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Yellow Nutsedge (*Cyperus esculentus*) Control with Methyl Iodide in Combination with Totally Impermeable Film

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Methyl bromide (MBr) has been an industry standard for soil fumigation in a multitude of crops for decades. However, it has been banned by the United Nations Environment Programme, and alternatives to MBr must be implemented to sustain productivity in many vegetable crops that depend on soil fumigation. One alternative that has been implemented in some areas is methyl iodide (MeI). Efficacy of MeI has been demonstrated on many pest species and has been generally similar to MBr. Methyl iodide is a costly material, which has likely limited its adoption. Virtually impermeable film (VIF) and totally impermeable film (TIF) provide greater fumigant retention than low-density and high-density polyethylene film, which can allow for reduced fumigant application rates while maintaining fumigant efficacy. The objectives of this research were to evaluate TIF with reduced rates of shank-applied MeI : chloropicrin (Pic) (50 : 50 w/w) for the control of yellow nutsedge in tomato. Treatments included a standard rate of MeI : Pic (93.3 L ha^{-1} [178 kg ha^{-1} broadcast]) under VIF and TIF, three reduced rates (37.3, 56, 74.6 L ha^{-1} [71.2, 106.8, 142.5 kg ha^{-1} broadcast, respectively]) under TIF, and a nontreated control under TIF. Results indicate fumigant use rates may be reduced from a standard 93.3 L ha^{-1} under VIF to 37.3 L ha^{-1} (60% reduction) under TIF while providing yellow nutsedge control and maintaining tomato yields.

Nomenclature: Methyl iodide; chloropicrin; yellow nutsedge, *Cyperus esculentus* L.; tomato, *Solanum lycopersicum* L.
Key words: Fumigant, methyl bromide alternatives, nutsedge, plasticulture, retention, weed control.

Methyl bromide (MBr) ha sido el estándar de la industria para la fumigación de suelo en múltiples cultivos por décadas. Sin embargo, debido a que ha sido prohibido por el Programa para el Ambiente de las Naciones Unidas, alternativas a MBr deben ser implementadas para mantener la productividad de muchos vegetales que dependen de la fumigación del suelo. Una alternativa que ha sido implementada en varias áreas es methyl iodide (MeI). La eficacia de MeI ha sido demostrada en muchas especies de plagas y ha sido generalmente similar a MBr. Methyl iodide es un material costoso, lo que probablemente ha limitado su adopción. Coberturas virtualmente impermeables (VIF) y coberturas totalmente impermeables (TIF) brindan mayor retención del fumigante que las coberturas de polyethylene de baja o alta densidad, lo que permite el uso de dosis reducidas de fumigante manteniendo su eficacia. Los objetivos de esta investigación fueron evaluar TIF con dosis reducidas inyectadas al suelo de MeI:chloropicrin (Pic) (50:50 w/w) para el control de *Cyperus esculentus* en tomate. Los tratamientos incluyeron una dosis estándar de MeI:Pic (93.3 L ha^{-1} [178 kg ha^{-1} aplicación generalizada]) bajo VIF y TIF, tres dosis reducidas (37.3, 56, 74.6 L ha^{-1} [71.2, 106.8, 142. 5 kg ha^{-1} aplicación generalizada, respectivamente]) bajo TIF y un testigo no tratado bajo TIF. Los resultados indican que las dosis de fumigante pueden ser reducidas desde el estándar 93.3 L ha^{-1} bajo VIF a 37.3 L ha^{-1} (reducción del 60%) bajo TIF al tiempo que se obtiene el control de *C. esculentus* y se mantiene el rendimiento del tomate.

The primary weed controlled by methyl bromide (MBr) in tomato production on the eastern shore of Virginia is yellow nutsedge. In the southern United States, yellow nutsedge is among the most common and troublesome weeds in fruiting vegetables (Webster 2006). Yellow nutsedge is not completely controlled by plastic mulch, because the plant possesses sharp leaf tips that readily puncture and emerge through the plastic. Black mulch does suppress yellow nutsedge spread in terms of shoot production and lateral expansion compared to a nonmulched control. It is estimated that a single yellow nutsedge tuber produced 62 shoots by 24 wk after planting in black mulch compared to 208 shoots produced in the nonmulched control during the same time period (Webster 2005).

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Relatively low infestations of yellow nutsedge can result in decreased tomato yields. Stall and Morales-Payan (2000) found that season-long interference of 25 yellow nutsedge shoots m^{-2} resulted in a 10% marketable yield loss of tomato. In addition, the critical weed-free period for yellow nutsedge in tomato is between 2 and 10 wk after transplanting to avoid tomato yield losses above 5%. Other studies have shown season-long interference of yellow nutsedge resulted in yield loss of up to 100% in bell pepper (*Capsicum annum* L.) (Motis et al. 2003; Santos et al. 2007a), 94% in watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] (Buker et al. 2003), and 85% in cucumber (*Cucumis sativus* L.) (Johnson and Mullinix 1999).

Methyl iodide (MeI), also referred to as iodomethane, is an alternative to MBr for preplant soil fumigation (Duniway 2002). Title 5, section 602 of the Clean Air Act orders the U.S. Environmental Protection Agency (USEPA) to list any substance with an ozone depletion potential (ODP) of 0.2 or greater as a Class 1 ozone depleter. The ODP of MeI is likely less than 0.016, which is much lower than the level of Class 1 ozone depleters (Ohr et al. 1996). MeI is a general biocide similar to MBr. Ohr et al. (1996) described MeI as being a better methylating agent than MBr and equal to or better at controlling certain soil-borne pathogens and weeds than MBr at equivalent molar rates. MeI is an ozone-safe alternative to MBr because of rapid degradation by UV light and a logical candidate as a single chemical replacement for MBr (Ohr et al. 1996).

In a dose-response experiment on yellow nutsedge, the EC50 (effective concentration to provide 50% control) for MeI applied alone was 2.6 times less than for MBr (Hutchinson et al. 2003). This indicates that 2.6 times less chemical is needed to provide similar levels of control, thus MeI is more efficacious at controlling yellow nutsedge compared to MBr. Combining MeI with 17% chloropicrin (Pic) resulted in a synergistic response. The relative potency of MeI increased 1.7 times when 17% Pic was added. There was no significant difference between the EC50 values of MBr and MeI when both fumigants were combined with Pic (Hutchinson et al. 2003). A separate laboratory bioassay experiment also indicated that MeI was more effective at controlling weeds than MBr. Zhang et al. (1997) found that the dose of MeI needed to control redroot pigweed (*Amaranthus retroflexus* L.) was similar to MBr and that MeI was more effective at controlling lambsquarters (*Chenopodium album* L.), purple nutsedge (*Cyperus rotundus* L.), yellow nutsedge (*Cyperus esculentus* L.), wild mustard [*Brassica kaber* (D.C.) L.C. wheeler], Italian ryegrass (*Lolium multiflorum* Lam.), velvetleaf (*Abutilon theophrasti* Medik.), and common purslane (*Portulaca oleracea* L.). MeI is very costly compared to other soil fumigants; therefore reduced application rates would be beneficial to growers (Gilreath and Santos 2011). MeI : Pic (98:2 and 50:50 w/w) applied at rates of 140 and 224 kg ha^{-1}, respectively, under high-density polyethylene (HDPE) mulch provided the greatest marketable tomato fruit yields and provided the greatest control of purple and yellow nutsedge (Gilreath and Santos 2011). These results were similar to a MBr : Pic treatment (67 : 33 [w/w] at a rate of 392 kg ha^{-1}). Iodomethane was marketed in the United States under the trade name Midas® (Arysta LifeScience Corporation, Cary, NC, USA) and was labeled for nutsedge control in tomatoes when the research was conducted. However, the company has pulled the state labels but not the national label. Therefore, it is possible that the product may return to the market, but at the time of publication it is not available for purchase. Midas® is registered for use in seven other countries, including Japan, Mexico, Guatemala, Morocco, Turkey, New Zealand, and Uruguay.

The most advanced high-retention films are virtually impermeable film (VIF) and totally impermeable film (TIF). Low-density polyethylene (LDPE) is the most permeable mulch to fumigants, followed by HDPE, and virtually impermeable film (VIF) (Noling 2002). Films manufactured by coextrusion containing multilayers with barrier polymers, such as ethyl vinyl alcohol (EVOH) or polyamide (nylon) are significantly less permeable to fumigants than LDPE and HDPE (Chellemi et al. 2011; Fennimore and Ajwa 2011; Gamliel et al. 1997; Gao et al. 2011a; Ou et al. 2007; Qin et al. 2011; Santos et al. 2007b; Wang et al. 1998; Yates et al. 2002). Films containing an EVOH barrier layer are currently referred to as totally impermeable film (TIF) (Chow 2008; Fennimore and Ajwa 2011; Gao et al. 2011b; Qin et al. 2011). Characteristics of TIF include good film-handling properties (resistance to stretching, tearing, and puncturing) and extremely low fumigant vapor permeation (Chow 2009; Fennimore and Ajwa 2011; Qin et al. 2011).

Dosage (D) is the product of pesticide concentration (C) and the time (T) of exposure to the target organism (Lembright 1990). Efficacy of a fumigant is determined by the dosage of that fumigant for a particular pest (Munnecke and Van Gundy 1979). Several papers make reference to C by T values required to kill certain pathogens with a specific fumigant (Gamliel et al., 1998; Minuto et al. 1999). Less-permeable mulches may retain fumigants longer at a greater concentration; therefore adequate fumigant concentrations for pest management within the soil may be achieved with lower fumigant application rates. Benefits of mulches with increased fumigant retention are a reduction in the amount of fumigant needed for effective pest management, lower emissions, and a decreased buffer zone (a required area surrounding the fumigated area that must be managed and kept free of bystanders for a certain period of time). A minimum buffer zone of 7.62 m is required surrounding all MeI applications. Previous studies on MBr : Pic and 1,3-D : Pic have shown that application rates under VIF and TIF can be reduced to 25 to 57% of the application rate under HDPE and LDPE while maintaining weed control and crop yields (Fennimore and Ajwa 2011; Gilreath et al. 2005b; Hamill et al. 2008; Santos et al. 2005, 2006, 2007b). The objective of this experiment was to test the efficacy of reduced rates of MeI in combination with TIF on yellow nutsedge and the effect on vegetable yields.

Materials and Methods

MeI efficacy experiments were conducted at the Virginia Tech Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, VA, USA during the spring and fall of 2010 and 2011. Soil type at ESAREC is a Bojac sandy loam (Thermic Typic Hapludults) with 59% sand, 30% silt, and 11% clay with pH ranging from 6.2 to 6.5 and organic matter content of 0.50 to 0.75%. Soil was cultivated to a depth of 30 cm prior to fumigation. If necessary, overhead sprinkler irrigation was used to bring soil moisture capacity to between 50 and 75% field capacity. The fumigant formulation used was MeI : Pic 50:50 (w/w) (Arysta LifeScience Corporation, Cary, NC, USA). The fumigant was shank applied with the use of a single row combination bed press 76 cm wide and 20 cm high with three backswept shanks. Shanks were 20 cm long and fumigant was released at the bottom of the shank, 20 cm from the surface of the raised bed. Experimental plots were 24 m long with a between-row spacing of 1.8 m.

The treatments in the experiment were an nontreated (nonfumigated) control utilizing TIF, a standard rate for highly retentive films (93.3 L ha^{-1} [178 kg ha^{-1} broadcast]) under VIF and TIF, and reduced rates (37.3, 56, 74.6 L ha^{-1}

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Table 1. Effect of totally impermeable film (TIF) and virtually impermeable film (VIF) in combination with various rates of a methyl iodide:chloropicrin (50 : 50 w/w) mixture on tomato yield and yellow nutsedge densities at harvest. Experiments were performed in Painter, VA during the spring of 2010.

Treatment	Emerged nutsedge	Yield[a,b]			
		Medium	Large	Extra large	Marketable
	m^{-2}	kg ha^{-1}			
Untreated TIF	1.90 a[c]	5,780 ns[d]	9,317 c	21,277 ns	36,373 ns
37.3 L ha^{-1} TIF	0.05 b	4,316	11,153 bc	22,821	38,292
56.0 L ha^{-1} TIF	0.00 b	4,859	12,454 ab	22,558	39,870
74.6 L ha^{-1} TIF	0.00 b	5,876	13,220 ab	23,425	42,520
93.3 L ha^{-1} TIF	0.00 b	6,681	14,758 a	24,631	46,070
93.3 L ha^{-1} VIF	0.03 b	5,861	14,020 ab	29,287	49,168

[a] Yield estimates are based on two harvests from 10 plants per plot.

[b] Size categories are based on USDA standards for fresh tomatoes; medium = 5.71-6.42 cm; large = 6.35–7.06 cm; extra-large = 6.98 cm and greater; Total marketable is the sum of medium, large, and extra-large fruit.

[c] Values followed by the same letter do not differ at the 5% significance level. Means are to be compared within columns.

[d] ns = not significant.

Table 2. Effect of totally impermeable film (TIF) and virtually impermeable film (VIF) in combination with various rates of a methyl iodide:chloropicrin (50 : 50 w/w) mixture on tomato yield and yellow nutsedge densities at harvest. Experiments were performed in Painter, VA during the fall of 2010.

Treatment	Emerged nutsedge	Yield[a,b]			
		Medium	Large	Extra large	Marketable
	m^{-2}	kg ha^{-1}			
Untreated TIF	130.0 a[c]	6,322 ns[d]	7,040 ns	13,498 b	26,860 b
37.3 L ha^{-1} TIF	4.2 b	8,558	10,435	25,695 a	44,688 a
56.0 L ha^{-1} TIF	1.0 b	7,677	9,866	23,194 a	40,738 a
74.6 L ha^{-1} TIF	1.2 b	7,467	10,177	22,863 a	40,507 a
93.3 L ha^{-1} TIF	0.2 b	8,091	10,795	23,092 a	41,978 a
93.3 L ha^{-1} VIF	8.8 b	8,484	12,508	29,219 a	50,211 a

[a] Yield estimates are based on two harvests from ten plants per plot.

[b] Size categories are based on USDA standards for fresh tomatoes; medium = 5.71-6.42 cm; large = 6.35–7.06 cm; extra-large = 6.98 cm and greater; Total marketable is the sum of medium, large, and extra-large fruit.

[c] Values followed by the same letter do not differ at the 5% significance level. Means are to be compared within columns.

[d] ns = not significant.

[71.2, 106.8, 142.5 kg ha^{-1} broadcast]) under TIF. Experimental plots were arranged as a randomized complete block design with four replications. Black films were used in the spring and white on black films were used in the fall seasons. The mulches used were a 0.03-mm-thick Blockade® VIF (Berry Plastics Corp., Evansville, IN, USA) embossed polyethylene mulch containing a nylon barrier and a 0.05-mm-thick Vaporsafe® TIF (Raven Industries Inc., Sioux Falls, SD, USA) polyethylene mulch containing an EVOH barrier. The lowest rate used under VIF was 93.3 L ha^{-1} (178 kg ha^{-1}) because this is the lowest labeled rate under highly retentive tarps for nutsedge control in tomato. Fumigant application rates were adjusted by flow rate (measured by King® flow meter (King Instrument Company, Garden Grove, CA, USA) with the use of a 10W float (0.75 L min^{-1} of water at 100% flow) and tractor speed. In order to achieve uniform fumigant delivery between chisels in the bed with low fumigant rates, small-diameter tubing (1.6 mm) was used, and lines were fully charged before fumigating plots as described by Gilreath et al. (2005a). Experiments were fumigated on 15 April 2010, 18 June 2010, 27 April 2011, and 11 August 2011.

These experiments were planted on May 11, 2010, July 13, 2010, May 17, 2011, and August 22, 2011. Once the fumigant had dissipated, the beds were planted with a crop. Tomato cultivar 'BHN 602′ (BHN Seed, Immokalee, FL, USA) was planted during every experiment, except in the fall of 2011. Adverse weather conditions prohibited timely fumigant application during the fall of 2011. This delayed planting beyond a date suitable for tomato. In order to maintain as much similarity between seasons, 'Packman' broccoli (Seminis Vegetable Seeds, Inc., St. Louis, MO, USA) was established to maintain fertigation and irrigation effects on nutsedge growth. Experimental plots contained 25 plants spaced 46 cm apart within the row. Drip irrigation was provided to meet the water requirements of the crop. The crop was fertilized based on cooperative extension production recommendations (Wilson et al. 2010). Current recommended cultural and disease management practices for tomato and broccoli in Virginia were implemented (Wilson et al. 2010).

Tomato fruit were harvested twice per season at the mature green stage. Broccoli was harvested once. Harvested tomato fruit were graded and sized according to the U.S. Department of Agriculture (USDA) standards for grades of fresh tomatoes (USDA 1991). Tomato yields combined from both harvests for each season are presented. In the spring of 2010, tomato fruit were picked on July 21 and July 30, in the fall of 2010 tomatoes were harvested on September 29 and October 7, in the spring of 2011 tomato fruit were harvested on July 27 and August 5, and in the fall of 2011 broccoli was harvested on October 17. Yellow nutsedge shoot counts were taken from two random sites measuring 1 m in length within the plots at harvest. Yellow nutsedge counts were taken on July 21, 2010, September 20, 2010, August 2, 2011, and October 24, 2011. Statistical differences in nutsedge populations and crop yields between treatments were determined by ANOVA (SAS Institute, Cary, NC, USA). Each season was analyzed separately because of the variability between nutsedge pressure, soil diseases, and weather between seasons. Significant differences between treatment means were separated with the use of Duncan's multiple range test at $P < 0.05$.

Results and Discussion

Spring 2010. A standard MeI rate under both films (0.00 to 0.03 shoots m^{-2}) and reduced rates under TIF (0.00 to 0.05 shoots m^{-2}) controlled yellow nutsedge better than the nontreated TIF (1.90 shoots m^{-2}) (Table 1). There were no differences in yellow nutsedge control (0.00 to 0.05 shoots m^{-2}) between MeI fumigated plots. There were no yield differences between treatments for medium, extra-large, and marketable-sized fruits (Table 2). However, MeI applied at a standard rate (93.3 L ha^{-1}) under TIF resulted in greater large-fruit yields (14,758 kg ha^{-1}) than the lowest rate (37.3 L ha^{-1}) applied under TIF (11,153 kg ha^{-1}). All fumigant treatments (12,454 to 14,758 kg ha^{-1}), except the 37.3–L

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Table 3. Effect of totally impermeable film (TIF) and virtually impermeable film (VIF) in combination with various rates of a methyl iodide:chloropicrin (50:50 w/w) mixture on tomato yield and yellow nutsedge densities at harvest. Experiments were performed in Painter, VA during the spring of 2011.

Treatment	Emerged nutsedge	Yield[a,b]			
		Medium	Large	Extra large	Marketable
	m^{-2}	kg ha^{-1}			
Untreated TIF	3.80 a[c]	6,180 ns[d]	18,986 ns	37,627 ns	62,793 ns
37.3 L ha^{-1} TIF	0.03 b	6,756	17,828	37,437	62,021
56.0 L ha^{-1} TIF	0.00 b	7,325	23,459	37,641	68,424
74.6 L ha^{-1} TIF	0.00 b	7,657	23,506	38,657	69,820
93.3 L ha^{-1} TIF	0.10 b	6,624	23,770	35,330	65,724
93.3 L ha^{-1} VIF	0.05 b	7,379	21,460	39,531	68,370

[a] Yield estimates are based on two harvests from ten plants per plot.

[b] Size categories are based on USDA standards for fresh tomatoes; medium = 5.71-6.42 cm; large = 6.35–7.06 cm; extra-large = 6.98 cm and greater; Total marketable is the sum of medium, large, and extra-large fruit.

[c] Values followed by the same letter do not differ at the 5% significance level. Means are to be compared within columns.

[d] ns = not significant.

Table 4. Effect of totally impermeable film (TIF) and virtually impermeable film (VIF) in combination with various rates of a methyl iodide:chloropicrin (50:50 w/w) mixture on broccoli yield and yellow nutsedge densities at harvest. Experiments were performed in Painter, VA during the fall of 2011.

Treatment	Emerged nutsedge	Broccoli yield[a]	
		Heads	Yield
	m^{-2}	ha^{-1}	kg ha^{-1}
Untreated TIF	49 a[b]	1,230 c	2,462 c
37.3 L ha^{-1} TIF	22 b	1,653 a	4,853 a
56.0 L ha^{-1} TIF	16 bc	1,763 a	4,871 a
74.6 L ha^{-1} TIF	13 bc	1,708 a	4,983 a
93.3 L ha^{-1} TIF	3 c	1,579 ab	4,526 a
93.3 L ha^{-1} VIF	19 bc	1,341 bc	3,451 b

[a] Yield estimates are based on one harvest from 27 plants per plot.

[b] Values followed by the same letter do not differ at the 5% significance level. Means are to be compared within columns.

ha^{-1} rate under TIF (11,153 kg ha^{-1}), produced greater large-fruit yield than the nontreated TIF (9,317 kg ha^{-1}).

Fall 2010. MeI applied at the labeled rate under both films and at reduced rates under TIF (0.2 to 8.8 shoots m^{-2}) provided 93% or greater yellow nutsedge control compared to the nontreated TIF (130.0 shoots m^{-2}) (Table 2). There were no yield differences in medium- and large-sized fruits between treatments. All MeI treatments regardless of rate or mulch type provided greater extra-large (22,863 to 29,219 kg ha^{-1}), and marketable tomato yields (40,507 to 50,211 kg ha^{-1}) compared to the nontreated TIF (13,498 and 26,860 kg ha^{-1}, respectively).

Spring 2011. Reduced rates of MeI under TIF and the labeled rate under both films controlled yellow nutsedge (0.0 to 0.1 shoots m^{-2}) better than the nontreated TIF (3.8 shoots m^{-2}) (Table 3). There were no differences in yield for any fruit size category between treatments. It appears the low nutsedge densities encountered, even in the nontreated TIF, did not have a significant impact on tomato yield.

Fall 2011. All MeI treatments (3.3 to 22.0 shoots m^{-2}) controlled yellow nutsedge better than the nontreated TIF (49 shoots m^{-2}) (Table 4). The standard rate (93.3 L ha^{-1}) applied under TIF (3.3 shoots m^{-2}) provided greater nutsedge control than the lowest rate (37.3 L ha^{-1}) under TIF (22 shoots m^{-2}). There were significant differences in yield (broccoli number and weight) between treatments. MeI applied under TIF resulted in a greater number of broccoli heads (1,579 to 1,763 heads ha^{-1}) than the nontreated TIF (1,230 heads ha^{-1}). Reduced MeI rates (37.3, 56, and 74.6 L ha^{-1}) under TIF resulted in greater number of broccoli heads (1,653 to 1,763 heads ha^{-1}) than the labeled rate (93.3 L ha^{-1}) under VIF (1,341 heads ha^{-1}). MeI applied under TIF at various rates resulted in higher broccoli yields (4,526 to 4,983 kg ha^{-1}) than the labeled rate under VIF (93.3 L ha^{-1}) (3,451 kg ha^{-1}). Fumigation with MeI at a standard rate under both films (3,451 to 4,526 kg ha^{-1}) and at reduced rates under TIF (4,853 to 4,983 kg ha^{-1}) provided higher broccoli yields than the nontreated TIF (2,462 kg ha^{-1}).

These data show that TIF can be used with reduced rates of MeI while providing acceptable yellow nutsedge control and tomato and broccoli yields. During several seasons, nutsedge emergence in the nontreated TIF was low. Other research has shown that TIF alone can suppress nutsedge emergence compared to VIF so populations would likely have been higher if a nontreated VIF or LDPE was included (Freeman and McAvoy 2011). Several laboratory and field studies have shown MeI to be as or more effective than MBr at controlling yellow nutsedge (Hutchinson et al. 2003; Zhang et al. 1997; Olson and Kreger 2007; Gilreath and Santos 2011). Furthermore, MeI is very costly compared to other soil fumigants; therefore, reduced application rates and formulations with lesser MeI concentrations would be economically beneficial to growers (Gilreath and Santos 2011; Sydorovych et al. 2008). Field experiments have shown reduced MeI rates under VIF mulch can result in tomato yields similar to MBr (Olson and Kreger 2007; Gilreath and Santos 2011). Rates of 1,3-D plus Pic could be reduced by 33% under TIF compared to HDPE, while maintaining similar weed control (yellow nutsedge, common purslane, and common chickweed) and strawberry fruit yield as a standard rate (392 kg ha^{-1}) of MeBr under HDPE (Fennimore and Ajwa 2011). TIF has been shown to maintain fumigant concentration in the soil longer than HDPE, which allows for greater degradation in the soil environment and less emission into the atmosphere (Qin et al. 2011). This reduces the risk of bystander and field worker exposure to elevated fumigant concentrations. This is likely why the USEPA has amended recent fumigant reregistration eligibility decisions to approve a 60% buffer zone reduction credit for MBr : Pic when applied under certain types of TIF (USEPA 2009). In the fall 2011, yellow nutsedge populations were greater in the MeI-treated plots than in previous seasons. It is unclear why nutsedge control was decreased during this season. The nutsedge densities present in the reduced rates during this season would likely be problematic in the long term, but control provided by these rates in previous seasons was acceptable. The results followed the same trends but overall populations were increased. Also, during the fall 2011 it appears broccoli may

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be superior at suppressing yellow nutsedge populations in the nontreated plots compared to tomato, when populations from both fall seasons are compared. This is likely due to shading from the growth habit of broccoli (horizontal leaf orientation) and the competitive advantage broccoli (cool season crop) had in the cooler late fall temperatures.

These data illustrate that MeI rates could be reduced from 93.3 L ha^{-1} under VIF to 37.3 L ha^{-1} under TIF (60% rate reduction) while providing similar nutsedge control and vegetable yields. MeI fumigation under both films increased yellow nutsedge control and tomato/broccoli yield compared to the nontreated TIF. TIF can reduce buffer-zone requirements, application rates, and possibly lower input costs when used with MeI while increasing nutsedge efficacy and vegetable yields. Further experimentation must be done to determine the management potential of these reduced rates on other soil-borne pests such as fungi, bacteria, and nematodes, but these data demonstrate their efficacy on yellow nutsedge. TIF may become a valuable tool for easing the transition from methyl bromide to alternative fumigants while maintaining acceptable levels of pest management. TIF may also be a tool to help producers cope with increasing fumigant costs.

Literature Cited

Buker, R. S., III, W. M. Stall, S. M. Olson, and D. G. Schilling. 2003. Season-long interference of yellow nutsedge (*Cyperus esculentus*) with direct-seeded and transplanted watermelon (*Citrullus lanatus*). Weed Technol. 17:751–754.

Chellemi, D. O., H. A. Ajwa, D. A. Sullivan, R. Alessandro, J. P. Gilreath, and S. R. Yates. 2011. Soil fate of agricultural fumigants in raised-bed, plasticulture systems in the southeastern United States. J. Environ. Qual. 40:1204–1214.

Chow, E. 2008. Properties of EVOH and TIF films for the reduction of fumigant dosage and VOC emission. Proc. 2008 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. http://mbao.org/2008/Proceedings/038ChowEMBAO2008Kuraray.pdf. Accessed: March 18, 2012.

Chow, E. 2009. An update on the development of TIF mulching films. Proc. 2009 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. http://www.mbao.org/2009/Proceedings/050ChowEMBAO2009.pdf. Accessed: March 18, 2012.

Duniway, J. M. 2002. Status of chemical alternatives to methyl bromide for preplant fumigation of soil. Phytopathology 92:1337–1343.

Fennimore, S. A. and H. A. Ajwa. 2011. Totally impermeable film retains fumigants, allowing lower application rates in strawberry. Calif. Agric. 65:211–215.

Freeman, J. H. and T. McAvoy. 2011. Reduced rates of dimethyl disulfide in combination with totally impermeable film. Proc. 2011 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. http://mbao.org/2011/Proceedings/35FreemanJDMDSTIF.pdf. Accessed: August 21, 2012.

Gamliel, A., A. Grinstein, Y. Peretz, L. Klein, A. Nachmias, L. Tsror, L. Livescu, and J. Katan. 1997. Reduced dosage of methyl bromide for controlling verticillium wilt of potato in experimental and commercial plots. Plant Dis. 81:469–474.

Gamliel, A., A. Grinstein, L. Klein, Y. Cohen, and J. Katan. 1998. Permeability of plastic films to methyl bromide: field study. Crop Prot. 17:241–248.

Gao, S., B. D. Hanson, R. Qin, D. Wang, and S. R. Yates. 2011a. Comparisons of soil surface sealing methods to reduce fumigant emission loss. J. Environ. Qual. 40:1480–1487.

Gao, S., B. D. Hanson, D. Wang, G. T. Browne, R. Qin, H. A. Ajwa, and S. R. Yates. 2011b. Methods evaluated to minimize emissions from preplant soil fumigation. Calif. Agric. 65:41–46.

Gilreath, J., B. Santos, J. Mirusso, J. Noling, and P. Gilreath. 2005a. Application considerations for successful use of VIF and metalized mulches with reduced fumigant rates in tomato. http://edis.ifas.ufl.edu/hs270. Accessed: March 21, 2012.

Gilreath, J. P., T. N. Motis, and B. M. Santos. 2005b. *Cyperus* spp. control with reduced methyl bromide plus chloropicrin doses under virtually impermeable films in pepper. Crop Prot. 24:285–287.

Gilreath, J. P. and B. M. Santos. 2011. Methyl iodide plus chloropicrin rates and formulations for nutsedge management in tomato. HortTechnology 21:51–55.

Hamill, J. E., J. E. Thomas, L. T. Ou, L. H. Allen, Jr., N. Kokalis-Burelle, and D. W. Dickson. 2008. Effects of reduced rates of Telone C35 and methyl bromide in conjunction with virtually impermeable film on weeds and root-knot nematodes. Nematropica 38:37–46.

Hutchinson, C. M., Jr., M. E. McGriffen, J. J. Sims, and J. O. Becker. 2003. Fumigant combinations for *Cyperus esculentus* L. control. Pest Manag. Sci. 60:369–374.

Johnson, W. C., III, and B. G. Mullinix, Jr. 1999. *Cyperus esculentus* interference in *Cucumis sativus*. Weed Sci. 47:327–331.

Lembright, H. W. 1990. Soil fumigation: principles and application technology. J. Nematol. (Suppl.) 22:632–644.

Minuto, A., G. Gilardi, M. L. Gullino, and A. Garibaldi. 1999. Reduced dosages of methyl bromide applied under gas-impermeable plastic films for controlling soilborne pathogens of vegetable crops. Crop Prot. 18:365–371.

Motis, T. N., S. J. Locascio, J. P. Gilreath, and W. M. Stall. 2003. Season-long interference of yellow nutsedge (*Cyperus esculentus*) with polyethylene-mulched bell pepper (*Capsicum annuum*). Weed Technol. 17:543–549.

Munnecke, D. E., and S. D. Van Gundy. 1979. Movement of fumigants in soil, dosage responses, and differential effects. Annu. Rev. Phytopathol. 17:405–429.

Noling, J. W. 2002. Reducing methyl bromide field application rates with plastic mulch technology. http://edis.ifas.ufl.edu. Accessed: April 11, 2012.

Ohr, H. D., J. J. Sims, N. M. Grech, J. O. Becker, and M. E. McGiffen, Jr. 1996. Methyl iodide, an ozone-safe alternative to methyl bromide as a soil fumigant. Plant Dis. 80:731–735.

Ou, L.-T., J. E. Thomas, L. H. Allen, J. C. Vu, and D. W. Dickson. 2007. Emissions and distribution of methyl bromide in field beds applied at two rates and covered with two types of plastic mulches. J. Environ. Sci. Health 42:15–20.

Olson, S. M. and R. Kreger. 2007. Efficacy of Midas (50/50) as a soil fumigant for tomato production. Proc. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. http://mbao.org/2007/Proceedings/032OlsonStomato2007.pdf. Accessed: March 22, 2012.

Qin, R., S. Gao, H. Ajwa, D. Sullivan, D. Wang, and B. D. Hanson. 2011. Field evaluation of a new plastic film (Vapor Safe) to reduce fumigant emissions and improve distribution in soil. J. Environ. Qual. 40:1195–1203.

Santos, B. M., J. P. Gilreath, C. E. Esmel, and M. N. Siham. 2007a. Effects of yellow and purple nutsedge time of establishment on their distance of influence on bell pepper. HortTechnology 17:305–307.

Santos, B. M., J. P. Gilreath, and T. N. Motis. 2005. Managing nutsedge and stunt nematode in pepper with reduced methyl bromide plus chloropicrin rates under virtually impermeable films. HortTechnology 15:596–599.

Santos, B. M., J. P. Gilreath, T. N. Motis, M. von Hulten, and M. N. Siham. 2006. Effects of mulch types and concentrations of 1,3-dichloropropene plus chloropicrin on fumigant retention and nutsedge control. HortTechnology 16:637–640.

Santos, B. M., J. P. Gilreath, and M. N. Siham. 2007b. Comparing fumigant retention of polyethylene mulches for nutsedge control in Florida spodosols. HortTechnology 17:308–311.

Stall, W. M. and J. P. Morales-Payan. 2000. The critical period of nutsedge interference in tomato. http://hendry.ifas.ufl.edu/index_march-april2000.htm#The%20Critical%20Period%20of%20Nutsedge. Accessed: March 18, 2012.

Sydorovych, O., C. D. Safley, R. M. Welker, L. M. Ferguson, D. W. Monks, K. Jennings, J. Driver, and F. J. Louws. 2008. Economic evaluation of methyl bromide alternatives for the production of tomatoes in North Carolina. HortTechnology 18:705–713.

[USDA] U.S. Department of Agriculture. 1991. United States Standards for Grades of Fresh Tomato. USDA Agric. Marketing Serv. http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331. Accessed: October 22, 2011.

[USEPA] U.S. Environmental Protection Agency. 2009. Amended reregistration eligibility decision for methyl bromide (soil and non-food structural uses). http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OPP-2005-0123-0716. Accessed: February 15, 2012.

Wang, D., S. R. Yates, and W. A. Jury. 1998. Temperature effect on methyl bromide volatilization: permeability of plastic cover films. J. Environ. Qual. 27:821–827.
Webster, T. M. 2005. Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53:839–845.
Webster, T. M. 2006. Weed survey – southern states: vegetable, fruit and nut crops subsection. Proc. South. Weed Sci. Soc. 59:260–277.
Wilson, H. P., T. P. Kuhar, S. L. Rideout, J. H. Freeman, M. S. Reiter, R. A. Straw, T. E. Hines, C. M. Waldenmaier, H. B. Doughty, and U. T. Deitch. 2010. Virginia commercial vegetable production recommendations for 2010. Virginia Coop. Ext. Pub. 456-420.
Yates, S. R., J. Gan, S. K. Papiernik, R. Dungan, and D. Wang. 2002. Reducing fumigant emissions after soil application. Phytopathology 92:1344–1348.
Zhang, W. M., M. E. McGiffen, Jr., J. O. Becker, H. D. Ohr, J. J. Sims, and R. L. Kallenbach. 1997. Dose response of weeds to methyl iodide and methyl bromide. Weed Res. 37:181–189.

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