Economic Returns in Plasticulture Tomato Production from Crucifer Cover Crops as a Methyl Bromide Alternative for Weed Management

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Summary. The phase-out of methyl bromide required an effective and economically viable alternative for weed management in polyethylene-mulched tomato (*Solanum lycopersicum*). A field experiment was conducted to compare economics of tomato production associated with crucifer (Brassicaceae) cover crops under low-density polyethylene mulch (LDPE) and virtually impermeable film (VIF) mulch with a standard treatment of methyl bromide:chloropicrin (67:33) at 350 lb/acre. Three crucifer cover crops, 'Seventop' turnip (*Brassica rapa*), 'Pacific Gold' oriental mustard (*Brassica juncea*), and Caliente [a blend of brown mustard (*B. juncea*) and white mustard (*Sinapis alba*)], were evaluated in combination with hand-weeding. Because of marginal weed control from crucifer cover crops, hand-weeding cost in all cover crop plots, regardless of mulch type, increased from $380.54/acre to $489.10/acre over that in methyl bromide plots. However, total weed management costs in the untreated control and cover crops with LDPE treatments were $17.82/acre to $111.33/acre lower than methyl bromide. Because of mulch expenses, VIF mulch increased the total weed management cost by $328.16/acre over LDPE mulch in the untreated control and cover crop treatments. Because of equivalent marketable yield, gross returns ($21,040.43/acre) were identical in all treatments. Preplant fumigation with methyl bromide provided $6260.90/acre of net returns in tomato production. The untreated control, 'Seventop' turnip, 'Pacific Gold' oriental mustard, and Caliente mustard under LDPE treatment were $54/acre, $54/acre, $98/acre, and $147/acre more profitable, respectively, than methyl bromide. However, in all other treatments under VIF, net returns relative to methyl bromide were reduced from $181/acre to $274/acre. Therefore, regardless of soil amendment with crucifer cover crops, hand-weeding can serve as an economically viable alternative to methyl bromide for weed control in LDPE-mulched tomato production, depending on the nature and level of pest infestation, labor availability, and wages.

Tomato is the top-ranking fresh-market vegetable crop in the United States with an annual market value of $1.3 billion (U.S. Department of Agriculture, 2010a). Weeds are a major constraint to vegetable production, reducing fruit yield and quality and decreasing harvesting efficiency. The most troublesome weed species in tomato production in the southern United States are purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) (Webster, 2002). In a plasticulture production system, fresh-market tomatoes are grown on plastic-mulched raised beds and irrigated and fertilized through drip tape lying under the plastic. Plastic mulches help in suppressing weeds by providing a physical barrier and by altering the light quantity and quality beneath the mulch. However, the physical barrier is ineffective against nutsedge species because their sharp-pointed shoot tips can pierce the plastic mulch (Patterson, 1998). For effective weed control, methyl bromide, a preplant soil fumigant, is applied under the plastic mulch in commercial tomato production (Duniway, 2002). Methyl bromide is a highly effective and broad-spectrum fumigant with activity on a wide array of pests, including nutsedge species. However, methyl bromide is a major contributor to ozone depletion and therefore is being phased out of U.S. agriculture (U.S. Environmental Protection Agency, 2008). In the absence of methyl bromide, weed management, especially nutsedge control, will be difficult, resulting in relatively higher production cost and lower yield and net returns. Therefore, there is a need to develop an effective alternative to methyl bromide in plasticulture tomato production.

Volatile allelopathic compounds like isothiocyanates (ITCs) are gaining attention in recent years as a methyl bromide alternative as a result of their lethal activity on several pests, including weeds (Baysal and Miller, 2009; Boydston and Hang, 1995; Buskov et al., 2002; Matthiessen and Shackleton, 2005; Mattner et al., 2008; Norsworthy and Meehan, 2005a, 2005b, 2005c). ITCs are byproducts of glucosinolates, secondary metabolites produced by crucifer plants, making crucifer crops a potential "biofumigant" for controlling weeds (Angus et al., 1994; Brown and Morra, 1995). Aqueous extracts of winter rape (*Brassica napus*) shoots inhibited lettuce (*Lactuca sativa*) seed germination (Brown and Morra, 1996). Similarly, hemp sesbania (*Sesbania herbacea*) germination and fresh weight were reduced greater than 95% by isothiocyanates released from chopped leaves of *Brassica* species (Vaughn and Boydston, 1997). Isothiocyanates also reduced yellow

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg\cdot ha^{-1}$	0.8922
0.0254	mil	mm	39.3701

nutsedge emergence and shoot production in purple and yellow nutsedge (Norsworthy and Meehan, 2005c; Norsworthy et al., 2006). According to Uremis et al. (2009), herbicide applications to control johnsongrass (*Sorghum halepense*) can be reduced by incorporating crucifer green manure in soil before planting a commercial crop. Therefore, incorporating crucifer cover crop tissues before planting a commercial crop may reduce early-season weed competition in tomato.

Although the use of crucifer cover crops for weed management appears promising, the magnitude of weed suppression is either marginal or inconsistent under field conditions (Haramoto and Gallandt, 2005; Krishnan et al., 1998; Norsworthy et al., 2005), which indicates that cover crops alone will not replace methyl bromide. Thus, crucifer cover crops should be integrated with other strategies to achieve weed control equivalent to methyl bromide. One possible reason of limited weed suppression using an ITC strategy could be the result of the low amount of allelopathic ITCs released to soil after crucifer tissue incorporation (Morra and Kirkegaard, 2002; Peterson et al., 2001). Moreover, ITCs are volatile compounds, and volatilization losses of ITCs could limit and cause variability in the activity against weeds (Brown and Morra, 1996; Morra and Kirkegaard, 2002; Peterson et al., 2001). Volatilization losses of ITCs in the field can be minimized by covering the soil with low-permeability plastic mulches immediately after incorporating the crucifer tissues (Price et al., 2005). In previous laboratory experiments, virtually impermeable film mulch has reduced the losses of methyl and phenyl ITCs compared with conventionally used low-density polyethylene mulch (Austerweil et al., 2006; Bangarwa et al., 2010).

In addition to weed control efficacy, the success of any methyl bromide alternative depends on its economic viability. Therefore, it is imperative to evaluate the economic viability of an alternative relative to methyl bromide. In the past, some studies evaluated the economics of vegetable production using nonchemical weed control methods such as hand-weeding, cultivation, solarization, and grass and legume cover crops, whereas others evaluated the economics with herbicidal weed control methods (Bell et al., 2000; Lanini and Strange, 1994; Ogbuchiekwe and McGiffen, 2001; Ogbuchiekwe et al., 2004; Wang et al., 2009). Sydorovych et al. (2006, 2008) published a thorough economic evaluation associated with various chemical fumigant alternatives to methyl bromide in plasticulture tomato and strawberry (*Fragaria ×ananassa*) production. However, the economics of vegetable production associated with crucifer cover crops as a methyl bromide alternative has not been evaluated in the previous studies. A useful tool for producers is partial budget analysis, which provides the framework to compare the economic viability of various alternative production systems (Rainey, 2010). Therefore, the objective of this research was to compare the total costs, gross returns, and net returns in plasticulture tomato production associated with the standard fumigant methyl bromide versus crucifer cover crops followed by hand-weeding.

Materials and methods

Location and soil type. A field experiment was conducted in 2007 at the Arkansas Agricultural Research and Extension Center at Fayetteville. The soil type at the experimental site was a silt loam (fine-loamy, mixed, active, non-acid) with 1.7% organic matter and a pH of 6.1.

Experimental design. The experimental design was a split plot with two whole plots and four subplot treatments replicated four times. Whole plot treatments were mulch types, low-density polyethylene mulch (LDPE) and virtually impermeable film (VIF), and subplot treatments were cover crop types, an untreated control and the cover crops 'Seventop' turnip (Green Seed, Springfield, MO), 'Pacific Gold' oriental mustard (University of Idaho, Moscow, ID), and Caliente mustard (a blend of brown mustard and white mustard; Santa Clara Seeds, Greenfield, CA). A standard treatment of methyl bromide:chloropicrin (67:33) at 350 lb/acre under LDPE mulch was also established in each replication.

Experimental procedure. The entire experimental site was limed followed by a chisel plow in early spring. The cover crop plot area was cultivated twice with a disk harrow and then followed by a field cultivator before planting the cover crops on 14 Mar. 2007. Before disking, 36 lb/acre of nitrogen (N) was broadcast over the cover crop area as a starter fertilizer. All cover crops were drill-seeded in 25-ft-long plots using a 10-row drill with 7-inch row spacing. The seeding rates were 5 lb/acre for 'Seventop' turnip and 8 lb/acre for 'Pacific Gold' oriental mustard and Caliente mustard. Simultaneously, two fallow treatments with no cover crop were established, one of which was used as an untreated control and the other later for methyl bromide treatment. Cover crops were top-dressed with 36 lb/acre N and 27 lb/acre sulfur at 5 weeks after planting (WAP). Cover crops were not irrigated because of adequate rainfall received during the spring. At 9 WAP on 22 May 2007, cover crops were flail-mowed and cover crop tissues were immediately incorporated into the soil to a 3-inch depth using a rototiller. Immediately after incorporation, 6-inch-high raised beds 2.3 ft wide at the top were prepared on 6-ft centers and covered with a black LDPE mulch (1 mil thick; Robert Marvel Plastic Mulch, Annville, PA) or black/white VIF mulch (1.3 mil thick; Polygro, Tampa, FL) using a plastic layer. Simultaneously, a single row of drip tape was placed in the bed center under the plastic mulch. Treatments were separated by cutting the plastic and covering with soil to avoid volatile ITC movement across the treatments. Similarly, raised beds were formed and covered with plastic mulch in untreated control plots. Weed densities were taken in untreated control plots before forming beds. Averaged over four plots, the untreated controls have 73 shoots/m^2 of yellow nutsedge and 3 plants/m^2 of johnsongrass. The incorporated crucifer tissues were allowed to fumigate the beds for 1 week, after which, on 29 May 2007, tomato were transplanted on beds. The methyl bromide was applied under LDPE mulch on 8 May 2007, and beds were allowed to fumigate for 3 weeks before transplanting tomato on 29 May 2007. For transplanting, holes were punched in the plastic 24 inches apart at the center of the bed, and a single row of seven 'Amelia' tomato plants (5-week-old seedlings) were planted in the center of each plot. All production and management practices were according to standard recommendations for drip-irrigated fresh-market plasticulture tomato production (Bryant et al., 2004; Holmes and Kemble, 2010). Row middles between the plastic-covered beds were kept weed-free throughout the season by hooded-sprayer application of 0.95 lb/acre *S*-metolachlor (Dual Magnum 7.62 EC; Syngenta Crop Protection, Greensboro, NC) once at 2 weeks after transplanting (WATP) and 0.5 lb/acre paraquat (Gramoxone Inteon 2 EC; Syngenta Crop Protection, Greensboro, NC) three times from 4 to 8 WATP.

Data collection. Data were collected on crop injury, hand-weeding time, and marketable fruit yield. The plots were visually rated for crop injury at 2, 4, and 6 WATP. Visual ratings were based on a scale of 0% to 100%, in which 0 = no tomato injury and 100 = tomato. The plots were hand-weeded every week and time in seconds per plot was recorded for hand-weeding each treatment. Total weeding time for the season was calculated by adding individual weekly weeding times for each treatment and converting into hours/acre. The weeding time was used to determine the hand-weeding cost associated with each treatment for the entire growing season. Tomato fruits were harvested seven times during the growing season and graded into six categories (jumbo, extralarge, large, medium, small, and nonmarketable culls) based on fruit size standards for fresh market tomato [U.S. Department of Agriculture (USDA), 1997].

Statistical analysis. Data on tomato injury, hand-weeding time, and grade-wise and total marketable fruit yield were subjected to analysis of variance with a split-plot structure using PROC GLM in SAS (Version 9.2; SAS Institute, Cary, NC). Replications were treated as a random factor, whereas mulch types and cover crops were treated as fixed factors. Whole plot treatment was mulch type (two levels) in a randomized complete block, and cover crops were the split-plot factor (four levels). In addition, methyl bromide treatment was included as another level in the subplot factor. Because of unequal cell sizes, Type III statistics were used to test all possible fixed effects and interactions, and treatment means were separated by Fisher's protected least significant difference at $\alpha = 0.05$.

Economic analysis. Economic analysis was conducted to compare the net returns from crucifer cover crops under LDPE and VIF mulch with the methyl bromide under LDPE mulch, all in combination with hand-weeding. Net returns from each treatment were calculated by subtracting the total costs from the gross returns associated with that particular treatment. Total costs were further subdivided into three categories: preharvest costs, weed management costs, and harvesting and marketing costs. For the untreated control, weed management cost consisted of cost of plastic mulch (LDPE or VIF) and labor used for hand-weeding throughout the season. For the methyl bromide treatment, fumigant cost was added to mulch and labor cost, and for cover crop treatments, cover crop production and termination cost were added to mulch and labor cost. Harvesting and marketing costs included costs of labor, material, machinery, and diesel for harvesting, grading and packing, and hauling. Harvesting and marketing costs were estimated based on a charge of $4.98 per 25-lb box of tomato regardless of grade. All cost estimates were based on the common production cost model of drip-irrigated tomato (MALTAG) published by the University of Arkansas in collaboration with state universities of Alabama, Louisiana, Mississippi, Tennessee, and Georgia (Bryant et al., 2004; MALTAG, 2008). MALTAG is a multistate group formed in 2003 to develop vegetable enterprise budgets for the southeastern United States. Appropriate adjustments were made in this model according to management practices followed in the current experiment and 2007 prices for labor, materials, machinery, diesel, and interest rate. Diesel charges of $2.33/gal were used for calculating the cost of diesel. An annual interest rate of 6% was used on the operating capital, which was charged for 2 months for cover crop production and 6 months for tomato production and harvesting and marketing. Labor charges of $8.19/h and $9.50/h were used for hired and operating labor for farming operations in Arkansas in 2007, respectively. Land rent and overhead charges were not included in the budget. Gross returns were estimated by adding all the returns from each grade of tomato fruits, which were calculated by multiplying the yield of each grade to the respective average prices of that grade obtained from the Dallas terminal market report on vine-ripe tomato for early Aug. 2007 (USDA, 2010b). The tomato prices used to calculate gross returns were $11.25, $10.00, $9.00, $8.15, and $7.50 per 25-lb box of jumbo, extralarge, large, medium, and small size tomato fruits, respectively. Because the prices for medium- and small-grade tomato were not available in the terminal market report, prices were assumed for these two grades.

Results and discussion

Tomato injury. Tomato plants were unaffected by any cover crop treatment with no visual injury at any rating (data not shown). Therefore, soil amendment with crucifer cover crops has no deleterious effect on transplanted tomato. Our results are in agreement with the results of previous greenhouse and field studies, in which no injury was observed in tomato transplanted to soil amended with Caliente mustard, turnip, or other crucifer plants (Bangarwa et al., 2009; Baysal and Miller, 2009; Norsworthy and Meehan, 2005a; Saini et al., 2008).

Preharvest costs. Estimated preharvest costs per acre of producing tomato in a plasticulture production system were $3674.43/acre for the untreated control and methyl bromide treatments and $3611.47/acre in all cover crop treatments (Table 1). Preharvest costs included all the costs of producing plastic-mulched tomato except harvesting and marketing. Although weed management is a preharvest operation, weed management costs are presented separately. Because the purpose of this study was to compare various weed management strategies, a detailed comparison of cost of each component of various weed management strategies is more informative. Total preharvest cost was divided into two categories: variable and fixed costs. Preharvest variable cost was estimated to be $3130.38/acre in the untreated control and methyl bromide

Table 1. Estimated preharvest costs per acre of plasticulture tomato production associated with various weed control treatments.[z]

Item	Untreated control or methyl bromide treatment[y]	Cover crop treatments[x]
	Costs ($/acre)[w]	
A. Variable costs[v]:		
Mulch cleanup	134.26	134.26
Liming and land preparation	26.81	0.00
Preplant fertilization	82.79	82.79
Bed formation, plastic laying, and drip tape (excluding plastic mulch cost)	220.56	220.56
Transplanting	770.72	770.72
Irrigation	423.00	423.00
Fertigation	170.28	170.28
Insecticide	143.23	143.23
Fungicide	148.23	148.23
Herbicide for row middles	104.47	104.47
Staking and tying	773.90	773.90
Pruning	40.95	40.95
Interest on operating capital (6%)	91.18	90.37
Total preharvest variable cost	3130.38	3102.76
B. Fixed costs[u]:		
Machinery	60.55	52.21
Irrigation setup	456.50	456.50
Total preharvest fixed costs	517.05	508.71
Total preharvest costs (A + B)	**3647.43**	**3611.47**

[z]Cost of preplant weed management is excluded from the preharvest cost and is presented separately in Table 3.
[y]Cost of fumigant (methyl bromide: chloropicrin, 67:33) is excluded from methyl bromide treatment.
[x]Cost (variable and fixed) of liming and land preparation is excluded from cover crop treatments because these operations were performed before planting cover crops.
[w]$1.00/acre = $2.4711/ ha.
[v]Variable costs include the cost of labor, materials, diesel, repair and maintenance of tractor and equipments, and interest on operating capital (6% annual for 6 months).
[u]Fixed costs include the equipment ownership cost of tractor, implements, and irrigation setup. Land rent and overhead charges were not included.

Table 2. Estimated costs per acre of cover crop production and termination for three crucifer cover crop treatments before transplanting tomato.[z]

Item	'Pacific Gold' mustard	Caliente mustard[y]	'Seventop' turnip
		Costs ($/acre)[x]	
A. Variable costs[w]:			
Liming and land preparation	36.60	36.60	36.60
Preplant fertilization	18.61	18.61	18.61
Planting	33.54	34.74	19.84
Irrigation (rain-fed)	0.00	0.00	0.00
Postplant fertilization	28.06	28.06	28.06
Flail mowing	8.34	8.34	8.34
Incorporation in soil	16.68	16.68	16.68
Interest on operating capital (6%)	1.42	1.43	1.28
Total cover crop variable cost	143.25	144.46	129.41
B. Fixed costs[v]:			
Machinery	21.58	21.58	21.58
Total cover crop fixed costs	21.58	21.58	21.58
Total cover crop costs (A + B)	**164.83**	**166.04**	**150.99**

[z]Cost of irrigation is excluded from the production cost as cover crops received rainfall throughout growing season.
[y]Blend of brown mustard and white mustard (Santa Clara Seeds, Greenfield, CA).
[x]$1.00/acre = $2.4711/ ha.
[w]Variable costs include the cost of labor, materials, diesel, repair and maintenance of tractor and equipments, and interest on operating capital (6% annual for 2 mo.).
[v]Fixed costs include the equipment ownership cost of tractor and implements. Land rent and overhead charges were not included.

treatments and $3102.76/acre in all three cover crop treatments. Preharvest variable costs included the cost of labor, production inputs (lime, transplants, fertilizers, irrigation water, and pesticides), diesel, repair and maintenance of tractor and implements, and interest on operating capital. Preharvest fixed costs included the equipment ownership costs of irrigation setup, tractors, and implements, which were an estimated $517.05/acre for the untreated control and methyl bromide treatments and $508.71/acre for cover crop treatments. The lower preharvest costs in cover crop treatments than in the untreated control or methyl bromide treatments were the result of exclusion of variable and fixed costs associated with liming and land preparation from cover crop treatments. This is because liming and land preparation operations were already performed before seeding cover crops.

Cover crop costs. Cover crop costs included the production and termination costs of each crucifer cover crop (Table 2). Variable costs consisted of costs of labor, production inputs (lime, seeds, and fertilizers), diesel, and repair and maintenance costs of tractor and implements. Irrigation cost was not included because the cover crops received spring rainfall during the growing period. Variable costs for Caliente mustard and 'Pacific Gold' oriental mustard were estimated at $166.04/acre and $164.83/acre, respectively. In a previous experiment conducted in 2002, the variable cost of production and termination of mustard green manure was estimated to be $114/acre (McGuire, 2003). 'Seventop' turnip had lower variable costs ($129.41/acre) than other mustard cover crops in the present experiment, which was mainly the result of relatively lower planting cost (Table 2). The low planting cost for turnip was related to its low per-acre seed cost ($11.50/acre) compared with the Caliente mustard ($26.40/acre) and 'Pacific Gold' oriental mustard ($25.20/acre). The low seed cost of turnip was associated with a relatively lower seeding rate (5 lb/acre) and unit seed price ($2.30/lb) compared with the other cover crops. The seeding rate of turnip was 3 lb/acre lower than the other two mustards. The unit seed

Table 3. Estimated weed management costs per acre associated with various weed control treatments in plasticulture tomato production.[z]

Fumigant or cover crop	Plastic mulch[y]	Cover crop costs ($/acre)[x]	Methyl bromide costs ($/acre)	Plastic mulch costs ($/acre)	Hand-weeding costs ($/acre)[w]	Total weed management costs ($/acre)
Methyl bromide[v]	LDPE	0.00	657.91	274.39	134.80	1067.10
'Pacific Gold' mustard	LDPE	164.83	0.00	274.39	565.95	1005.17
Caliente mustard[u]	LDPE	166.04	0.00	274.39	515.34	955.77
'Seventop' turnip	LDPE	150.99	0.00	274.39	623.90	1049.28
Untreated control	LDPE	0.00	0.00	274.39	738.80	1013.19
'Pacific Gold' mustard	VIF	164.83	0.00	602.55	565.95	1333.33
Caliente mustard[u]	VIF	166.04	0.00	602.55	515.34	1283.93
'Seventop' turnip	VIF	150.99	0.00	602.55	623.90	1377.44
Untreated control	VIF	0.00	0.00	602.55	738.80	1341.35

[z]Interest on operating capital included in the costs of plastic mulch, methyl bromide, and hand-weeding costs (6% annual for 6 mo.).
[y]Plastic mulch, LDPE = low-density polyethylene mulch (black, 1.0 mil), VIF = virtually impermeable film mulch (black/white, 1.3 mil); 1 mil = 0.0254 mm.
[x]$1.00/acre = $2.4711/ha.
[w]Hand-weeding costs are for the entire growing season and are based on hired labor charges of $8.19/h and included interest on total cost (6% annual for 6 months).
[v]Methyl bromide: chloropicrin (67:33) at 350 lb/acre (treated); 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$.
[u]Blend of brown mustard and white mustard (Santa Clara Seeds, Greenfield, CA).

price of 'Seventop' turnip was $0.85/lb and $1.0/lb cheaper than the Caliente mustard and 'Pacific Gold' oriental mustard, respectively. Fixed cost was identical ($21.58/acre) in all cover crop treatments and included equipment ownership costs of tractors and implements.

WEED MANAGEMENT COSTS. Estimated weed management costs associated with various weed control treatments are shown in Table 3 and ranged from $1067.10/acre to $1377.44/acre. This indicates that weed management is the most expensive preharvest operation for tomato producers (Tables 1 and 3). Total weed management costs were broken into costs of cover crop or fumigant, plastic mulch, and hand-weeding. Cost of the methyl bromide:chloropicrin (67:33) mixture was $657.91/acre. A total of 1.8 rolls (five × 4000 ft per roll) of plastic mulch was used for a 1-acre tomato field with beds on 6-ft centers. VIF mulch cost was $602.55/acre, which was 2.2 times more costly than LDPE mulch ($274.39/acre). The analysis of variance of hand-weeding time indicated a significant difference ($P = 0.0073$) among cover crops with no significant mulch effect or any cover crop by mulch interaction ($P \geq 0.2366$). Hand-weeding time was shortest (15.98 h/acre) in the methyl bromide treatment (data not shown). Hand-weeding times in the control and cover crop treatments were similar and were over 3.82 times that in the methyl bromide treatment. Averaged over mulch type, weeding time in Caliente mustard, 'Pacific Gold' oriental mustard, 'Seventop' turnip, and untreated control treatments was 61.09, 67.09, 73.96, and 87.58 h/acre, respectively (data not shown). Because of shortest weeding time, hand-weeding cost was minimum ($134.80/acre) in methyl bromide plots (Table 3). Hand-weeding in the control and cover crops plots with LDPE or VIF cost $380.54/acre to $604.00/acre more than in methyl bromide plots. Weeding cost is related to weeding time, which in turn is related to the level of weed infestation. Higher weeding cost in cover crop plots indicates the limited activity of the crucifer cover crops under both mulches against yellow nutsedge and johnsongrass. Similarly, in previous field experiments, weed control provided by crucifer green manures in succeeding commercial crops was limited and short-term (Bangarwa et al., 2009; Bensen et al., 2009; Norsworthy et al., 2007). This limited activity of crucifer against weeds may be attributed to low ITC concentrations in the soil after incorporation of crucifer plant tissues. In previous research, the maximum amount of total ITCs (shoots and roots) produced by turnip green manure was 4.1 lb/acre (Petersen et al., 2001). However, at a labeled product rate of 320 lb/acre with 90% conversion efficiency, the fumigant metam sodium generates 288 lb/acre of methyl ITC, which is 70.2 times greater than that produced by turnip green manure (AMVAC Chemical Corp., 2008). Therefore, because of low ITC production, crucifer cover crops alone did not provide effective, season-long weed control, and even VIF mulch failed to improve weed control.

Total weed management cost associated with the methyl bromide treatment was an estimated $1067.10/acre, which included the costs of fumigant, mulch, and hand-weeding (Table 3). Despite lower hand-weeding cost in the methyl bromide treatment, the total weed management cost in 'Seventop' turnip, untreated control, 'Pacific Gold' oriental mustard, and Caliente mustard under LDPE treatment was $17.82/acre, $53.91/acre, $61.93/acre, and $111.33/acre less, respectively, than the methyl bromide treatment. The relatively higher weed management cost of methyl bromide is mainly attributed to its expense ($3.65/lb of methyl bromide:chloropicrin mixture), which is expected to further increase in the future as the available supply diminishes. Therefore, crucifer cover crop or untreated control under LDPE mulch followed by hand-weeding could be an equivalent or more cost-effective weed management option in plasticulture tomato than fumigation with methyl bromide. In contrast to LDPE mulch, total weed management was $216.83/acre to $310.34/acre more expensive than methyl bromide when using a VIF mulch with untreated control or cover crops and was mainly attributed to increased VIF mulch expenses, which are $328.16/acre more expensive than LDPE mulch.

MARKETABLE YIELD, HARVESTING AND MARKETING COSTS, AND GROSS RETURNS. There was no significant cover crop or mulch effects or cover crop by mulch interaction in grade-wise and total marketable tomato fruit yield ($P \geq 0.1440$). Therefore, yield data were averaged overall treatments with a total marketable tomato fruit yield of 50,528 lb/acre (data not shown). Plots were hand-weeded throughout the season, which eliminated competition from weeds and in turn yield loss in all treatment combinations irrespective of cover crop/fumigant treatment or plastic mulch type. Of average total marketable yield, jumbo, extralarge, large, medium, and small-grade fruits contributed 60.2%, 9.9%, 25.8%, 3.1%, and 1.0%, respectively (data not shown). Because a fixed charge of $4.98 was used for harvesting, grading and packing, and marketing a 25-lb box of tomatoes, the harvesting and marketing costs ($10,065.18/acre) were the same for all treatment combinations (data not shown). Similar to harvesting and marketing cost, gross returns ($21,040.43/acre) were similar among all treatment combinations regardless of mulch type or cover crop/fumigant (Table 4).

Net returns. Net returns were estimated by subtracting the total costs from gross returns and are shown in Table 4. Total costs were the sum of preharvest costs, weed management costs, and harvesting and marketing costs. The methyl bromide program resulted in total costs of $14,779.71/acre. Compared with methyl bromide, total cost was increased from $53.78/acre to 147.29/acre in the untreated control and cover crops with LDPE. Using VIF mulch further increased the total cost in the untreated control and cover crop treatments by $328.16/acre (mulch expense) over LDPE mulch. Net returns for the methyl bromide program were estimated at $6260.72/acre (Table 4). Net returns relative to methyl bromide were positive in all other treatments with LDPE mulch and were negative in all treatments with VIF mulch. There was a gain of $147/acre, $98/acre, $54/acre, and $54/acre in net return over methyl bromide in Caliente mustard, 'Pacific Gold' oriental mustard, 'Seventop' turnip, and the untreated control under LDPE, respectively. In the untreated control and cover crop treatments with VIF mulch, there was a loss of $181/acre or greater in net returns relative to methyl bromide. Loss of net returns relative to methyl bromide was highest ($274/acre) in the untreated control and 'Seventop' turnip under VIF mulch.

In summary, season-long hand-weeding can result in a net return in LDPE-mulched tomato production nearly equivalent to or greater than a standard methyl bromide program regardless of soil amendment with crucifer cover crops. However, hand-weeding labor cost in untreated control and cover crop treatments was 3.82 to 5.48 times greater, respectively, than the methyl bromide treatment. Similarly, Lanini and Strange (1994) concluded that it is profitable to grow bell pepper without herbicides, but hand-weeding costs are doubled in bell pepper (*Capsicum annuum*) compared with those in herbicide-treated plots. Therefore, before replacing methyl bromide with hand-weeding, it is important to consider the availability of labor during the tomato growing season and labor charges, which vary from area to area and season to season. Another important consideration before implementing any methyl bromide alternative is the level of pest infestation. The experimental site at Fayetteville was moderately infested with yellow nutsedge and johnsongrass. However, a high density of weeds, especially nutsedge species, requires intensive weeding (Bangarwa et al., 2008), which can further increase labor cost. Second, the experimental site had no history of serious soilborne insects, disease pathogens, or nematodes. In addition to weed control, the methyl bromide:chloropicrin mixture provides broad-spectrum control against a number of soilborne pests (Duniway, 2002). Because the ITCs released from crucifer cover crop incorporation

Table 4. Estimated total costs, gross returns, and net returns per acre associated with various weed control treatments in plasticulture tomato production.

Fumigant or cover crop	Plastic mulch[z]	Common preharvest costs ($/acre)[y]	Total weed management costs ($/acre)	Harvesting and marketing costs ($/acre)	Total costs ($/acre)[x]	Gross returns ($/acre)[w]	Net returns ($/acre)[v]	Net returns relative to methyl bromide ($/acre)[u]
Methyl bromide[t]	LDPE	3647.43	1067.10	10,065.18	14,779.71	21,040.43	6260.72	0
'Pacific Gold' mustard	LDPE	3611.47	1005.17	10,065.18	14,681.82	21,040.43	6358.61	+98
Caliente mustard[s]	LDPE	3611.47	955.77	10,065.18	14,632.42	21,040.43	6408.01	+147
'Seventop' turnip	LDPE	3611.47	1049.28	10,065.18	14,725.93	21,040.43	6314.49	+54
Untreated control	LDPE	3647.43	1013.19	10,065.18	14,725.80	21,040.43	6314.63	+54
'Pacific Gold' mustard	VIF	3611.47	1333.33	10,065.18	15,009.98	21,040.43	6030.45	–230
Caliente mustard[s]	VIF	3611.47	1283.93	10,065.18	14,960.58	21,040.43	6079.85	–181
'Seventop' turnip	VIF	3611.47	1377.44	10,065.18	15,054.09	21,040.43	5986.33	–274
Untreated control	VIF	3647.43	1341.35	10,065.18	15,053.96	21,040.43	5986.47	–274

[z]Plastic mulch, LDPE = low-density polyethylene mulch (black, 1.0 mil), VIF = virtually impermeable film mulch (black/white, 1.3 mil); 1 mil = 0.0254 mm.
[y]$1.00/acre = $2.4711/ha.
[x]Total costs include preharvest, weed management, and harvesting and marketing costs.
[w]Gross returns were calculated by multiplying the yield of each grade to respective price of that grade and by adding the returns from all grades in each treatment. Prices used for 25-lb (11.34 kg) box of various grades were: $11.25 for jumbo, $10.00 for extralarge, $9.00 for large, $8.15 for medium, and $7.50 for small-grade tomatoes.
[v]Net returns were calculated by subtracting the total costs from gross returns for each treatment.
[u]Net returns relative to methyl bromide of any treatment were calculated by subtracting the net returns of methyl bromide from the net returns of that treatment.
[t]Methyl bromide: chloropicrin (67:33) at 350 lb/acre (treated); 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$.
[s]Blend of brown mustard and white mustard (Santa Clara Seeds, Greenfield, CA).

in soil have shown activity against soilborne pests (Matthiessen and Shackleton, 2005), it would be beneficial to evaluate the technical and economical viability of crucifer cover crops in the presence of soilborne insects, pathogens, or nematodes.

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