alternative continues. A large component to determining which alternatives will be acceptable is the determination of the long term success of each system. The objective of this study was to determine the sustainability of alternative fumigant systems to methyl bromide for the management of weeds in tomato production over three years.

Materials and Methods

This study was conducted at the University of Florida/IFAS Gulf Coast Research and Education Center in Balm, Florida, U.S. The study lasted over a three year period from the fall of 2008 through the fall of 2010. Dates of fumigation, planting and harvest are available in Table 3.1.

The initial treatments included methyl bromide plus chloropicrin (MeBr:Pic 67:33) at 196 kg•ha^{-1}; dimethyl disulfide plus chloropicrin (DMDS:Pic 79:21) at 561 L•ha^{-1}; methyl iodide plus chloropicrin (MeI:Pic 50:50) at 179 kg•ha^{-1}; 1,3-dichloropropene at 112 L•ha^{-1} plus chloropicrin at 168 kg•ha^{-1} plus metam potassium at 561 L•ha^{-1}, collectively referred to as the 3-way system (1,3-D:Pic:Metam); and 1,3-dichloropropene at 112 L•ha^{-1} plus chloropicrin at 168kg•ha^{1}, collectively referred to as the 2-Way system (1,3-D:Pic); and a non-fumigated control.

Each treatment had a split plot of herbicide or no herbicide. However, the split plot treatment was not randomized among the whole plot fumigation treatment. In year one, the herbicides consisted of imazosulfuron (0.33 kg•ha^{-1}) and napropamide (2.24 kg•ha^{-1}). In years two and three, imazosulfuron was replaced by fomesafen at 0.28 kg•ha^{-1}.

The field was prepared using conventional tillage. A Yetter® coulter rig (Yetter Manufacturing Inc., Colchester, Illinois) was used to apply the 1,3-dichloropropene 30 to 35 cm below the bed top. A pre-bed was pulled and then shaped using a 3-row bed press rig. The remaining fumigants except for the metam potassium were injected via three shanks 20 cm deep into the bed using a nitrogen propelled single row fumigation rig. Beds were then sealed using a single row bed press. Herbicides were applied to subplot surfaces using a tractor mounted sprayer calibrated to deliver 280 L•ha^{-1} using TeeJet® 8004 DG nozzles (TeeJet Technologies, Springfield, Illinois). The polyethylene mulch (Pliant Blockade XL® 1.25 mil VIF, Berry Plastics Corporation, Evansville, IN) was applied using a speedroller with each bed receiving two drip tapes placed 30 cm apart and buried 2.5 cm deep capable of delivering 950 ml per emitter per hour on 30 cm spacing.

Metam potassium was injected into the beds two weeks after laying the plastic using double drip tape. The injection took place over a three hour period with 15 minutes of water applied prior to injection and 30 minutes of water following the injection period to flush the system of fumigant. A total of 3 cm•ha^{-1} of water was applied.

Each main plot consisted of three beds by 92 m long with 23 m long herbicide and non-herbicide sub-plots. Beds were on 1.5 m centers with a 75 cm bed top and 23 cm bed height. Treatments were arranged in a randomized complete block design with fumigation as the main plot effect and herbicide as a non-randomized subplot effect in four replicate blocks. The trial site and plot location were maintained throughout the length of the study to determine the effect of treatments over three years.

Once the fumigation concentration in the bed was low and safe enough to plant, holes were punched through the polyethylene about 30 minutes before hand transplanting the ‘Security 28’ tomato. Tomatoes were planted 45 cm apart and 10 cm deep. Drip irrigation and fertilizer injection was provided to the crops daily. The crop was produced using University of Florida recommended production practices (Olson et al. 2009).

Weed populations that escaped the control of the fumigants and/or herbicides were assessed a minimum of two times each cropping season. Within each plot, the number of purple and yellow nutsedge (*Cyperus* spp.) seedlings that emerged through the plastic and the number of annual grasses and broadleaf weeds that emerged from the planting holes were counted. The tomato crop was harvested and graded a minimum of twice per season (unless hindered by freezes) via USDA guidelines.

Generalized linear mixed models in the PROC GLIMMIX procedure of SAS, Version 9.2 (SAS Institute, Inc., Cary, NC) were used to determine the effect of fumigant on weed control and yield data over time. Fumigation treatment was considered a fixed effect, while block and block by treatment over time were treated as random effects in the analyses. Data from herbicide and non-herbicide treatments were analyzed separately. Weed count data were transformed using the lognormal distribution function in the model statement during the analyses, and the resulting least squares means were back transformed manually for presentation in figures and tables. The SLICE function was used to test the simple effect of fumigant and time at each level of the interaction.

Fisher's protected LSD (α = 0.05) test was used to compare least squares means among fumigant treatments at each level of time and for comparing fumigant across different levels of time.

Results

Nutsedge Shoot Emergence

In 2008, when applied without a herbicide, only the MeI:Pic and the 1,3-D:Pic:Metam had less shoot emergence than the non-treated control (Table 3-2). In 2009, the non-treated control had a higher nutsedge population than all but the DMDS:Pic treatment. In 2010, the non-treated control and the 1,3-D:Pic had the greatest number of nutsedge shoots followed by DMDS:Pic, MeBr:Pic, and 1,3-D:Pic:Metam. MeI:Pic had the least amount of nutsedge shoot emergence.

In 2008, when applied with a herbicide, the non-treated control and DMDS:Pic treatments had the greatest number of emerged nutsedge shoots, followed by the remaining four treatments (Table 3-2). In 2009, all fumigation treatments when followed by herbicide significantly reduced shoot emergence compared to the non-treated control. In 2010, the non-treated control and 1,3-D:Pic had a greater amount of nutsedge shoot emergence then the other four fumigant treatments.

When evaluating the data for each fumigant treatment, a significant increase in nutsedge shoot emergence was observed over time for all fumigant treatments in the absence of a herbicide treatment (Figure 3-1). For the non-treated control, even with a herbicide, the nutsedge population increased from 0.0007 to 0.0236 shoots•m^{-2} from 2008 to 2010 (Figure 3-2). While in the absence of a herbicide, nutsedge increased in the non-treated control from 0.049 to 9.753 shoots•m^{-2} over the same three year period. MeBr:Pic had increasing populations with 2010 nutsedge shoot emergence reaching

0.0006 and 1.088 shoots•m^{-2} when applied with and without a herbicide, respectively. Nutsedge populations of the DMDS:Pic treatment increased from 0.0012 to 0.0019 shoots•m^{-2} and from 0.050 to 2.217 shoots•m^{-2} when herbicides were applied or not applied, respectively. From 2008 to 2010, 1,3-D:Pic:Metam, without a herbicide, nutsedge shoot emergence increased from 0.001 to 0.588 shoots•m^{-2}, and with a herbicide increased from 0.0002 to 0.0010 shoots•m^{-2}. 1,3-D:Pic had increasing populations with 2010 nutsedge shoot emergence reaching 0.0165 and 7.589 shoots•m^{-2} when applied with herbicide and without a herbicide, respectively.

Grass

In 2008, without a herbicide, the non-treated control and DMDS:Pic had the greatest number of annual grasses emerging from the planting holes, followed by the remaining four treatments (Table 3-3). Similarly, in 2009, the non-treated control and DMDS:Pic had the greatest annual grass population. However, the 1,3-D:Pic had an annual grass population equal to the control, unlike 2008. The 1,3-D:Pic:Metam, MeI:Pic, and MeBr:Pic, had the lowest annual grass populations. In 2010, the non-treated control was similar to the 1,3-D:Pic and DMDS:Pic in annual grass population. Similar to 2008 and 2009, the remaining three treatments had significantly lower annual grass populations.

Similar to the no herbicide treatments in 2008, when applied with a herbicide, the non-treated control and DMDS:Pic had the greatest annual grass populations with the remaining four treatments providing the greatest control (Table 3-3). In 2009, DMDS:Pic, and 1,3-D:Pic had an annual grass population equal to the non-treated control. The remaining three treatments provided similar control to one another. In 2010 the non-treated control and DMDS:Pic had the greatest annual grass populations emerging from the planting holes, followed by 1,3-D:Pic. The remaining three treatments had the lowest annual grass populations.

Yield

In 2008, without a herbicide, the non-treated control had similar yields to all treatments except for 1,3-D:Pic:Metam which had greater yields than the non-treated control (Table 3-4). In 2009, the non-treated control had the lowest yield out of all the treatments. Both 1,3-D:Pic:Metam and MeBr:Pic had the greatest yield. The yields of MeI:Pic and 1,3-D:Pic were similar to MeBr:Pic, while the DMDS:Pic had a lower yield similar only to MeI:Pic and 1,3-D:Pic. In 2010, the non-treated control, 1,3-D:Pic, DMDS:Pic, and MeBr:Pic had similar yields. The yields of MeBr:Pic, DMDS:Pic and 1,3-D:Pic:Metam were all similar, while MeI:Pic had the greatest yield.

In 2008, with a herbicide, all treatments had a greater yield than the non-treated control (Table 3-4). Only the MeI:Pic treatment was similar to the non-treated control in 2009, with the remaining treatments similar to one another. In 2010, all treatments provided greater yields than the non-treated control.

Discussion

Sustainability, as it relates to fumigants, is defined as the ability of a fumigant to maintain pest populations equal to or below levels of the previous season. This sustainability needs to be shown over several years on the same field site. Nutsedge populations increased over the three growing seasons for all fumigant treatments in the absence of a herbicide (Figure 3-1). Nutsedge shoot emergence increased in 1,3-D:Pic similar to the control, and was also observed in previous studies (Gilreath et al., 2005a). However, MeI:Pic and MeBr:Pic did not show an increase over time when applied with a herbicide (Figure 3-2). In general, there were lower nutsedge populations for all treatments when a herbicide was applied. Gilreath et al., (2006) observed the addition of the herbicides pebulate and trifluralin to 1,3-D:Pic provided similar control of nutsedge compared to the MeBr:Pic standard. Thus, the sustainability of all systems can be benefitted with the addition of a herbicide.

When no herbicide was applied, MeI:Pic had the highest yield in the third season, making this treatment appear to be the most sustainable. This could be related to weather factors (i.e. rainfall) which provided an unfair advantage for the MeI:Pic. A Florida Department of Transportation (FDOT) restriction on the movement of MeI:Pic in the summer of 2010, delayed product delivery and soil application by three weeks relative to the other fumigant treatments. After initiation of the other five fumigant treatments we received a significant rainfall (10 cm) event which flooded the field and it remained saturated for two days. This may have adversely impacted those treatments, reducing nutsedge control leading to higher shoot emergence numbers. Thus, an accurate judgment of MeI:Pic sustainability in 2010 cannot be determined, due to the differences in environmental conditions. However, when a herbicide was applied, DMDS:Pic, 1,3-D:Pic:Metam, and MeI:Pic had the highest yields, thus furthering the argument that the addition of a herbicide will maximize sustainability for methyl bromide alternatives.

Without a herbicide program in combination with a fumigant application, the chance of sustainability is greatly decreased. The future adaptation of methyl bromide alternatives will be to ensure the addition of a herbicide program along with other practices to keep soilborne pest populations at the lowest level possible.

Table 3-1. Dates for fumigation, planting, harvest, and weed counts.

Data	Tomato		
	2008	2009	2010
Fumigation	12-Aug	28-July	05-Aug[1]
Planting	23-Sep	17-Sep	15-Sep
Harvest 1	15-Dec	02-Dec	08-Dec
Harvest 2	---	15-Dec	16-Dec
Harvest 3	29-Oct	21-Oct	13-Oct
Nutsedge Counts	29-Oct	21-Oct	13-Oct
Grass Counts	12-Aug	28-July	05-Aug[1]

[1]Methyl iodide plus chloropicrin was fumigated 27-Aug due to product availability.

Table 3-2. Effect of fumigant systems and herbicide on nutsedge shoot emergence 4 WATP of tomato

Treatment[1]	Nutsedge Shoot Emergence											
	No Herbicide						Herbicide[2]					
	Shoots•m^{-2}											
	2008		2009		2010		2008		2009		2010	
Control	0.049	a[3]	0.605	a	9.753	a	0.0007	ab	0.0013	a	0.0236	a
DMDS:Pic 79:21	0.050	a	0.018	ab	2.217	ab	0.0012	a	0.0003	b	0.0019	b
MeBr:Pic 67:33	0.005	ab	0.001	b	1.088	b	0.0004	b	0.0003	b	0.0006	c
MeI:Pic 50:50	0.001	b	0.008	b	0.019	c	0.0004	b	0.0004	b	0.0007	bc
1,3-D:Pic	0.007	ab	0.005	b	7.589	a	0.0003	c	0.0003	b	0.0165	a
1,3-D:Pic:Metam	0.001	b	0.001	b	0.588	bc	0.0002	c	0.0002	b	0.0010	bc

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]In year 1, the herbicides consisted of imazosulfuron (0.33 kg•ha^{-1}) and napropamide (2.24 kg•ha^{-1}). In years 2 and 3, imazosulfuron was replaced by fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

Table 3-3. Effect of fumigant systems and herbicide on grass control 4 WATP of tomato

Treatment[1]	Grass Emergence											
	No Herbicide						Herbicide[2]					
	Plants•m^{-2}											
	2008		2009		2010		2008		2009		2010	
Control	0.210	a[3]	0.380	a	0.072	a	0.0061	a	0.0089	ab	0.0055	a
DMDS:Pic 79:21	0.329	a	0.993	a	0.296	a	0.0039	a	0.0127	a	0.0063	a
MeBr:Pic 67:33	0.001	bc	0.001	b	0.001	b	0.0006	b	0.0004	c	0.0006	c
MeI:Pic 50:50	0.000	c	0.002	b	0.001	b	0.0003	b	0.0003	c	0.0005	c
1,3-D:Pic	0.004	b	0.064	a	0.045	a	0.0005	b	0.0033	b	0.0019	b
1,3-D:Pic:Metam	0.001	bc	0.001	b	0.002	b	0.0003	b	0.0006	c	0.0003	c

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]In year 1, the herbicides consisted of imazosulfuron (0.33 kg•ha^{-1}) and napropamide (2.24 kg•ha^{-1}). In years 2 and 3, imazosulfuron was replaced by fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

Table 3-4. Effect of fumigant systems and herbicide on yield in tomato

Treatment[1]	Tomato Yield t•Ha^{-1}											
	No Herbicide						Herbicide[2]					
	2008		2009		2010		2008		2009		2010	
Control	26.36	b[3]	29.69	d	24.12	c	25.58	b	31.22	c	21.94	c
DMDS:Pic 79:21	31.69	ab	37.13	c	26.05	c	32.81	a	38.17	ab	30.09	ab
MeBr:Pic 67:33	28.79	ab	42.57	ab	29.02	bc	31.77	a	40.17	ab	28.29	b
MeI:Pic 50:50	30.15	ab	38.44	c	39.24	a	30.99	a	35.74	bc	34.05	a
1,3-D:Pic	27.07	ab	39.71	bc	25.78	c	30.70	a	40.05	ab	28.38	b
1,3-D:Pic:Metam	32.79	a	45.11	a	32.92	b	34.24	a	42.57	a	30.10	ab

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]In year 1, the herbicides consisted of imazosulfuron (0.33 kg•ha^{-1}) and napropamide (2.24 kg•ha^{-1}). In years 2 and 3, imazosulfuron was replaced by fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05).

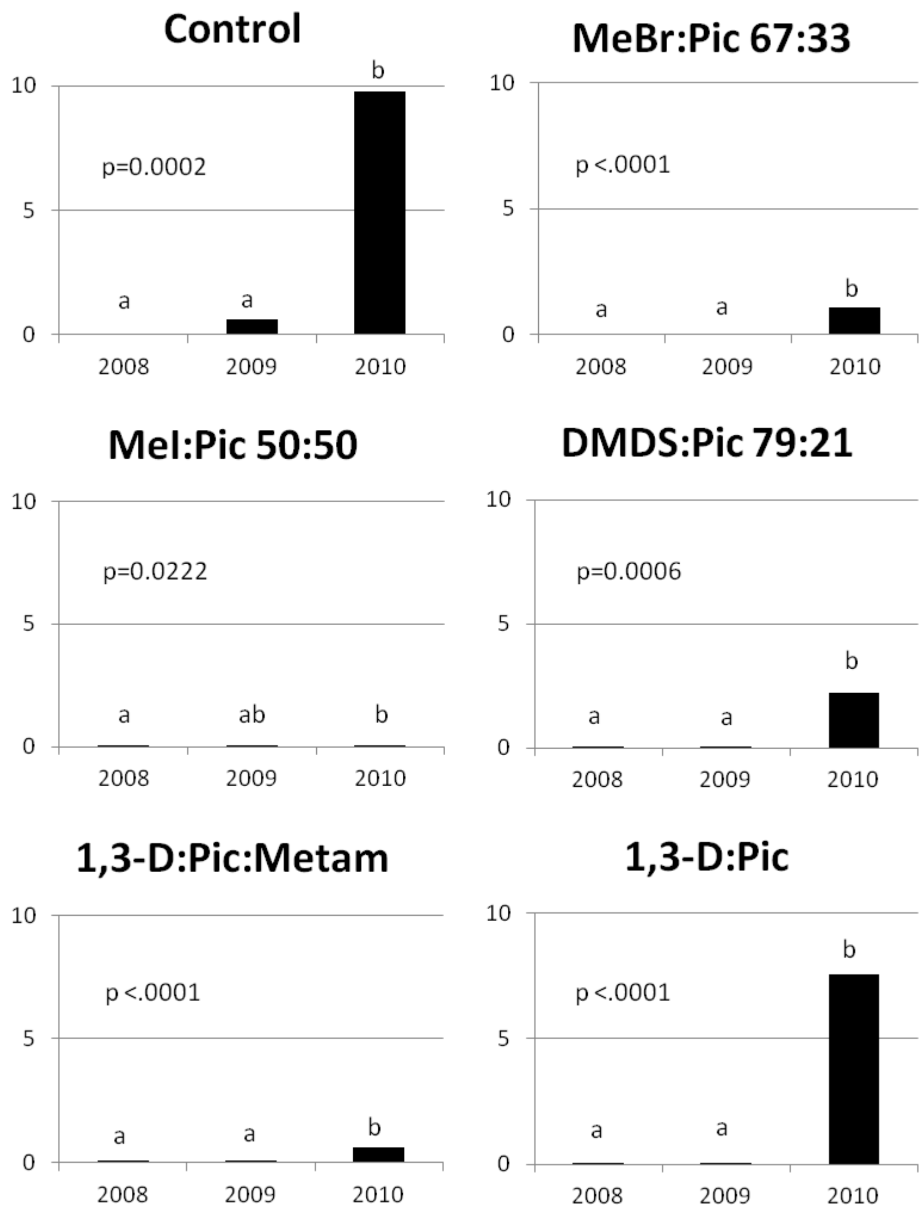

Figure 3-1. Nutsedge shoot emergence 4 weeks after transplanting (shoots•m^2) tomato without a herbicide for the 2008, 2009, and 2010 growing seasons. Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin. Bars with the same letter are not different based on contrast statements within individual fumigant treatments using general linear mixed model analysis at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

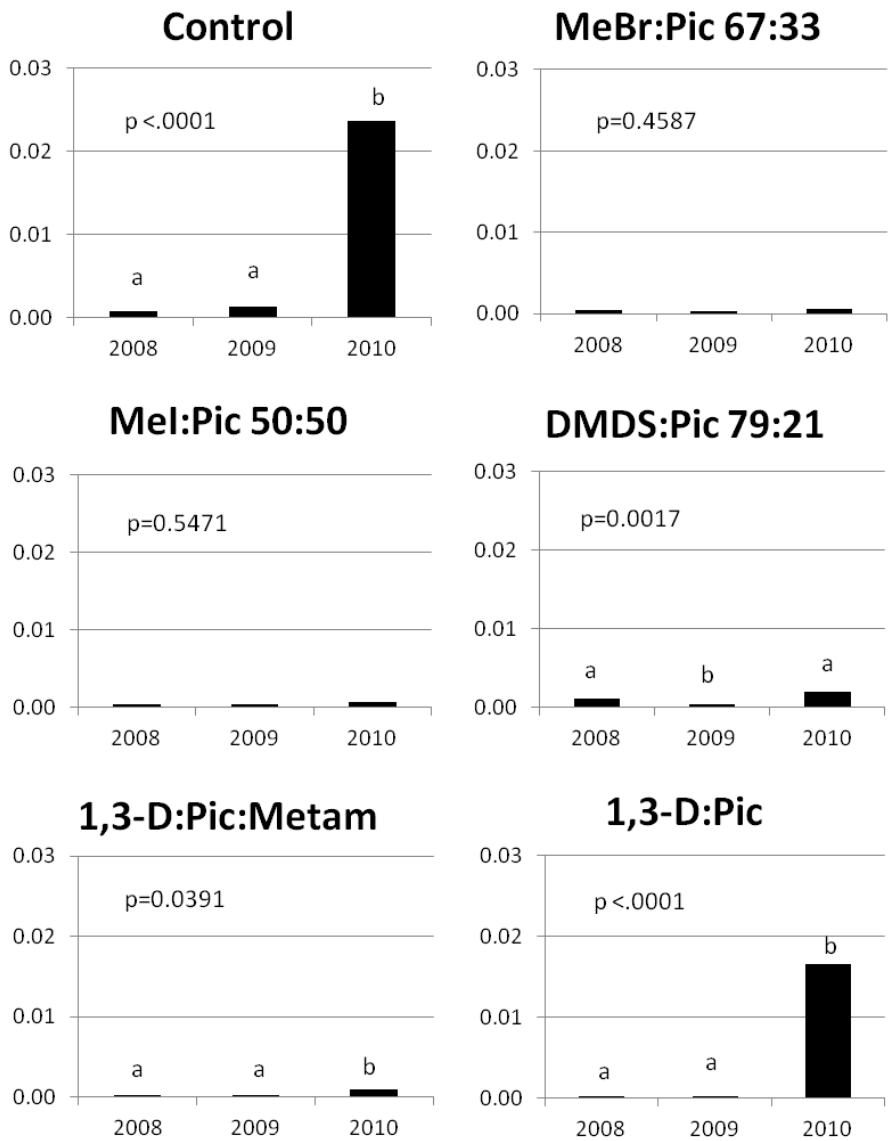

Figure 3-2. Nutsedge shoot emergence 4 weeks after transplanting (shoots•m^{2}) tomato with a herbicide for the 2008, 2009, and 2010 growing seasons. Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin. n year 1, the herbicides consisted of imazosulfuron (0.33 kg•ha^{-1}) and napropamide (2.24 kg•ha^{-1}). In years 2 and 3, imazosulfuron was replaced by fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch. Bars with the same letter are not different based on contrast statements within individual fumigant treatments using general linear mixed model analysis at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

CHAPTER 4
THE SUSTAINABILITY OF METHYL BROMIDE ALTERNATIVE SYSTEMS ON BELL PEPPER PRODUCTION

Introduction

The reduction in supply of methyl bromide has led to a need for alternative fumigants that are economical and provide acceptable control of weeds. The long term success of methyl bromide alternative systems must be determined. The objective of this study was to determine the sustainability of alternative fumigant systems to methyl bromide for the management of weeds in bell pepper production over three years.

Materials and Methods

This study was conducted at the University of Florida/IFAS Gulf Coast Research and Education Center in Balm, Florida, U.S. The study lasted over a three year period from the fall of 2008 through the fall of 2010. Dates of fumigation, planting and harvest are available in Table 3.1.

The initial treatments included methyl bromide plus chloropicrin (MeBr:Pic 67:33) at 196 kg ha^{-1}; dimethyl disulfide plus chloropicrin (DMDS:Pic 79:21) at 561 L•ha^{-1}; methyl Iodide plus chloropicrin (MeI:Pic 50:50) at 179 kg•ha^{-1}; 1,3-dichloropropene at 112 L•ha^{-1} plus chloropicrin at 168 kg•ha^{-1} plus metam potassium at 561 L•ha^{-1}, collectively referred to as the 3-way system (1,3-D:Pic:Metam); and 1,3-dichloropropene at 112 L•ha^{-1} plus chloropicrin at 168kg•ha^{1}, collectively referred to as the 2-Way system (1,3-D:Pic); and a non-fumigated control.

Each treatment had a split plot of herbicide or no herbicide. However, the split plot treatment was not randomized among the whole plot fumigation treatment. The herbicides consisted of napropamide (2.24 kg•ha^{-1}) and fomesafen at 0.28 kg•ha^{-1} and were not included until 2009.

The field was prepared using conventional tillage. A Yetter® coulter rig (Yetter Manufacturing Inc., Colchester, Illinois) was used to apply the 1,3-dichloropropene 30 to 35 cm below the bed top. A pre-bed was pulled and then shaped using a 3-row bed press rig. The remaining fumigants except for the metam potassium were injected via three shanks 20 cm deep into the bed using a nitrogen propelled single row fumigation rig. Beds were then sealed using a single row bed press. Herbicides were applied to subplot surfaces using a tractor mounted sprayer calibrated to deliver 280 $L{\bullet}ha^{-1}$ using TeeJet® 8004 DG nozzles (TeeJet Technologies, Springfield, Illinois). The polyethylene mulch (Pliant Blockade XL® 1.25 mil VIF, Berry Plastics Corporation, Evansville, IN) was applied using a speedroller with each bed receiving two drip tapes placed 30 cm apart and buried 2.5 cm deep capable of delivering 950 ml per emitter per hour on 30 cm spacing.

Metam potassium was injected into the beds two weeks after laying the plastic using double drip tape. The injection took place over a three hour period with 15 minutes of water applied prior to injection and 30 minutes of water following the injection period to flush the system of fumigant. A total of 3 $cm{\bullet}ha^{-1}$ of water was applied.

Each main plot consisted of three beds by 92 m long with 23 m long herbicide and non-herbicide sub-plots. Beds were on 1.5 m centers with a 75 cm bed top and 23 cm bed height. Treatments were arranged in a randomized complete block design with fumigation as the main plot effect and herbicide as a non-randomized subplot effect in four replicate blocks. The trial site and plot location were maintained throughout the length of the study to determine the effect of treatments over three years.

Once the fumigation concentration in the bed was low and safe enough to plant, holes were punched through the polyethylene about 30 minutes before hand transplanting the ‘Patriot’ bell pepper. The peppers were planted on double rows with spacing 37.5 cm apart within the row and 10 cm deep. Drip irrigation and fertilizer injection was provided to the crops daily. The crop was produced using University of Florida recommended production practices (Olson et al. 2009).

Weed populations that escaped the control of the fumigants and/or herbicides were assessed a minimum of two times each cropping season. Within each plot, the number of purple and yellow nutsedge (*Cyperus* spp.) seedlings that emerged through the plastic and the number of annual grasses and broadleaf weeds that emerged from the planting holes were counted. The pepper crop was harvested and graded a minimum of twice per season (unless hindered by freezes) via USDA guidelines.

Generalized linear mixed models in the PROC GLIMMIX procedure of SAS, Version 9.2 (SAS Institute, Inc., Cary, NC) were used to determine the effect of fumigant on weed control and yield data over time. Fumigation treatment was considered a fixed effect, while block and block by treatment over time were treated as random effects in the analyses. Data from herbicide and non-herbicide treatments were analyzed separately. Weed count data were transformed using the lognormal distribution function in the model statement during the analyses, and the resulting least squares means were back transformed manually for presentation in figures and tables. The SLICE function was used to test the simple effect of fumigant and time at each level of the interaction. Fisher's protected LSD ($\alpha = 0.05$) test was used to compare least squares means among fumigant treatments at each level of time and for comparing fumigant across different levels of time.

Results

Nutsedge

In 2008, without a herbicide, DMDS:Pic, 1,3-D:Pic, and MeI:Pic had similar nutsedge shoot emergence as the non-treated control (Table 4-2). The remaining two treatments had less shoot emergence with only MeI:Pic being similar. In 2009, the non-treated control and 1,3-D:Pic had the greatest nutsedge populations. MeI:Pic had the lowest shoot emergence, but the emergence in MeBr:Pic and 1,3-D:Pic:Metam plots were similar. In 2010, all treatments except MeI:Pic were similar to the non-treated control. In 2009, when applied with a herbicide, only the 1,3-D:Pic was similar to the non-treated control (Table 4-2). In 2010, MeBr:Pic, DMDS:Pic, and 1,3-D:Pic had similar nutsedge shoot emergence as the non-treated control, while MeI:Pic had the lowest nutsedge populations.

A significant increase in nutsedge shoot emergence was observed over time for all fumigant treatments in the absence of a herbicide except MeI:Pic, with the control increasing from 0.05 to 14.2 shoots•m^{-2} (Figure 4-1). The fumigation treatments followed by herbicide showed an increase in the nutsedge population except for the non-treated control (Figure 4-2). For the non-treated control, even with a herbicide, the nutsedge population increased from 0.0136 to 0.0390 shoots•m^{-2}, from the 2009 to 2010 growing season. Even MeBr:Pic fumigated plots had increasing nutsedge populations that resulted in shoot emergence of 0.0248 and 4.725 shoots•m^{-2} when applied with and without a herbicide, respectively in 2010 (Figures 4-2 and 4-1). Nutsedge populations of the DMDS:Pic treatment increased from 0.0029 to 0.0216 shoots•m^{-2} with the aid of a herbicide and from 0.041 to 10.230 shoots•m^{-2} without a herbicide. Without a herbicide, nutsedge shoot emergence in 1,3-D:Pic:Metam plots increased from 0.003 in 2008 to 10.196 shoots•m^{-2} in 2010, and from 0.0018 in 2009 to 0.0104 shoots•m^{-2} in 2010 with the additional herbicide application. Nutsedge shoot emergence also increased in 1,3-D:Pic plots, reaching 0.0364 and 9.170 shoots•m^{2} with and without a herbicide, respectively, in 2010.

Grass

Without a herbicide, annual grass emergence from the planting holes was highest for the non-treated control and DMDS:Pic plots in 2008 (Table 4-3). All other treatments had lower and similar grass populations. In 2009, the non-treated control, DMDS:Pic, and 1,3-D:Pic were similar having the highest grass emergence. Likewise, in 2010, the non-treated control, DMDS:Pic and 1,3-D:Pic had the highest grass populations. MeI:Pic and 1,3-D:Pic:Metam had lower grass counts with only the 1,3-D:Pic:Metam having a similar population as MeBr:Pic. In 2009, with a herbicide, 1,3-D:Pic and DMDS:Pic had similar grass emergence to the non-treated control (Table 4-3). The remaining three treatments had lower grass populations while being found similar. The same results were observed in 2010.

Yield

In 2008, without a herbicide, all treatments were found to have similar marketable yields (Table 4-4). In 2009, the non-treated control had the lowest yields with all other treatments providing greater yields. In 2010, DMDS:Pic and 1,3-D:Pic had similar yields to the non-treated control, followed by MeBr:Pic and 1,3-D:Pic:Metam. MeBr:Pic was similar to the 1,3-D:Pic:Metam and 1,3-D:Pic treatments. In 2009, when a herbicide was applied, the non-treated control had significantly lower yields compared to the other treatments (Table 4-4). In 2010, MeBr:Pic and 1,3-D:Pic had similar yields to the non-treated control while DMDS:Pic had the lowest yields and MeI:Pic had the highest yields.

Discussion

When no herbicide was applied, nutsedge populations for all fumigant treatments except MeI:Pic increased over the three growing seasons (Figure 4-1). An increase was also observed over the two growing seasons for all fumigation treatments even with the addition of a herbicide; but in general, the nutsedge populations were relatively lower (Figure 4-2). Previous research demonstrated that high nutsedge populations can reduce pepper yield by 70-73% (Morales-Payan et al., 1998; Motis et al., 2003) and tomato yield by 51% (Gilreath and Santos, 2004c). Since nutsedge reduces pepper yield greater than it does tomato, it stands to reason that any nutsedge shoot emergence in pepper could lead to a quicker population increase. Thus, the addition of a herbicide allows these methyl bromide alternative systems to suppress nutsedge populations and ultimately extend the sustainability of these alternative systems.

Even though lower nutsedge populations were generally observed with the addition of a herbicide, no yield improvement for bell pepper was observed except in MeI:Pic fumigated plots (Table 4-4). Due to shipping restrictions, MeI:Pic was applied 22 days after the other fumigant treatments were applied in the third growing season. During which the other treatments received a heavy rainfall of 10 cm. These results captured the adverse effect of environmental conditions on the overall efficacy. This leads us to believe that these environmental factors detrimentally affected the sustainability of these methyl bromide alternatives in this trial. Our results appear to show that any adverse environmental factors may have an effect on methyl bromide alternatives and leaves us concern that there may be no sustainable alternatives in the post methyl bromide era for pepper production.

Table 4-1. Dates for fumigation, planting, harvest, and weed counts.

Data	Pepper		
	2008	2009	2010
Fumigation	12-Aug	28-July	05-Aug[1]
Planting	22-Sep	16-Sep	15-Sep
Harvest 1	25-Nov	24-Nov	22-Nov
Harvest 2	12-Dec	07-Dec	07-Dec
Harvest 3	---	16-Dec	14-Dec
Nutsedge Counts	27-Oct	21-Oct	15-Oct
Grass Counts	27-Oct	21-Oct	15-Oct

[1]Methyl iodide plus chloropicrin was fumigated 27-Aug due to product availability.

Table 4-2. Effect of fumigant systems and herbicide on nutsedge shoot emergence 4 WATP of pepper

Treatment[1]	Nutsedge Shoot Emergence											
	No Herbicide						Herbicide[2]					
	Shoots•m^{-2}											
	2008		2009		2010		2008		2009		2010	
Control	0.054	a[3]	1.572	a	14.179	a	------		0.0136	a	0.0390	a
DMDS:Pic 79:21	0.041	a	0.051	b	10.230	a	------		0.0029	b	0.0216	ab
MeBr:Pic 67:33	0.002	b	0.005	bc	4.725	a	------		0.0013	bc	0.0248	ab
MeI:Pic 50:50	0.010	ab	0.002	c	0.012	b	------		0.0005	c	0.0023	c
1,3-D:Pic	0.033	a	0.681	a	9.170	a	------		0.0044	ab	0.0364	a
1,3-D:Pic:Metam	0.003	b	0.006	bc	10.196	a	------		0.0018	bc	0.0104	b

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]Herbicide plots for bell pepper were not included until 2009. The herbicides consisted of napropamide (2.24 kg•ha^{-1}) and fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

Table 4-3. Effect of fumigant systems and herbicide on grass control 4 WATP of pepper

Treatment[1]	Grass Emergence										
	No Herbicide						Herbicide[2]				
	Plants•m^{-2}										
	2008		2009		2010		2008	2009		2010	
Control	0.363	a[3]	1.397	a	0.164	a	------	0.0164	a	0.0077	a
DMDS:Pic 79:21	0.152	a	1.619	a	0.259	a	------	0.0135	a	0.0054	a
MeBr:Pic 67:33	0.001	b	0.001	b	0.001	d	------	0.0006	b	0.0002	b
MeI:Pic 50:50	0.004	b	0.001	b	0.014	bc	------	0.0011	b	0.0004	b
1,3-D:Pic	0.002	b	0.990	a	0.067	ab	------	0.0075	a	0.0038	a
1,3-D:Pic:Metam	0.001	b	0.001	b	0.006	cd	------	0.0018	b	0.0007	b

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]Herbicide plots for bell pepper were not included until 2009. The herbicides consisted of napropamide (2.24 kg•ha^{-1}) and fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

Table 4-4. Effect of fumigant systems and herbicide on marketable yield in pepper

Treatment[1]	Pepper Yield (t•Ha^{-1})											
	No Herbicide						Herbicide					
	2008		2009		2010		2008[2]		2009		2010	
Control	14.56	a[3]	9.87	c	14.19	c	------		10.08	d	22.48	c
DMDS:Pic 79:21	14.66	a	19.88	b	17.79	c	------		16.70	c	19.10	d
MeBr:Pic 67:33	15.74	a	25.74	a	23.07	b	------		21.49	a	25.20	bc
MeI:Pic 50:50	13.73	a	21.95	ab	28.99	a	------		20.76	ab	31.73	a
1,3-D:Pic	12.65	a	22.98	ab	19.83	bc	------		19.05	bc	23.67	c
1,3-D:Pic:Metam	15.79	a	24.38	ab	22.03	b	------		20.92	ab	27.82	b

[1]Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin; WATP=weeks after transplant

[2]Herbicide plots for bell pepper were not included until 2009. The herbicides consisted of napropamide (2.24 kg•ha^{-1}) and fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch.

[3]Treatments by column with the same letter are not different based on general linear mixed model analysis of log-normal transformed data at the 95% level of confidence (α=0.05).

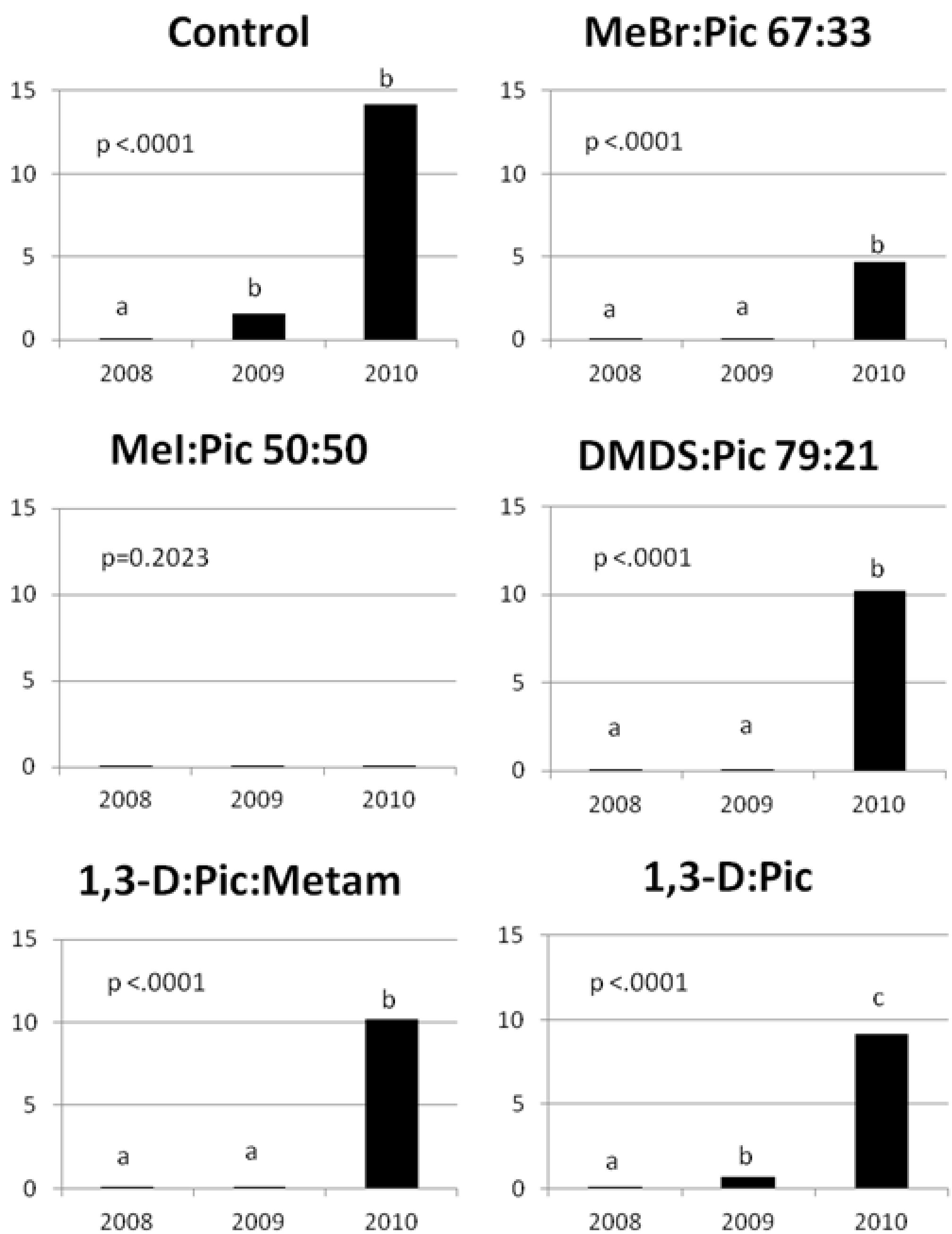

Figure 4-1. Nutsedge shoot emergence 4 weeks after transplanting (shoots•m^2) pepper without a herbicide for the 2008, 2009, and 2010 growing seasons. Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin. Bars with the same letter are not different based on contrast statements within individual fumigant treatments using general linear mixed model analysis at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

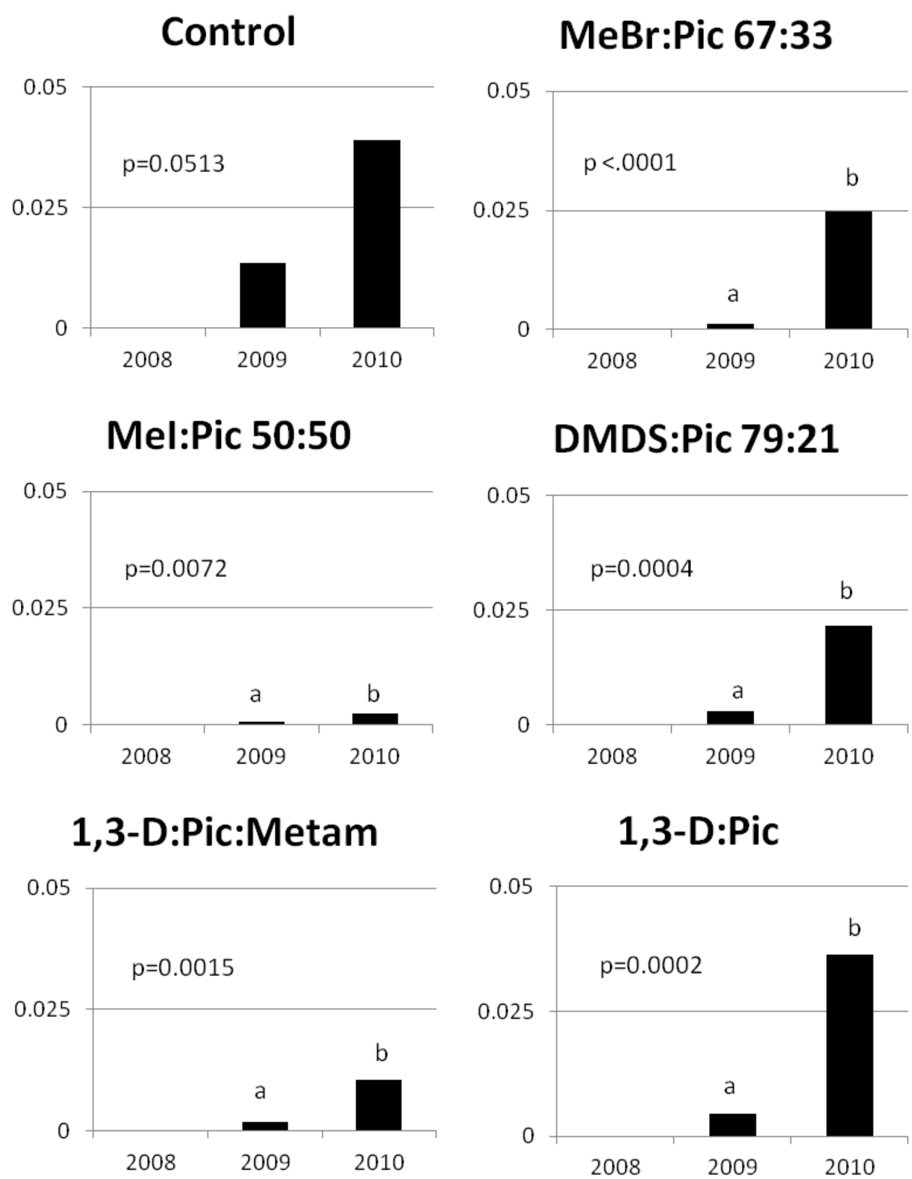

Figure 4-2. Nutsedge shoot emergence 4 weeks after transplanting (shoots•m^2) pepper with a herbicide for the 2009 and 2010 growing seasons. Abbreviations: MeBr:Pic = methyl bromide (67%) plus chloropicrin (33%); MeI:Pic = methyl iodide (50%) plus chloropicrin (50%); DMDS:Pic = dimethyl disulfide (79%) plus chloropicrin (21%); 1,3-D:Pic:Metam = 1,3-dichloroprone followed by chloropicrin followed by metam potassium; 1,3-D:Pic = 1,3-dichloropropene plus chloropicrin. The herbicides consisted of napropamide (2.24 kg•ha^{-1}) and fomesafen at 0.28 kg•ha^{-1}. All herbicides were applied to the final finished bed top prior to laying the polyethylene mulch. Bars with the same letter are not different based on contrast statements within individual fumigant treatments using general linear mixed model analysis at the 95% level of confidence (α=0.05). The data presented are the back-transformed means after analysis.

CHAPTER 5
CONCLUSION

The general definition of '*Sustainable*' is to be "capable of being sustained" (Meriam Webster Dictionary). Sustainable agriculture integrates three main goals of environmental health, economic profitability, and social and economic equality (United States Department of Agriculture, 2009). In this case, '*sustainability*' adheres to the principle that we must meet the needs of the present without compromising the ability of future generations to meet their own needs. To a grower, the definition of '*sustainable*' is the ability to maintain current economical profitability by maximizing crop production while minimizing crop inputs.

S*ustainability* as it relates to a fumigant, is the capacity for a fumigant or fumigant system to maintain soilborne pest pressure at a level equal to or less than the previous cropping cycle without any negative impact on yield while still being economically viable. This would also include any other crop inputs, besides fumigation, needed to maximize soilborne pest control.

Our research showed that nutsedge populations in tomato were increasing across three growing seasons with most fumigant systems. However, there is a strong possibility of successfully implementing the full fumigant systems combined with the herbicide program, as sustainable methyl bromide alternatives with additional crop inputs, such as a fallow weed management program. Our results do not show the same promise for fumigant systems in bell pepper. When looking at nutsedge alone, these systems will need to be integrated with other effective cultural practices such as progressed fallow herbicide and cultivation treatments, if only to delay the eventual collapse of sustainability.

The 1,3-D:Pic:Metam and MeI:Pic fumigant systems showed the best promise of sustainability for pepper and tomato. In tomato, the addition of a herbicide program made these two systems sustainable through year three. However, in pepper we did not find sustainability with 1,3-D:Pic:Metam and MeI:Pic with the addition of herbicides, but the possibility of sustainability with other additional crop inputs. Without knowledge of what additional crop inputs are required, the economic sustainability cannot be determined at this time. The adoption and sustainability of these fumigant systems at the farm level depends on individual field conditions, soilborne pest populations, and environmental conditions. The use of these systems at the farm level will ultimately show their weaknesses and strengths, as long as growers utilize the fumigant systems efficiently to maximize their potential.

Overall, our results showed MeI:Pic to have the greatest potential to be a sustainable fumigant system. However, in year three, MeI:Pic was not applied at the same time as the other fumigant systems. This resulted in MeI:Pic not being exposed to the adverse weather conditions (heavy rainfall) that affected the other treatments. The rainfall after application may have had the biggest impact with the DMDS:Pic and 1,3-D:Pic treatments in tomato. When nutsedge shoot numbers were converted to percent control, the MeI:Pic in the absence of a herbicide provided 98.6 and 99.8% control for season two and three, respectively. For this same time period, DMDS:Pic control dropped from 97 to 77.3% and 1,3-D:Pic dropped from 99.1 to 22%. We observed a greater impact on all the fumigant treatments in the peppers which were grown in the wetter portion of the field when compared to tomato. Thus, this lead to a longer period of saturated soil conditions after the rainfall event. In 2009, the MeBr:Pic, DMDS:Pic, MeI:Pic and 1,3-D:Pic:Metam all provided 96% or better control of nutsedge, without the addition of a herbicide program. However, in the third season, the MeI:Pic provided 99.9% control, while the remaining fumigant treatments provided 27 to 67% control. The combination of these environmental conditions and the higher price of MeI:Pic leaves uncertainty of its true sustainability, as it relates to either efficacy or the economics.

Economics were not taken into account in this study but it will always be a major limiting factor in the decision making process for a grower. Our results show that all fumigants required the addition of a herbicide program. In addition, the majority of these fumigant systems will require additional weed control measures to ensure sustainability or delay a significant increase in the weed population. These additional weed control measures will further impact the economic sustainability, and thus may prevent adoption by the growers. This economic impact will be greatest in bell pepper production, and without further research on what additional weed control measures are necessary, our results show that the current methyl bromide alternative systems that were tested may not be sustainable for bell pepper production.

Additional information needs to be generated on supplementary weed control methods that can be incorporated into tomato and bell pepper production. These may include extensive fallow weed management programs, additional herbicide programs, and cultural methods for weed control. The efficacy and economic benefits of any additional control measures must be included in the sustainability model to facilitate grower adoption.

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BIOGRAPHICAL SKETCH

Tyler Jacoby grew up in Lakeland, Florida. He graduated from Lake Gibson High School in 2005. That fall, he began coursework at Florida Southern College (Lakeland, Florida). In the spring of 2009, he received a Bachelor of Science degree in horticultural science. The next August, he began studies at the University of Florida on a Master of Science degree in horticultural science.