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Efficacy and Economics of Herbicide Programs Compared to Methyl Bromide for Weed Control in Polyethylene-Mulched Tomato

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Methyl bromide (MeBr), a widely used soil fumigant in tomato production, has been banned for ordinary agricultural uses. In the absence of MeBr, a viable alternative is imperative for weed control and prevention of economic loss in tomato production. A field study was conducted in the summers of 2010 and 2011 at Fayetteville, AR, to compare the efficacy and economics of herbicide programs consisting of pre-transplant followed by (fb) post-transplant herbicides in low-density polyethylene (LDPE) mulched tomato. Pre-transplant imazosulfuron at 0.112, 0.224, and 0.336 kg ai ha^{-1} and *S*-metolachlor at 1.6 kg ai ha^{-1} were fb a post-transplant mixture of trifloxysulfuron plus halosulfuron at 0.008 and 0.027 kg ai ha^{-1} at 4 wk after transplant (WATP). The standard MeBr treatment (2:1 mixture of MeBr plus chloropicrin at 390 kg ai ha^{-1}), weed-free (hand weeding) control, and nontreated weedy check were used for comparison. Pre-transplant *S*-metolachlor fb post-transplant herbicides controlled Palmer amaranth $\geq$ 89%, large crabgrass $\geq$ 88%, and yellow nutsedge $\geq$ 90%, which was comparable to the control with MeBr. Tomato recovered the injury ($\leq$ 19% at 6 WATP) from post-transplant herbicides in the later weeks. *S*-metolachlor–containing herbicide programs yielded marketable tomato fruit comparable to the yield with MeBr. Economic evaluation of the herbicide programs demonstrated a net return of \$3,758.50 ha^{-1} from the *S*-metolachlor–containing herbicide program in LDPE-mulched tomato. Likewise, this herbicide program showed minimum loss of $\leq$ \$671.61 ha^{-1} in net return relative to MeBr. In conclusion, a herbicide program consisting of pre-transplant *S*-metolachlor fb post-transplant trifloxysulfuron plus halosulfuron is a viable alternative to MeBr for weed control and marketable yield in LDPE-mulched tomato production.

Nomenclature: Halosulfuron; imazosulfuron; methyl bromide (MeBr); *S*-metolachlor; trifloxysulfuron; large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; tomato, *Solanum lycopersicum* L. 'Amelia'.

Key words: Economics of plasticulture tomato, herbicide programs, low-density polyethylene (LDPE) mulch, methyl bromide alternative, pre-transplant followed by (fb) post-transplant herbicide.

Methyl bromide (MeBr), un fumigante ampliamente usado en la producción de tomate, ha sido prohibido para usos agrícolas ordinarios. En ausencia de MeBr, una alternativa viable es imperativa para el control de malezas y la prevención de pérdidas económicas en la producción de tomate. En Fayetteville, AR, durante los veranos de 2010 y 2011, se realizó un estudio de campo para comparar la eficacia y la economía de programas de herbicidas para tomate que consistieron de herbicidas pre-trasplante seguidos de (fb) herbicidas pos-trasplante en coberturas plásticas de polyethylene de baja densidad (LDPE). Imazosulfuron en pre-trasplante a 0.112, 0.224, y 0.336 kg ai ha^{-1} y *S*-metolachlor a 1.6 kg ai ha^{-1} fueron fb una mezcla pos-trasplante de trifloxysulfuron más halosulfuron a 0.008 y 0.027 kg ai ha^{-1} a 4 semanas después del trasplante (WATP). Para fines de comparación, se usaron el tratamiento estándar de MeBr (mezcla 2:1 de MeBr más chloropicrin a 390 kg ai ha^{-1}), un testigo limpio de malezas (deshierba manual), y un testigo enmalezado sin tratamiento. *S*-metolachlor en pre-trasplante fb herbicidas pos-trasplante controlaron *Amaranthus palmeri* $\geq$89%, *Digitaria sanguinalis* $\geq$88%, y *Cyperus esculentus* $\geq$90%, lo que fue comparable al control con MeBr. El tomate se recuperó del daño ($\leq$19% a 6 WATP) causado por los herbicidas pos-trasplante en las semanas siguientes. Los programas de herbicidas que contenían *S*-metolachlor tuvieron rendimientos de tomate comercializable comparables al rendimiento con MeBr. La evaluación económica de los programas de herbicidas demostraron una ganancia neta de \$3,758.50 ha^{-1} para los programas que contenían *S*-metolachlor en tomate con cobertura plástica LDPE. De la misma manera, este programa de herbicidas mostró la pérdida mínima $\leq$\$671.61 en ganancia relativa a MeBr. En conclusión, un programa de herbicidas que consista de *S*-metolachlor en pre-trasplante fb trifloxysulfuron más halosulfuron en pos-trasplante es una alternativa viable al MeBr para el control de malezas y el rendimiento comercializable en la producción de tomate con cobertura plástica LDPE.

Tomato has considerable importance for commercial vegetable production in the United States. At present, with the advancement in vegetable production technology, plasticulture production is popular among commercial producers. Use of plastic mulch is advantageous for early maturity, higher yield, and superior fruit quality (Sanders et al. 1996). However, weeds are a major constraint for optimal yield plasticulture tomato production. Nutsedge species are the most problematic weed because they can penetrate through the polyethylene mulch and interfere with the main crop. In addition, other weed species emerge from transplant holes and splits on the polyethylene mulch, interfere with the crop, and reduce yield. Palmer amaranth and large crabgrass are problematic weeds in the southeastern United States (Webster

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2006) and are serious pests in plasticulture tomato production.

Palmer amaranth grows horizontally and vertically, with rapid height increase and canopy formation (Norsworthy et al. 2008). In plasticulture system, Palmer amaranth can grow to a height of more than 2 m and shade tomato plants, reducing fruit number and size (Garvey et al. 2012). Once large crabgrass reaches a height of 8 to 10 cm, it begins to form tillers and adventitious roots (Monks and Schultheis 1998). After tiller and adventitious root formation, large crabgrass management becomes difficult, and yield loss of the competing crop is prominent (Monks and Schultheis 1998). Yellow nutsedge is designated as a noxious weed in 10 states; meanwhile, it is considered a serious weed throughout the United States (Anderson 1999). Nutsedge infestation has been reported to cause yield losses from 30 to 89% in vegetable production (Morales-Payan et al. 1997). In polyethylene-mulched tomato production, yellow nutsedge is considered more problematic because it penetrates and emerges through the mulch (Henson and Little 1969; Webster 2005) and degrades the durability of mulch. Therefore, yellow nutsedge infestation is a serious concern for growers who want to use polyethylene mulch for multiple growing seasons with a single application (Morales-Payen et al. 1997; Santos et al. 1997).

In tomato production, weed management is a primary practice and often accounts for a significant portion of the total operating cost. In the past years, tomato growers heavily relied on MeBr for effective management of nutsedge species as well as other weeds common in tomato fields (Locascio et al. 1997). However, the Montreal Protocol and U.S. Clean Air Act mandated a ban on production and ordinary agricultural uses (except for use under critical-use exemption) of MeBr since January 2005. As a result of the ban on MeBr production, there are limited options for weed control in plasticulture tomato. Because of the polyethylene mulch on top of the bed and drip tape underneath the polyethylene mulch, mechanical weeding (such as tillage, hoeing, flaming) is not a practical option for weed management. Likewise, hand weeding might not be a feasible option for large-scale commercial production because of labor unavailability and higher cost for weed control at severe weed infestation (Strange et al. 2000). Weed control methods using cover crops, such as glucosinolate-producing crops, were also ineffective in controlling Palmer amaranth, large crabgrass, and nutsedge species in plasticulture tomato production (Bangarwa 2010; Norsworthy et al. 2007). Hence, herbicide-based weed management is a potential alternative to MeBr compared to manual, mechanical, or cultural weed control in plasticulture tomato production.

S-metolachlor applied pre-transplant controlled large crabgrass, pitted morningglory (*Ipomoea lacunosa* L.), eclipta (*Eclipta prostrata* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in plasticulture tomato (Adcock et al. 2008). Bollman and Sprague (2007) reported 94% control of pigweed (*Amaranthus*) spp. with *S*-metolachlor applied at 1.4 kg ha^{-1}. In a study with drip-applied *S*-metolachlor in tomato, Santos et al. (2008) reported that extra-large grade and total yields were increased by 75 and 57%, respectively, with an optimum control of broadleaf weeds. The sulfonylurea herbicide imazosulfuron controls annual and perennial broadleaf weeds and sedges (Dittmar et al. 2012; Riar and Norsworthy 2011). In a previous study, imazosulfuron has shown potential for suppressing yellow nutsedge, common lambsquarters, and pigweed spp. in potato (Boydston and Felix 2008). Therefore, imazosulfuron is being evaluated for possible registration on solanaceous crops for weed control with a major focus on nutsedge species.

Trifloxysulfuron controls various weeds including nutsedge spp., pigweed spp., and annual grasses (Branson et al. 2005). Bangarwa et al. (2009) reported yellow nutsedge, large crabgrass, and Palmer amaranth control in plasticulture tomato from post-transplant trifloxysulfuron. Similarly, trifloxysulfuron controlled yellow nutsedge in a greenhouse study, and it reduced yellow nutsedge density 13-fold compared to a nontreated control in a field study (Dittmar et al. 2012). Halosulfuron can be applied pre- or post-transplant for weed control in several vegetable crops (McElroy et al. 2004). Based on the halosulfuron rate required to reduce yellow nutsedge dry weight by 90% (GR_{90}), Adock et al. (2008) reported greater activity from post-transplant compared to pre-transplant halosulfuron. Bangarwa et al. (2009) also reported good control of yellow nutsedge from post-transplant halosulfuron in plasticulture tomato.

In previous studies, pre-transplant *S*-metolachlor or imazosulfuron and post-transplant trifloxysulfuron or halosulfuron have shown weed control potential in plasticulture tomato production (Bangarwa 2010). However, when applied alone, none of these pre-transplant or post-transplant herbicides were comparable to MeBr for weed control. At present, integrating pre-transplant and post-transplant herbicides is a more relevant alternative to MeBr for effective weed management in tomato production. Dittmar et al. (2012) emphasized the need for herbicide programs consisting of pre-transplant followed by (fb) post-transplant herbicides as an important tool for effective management of yellow nutsedge. Bangarwa (2010) also suggested that applying pre-transplant fb post-transplant herbicides could be a potential MeBr alternative for weed control in plasticulture tomato.

Success of a weed management program is related not only to weed control effectiveness but also to economic soundness. Therefore, while evaluating MeBr alternatives for weed control, it is important to determine the economic feasibility of proposed programs. Economic evaluation could be a critical tool for partial budget analysis in commercial production (Rainey 2010). Knowledge on the economics of available MeBr alternatives for weed control helps growers to incorporate the most economically sound weed management program in their production system. Previously, Sydorovych et al. (2008) evaluated the economics of soil fumigants as MeBr alternatives for tomato and strawberry (*Fragaria ananassa* L.) production in a polyethylene-mulched system. Similarly, Bangarwa et al. (2010) evaluated the economic returns from crucifer cover crops compared to MeBr in polyethylene-mulched tomato production. However, there is no published record on the economics of herbicide programs consisting of pre-transplant fb post-transplant herbicides as MeBr alternatives for weed control in plasticulture tomato

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production. Therefore, the primary objective of this research is to evaluate effectiveness and economics of pre-transplant fb post-transplant herbicides program compared to standard MeBr application for Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched tomato production system.

Materials and Methods

A field study was conducted to evaluate pre-transplant fb post-transplant herbicides for weed control in polyethylene-mulched (black, embossed, 1.0 mil thick, Polygro LLC, Tampa, FL, 33655) tomato production. The study was conducted at the Agricultural Research and Extension Center at the University of Arkansas, Fayetteville, AR, in the summers of 2010 and 2011. In 2010, the soil type at the study site was a Razort silt loam (fine–loamy, mixed, active, mesic Mollic Hapludalfs) with pH of 6.3 and organic matter content of 1.8%. In 2011, the study was conducted on a Captina silt loam (fine–silty, siliceous, active, mesic Typic Fragiudults) with pH of 6.1 and organic matter of 1.8% (U.S. Department of Agriculture [USDA] Web Soil Survey, 2012). The study fields were tilled in early April and in early May to clean, loosen, and aerate the soil. In order to evaluate uniform plant populations, Palmer amaranth and large crabgrass seed and yellow nutsedge tubers (Azlin Seed Company, 112 Lilac Drive, Leland, MS 38756) were broadcast and incorporated into the study field. Raised beds (0.2 m tall and 0.75 m wide at the top) were formed, and plots were laid out for treatment application.

The study was designed as a randomized complete block with four replications. Treatments consisted of pre-transplant imazosulfuron (75DG; Valent USA Co., Walnut Creek, CA) at 0.112, 0.224, and 0.336 kg ha^{-1} and *S*-metolachlor (Dual Magnum 7.62 EC; Syngenta Crop Protection, Greensboro, NC) at 1.60 kg ha^{-1}. In addition, a standard treatment of MeBr plus chloropicrin at 261 and 129 kg ha^{-1} (mixture of 67 and 33%), respectively, a weed-free control (hand weeded at 2, 4, 6, and 8 WATP) and a weedy check were included for the comparison. MeBr was injected into the raised bed with double knives attached to a tractor-mounted MeBr applicator and beds covered with LDPE mulch. Pre-transplant herbicide treatments were broadcast on top of the raised bed with the use of a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1}. After the treatment application, beds were covered with LDPE mulch and drip tape was laid underneath the LDPE mulch. LDPE mulch was used for the study because it is easy to handle (stretchable and less tearing), cost effective, and it has performed similarly to virtually impermeable film (VIF) mulch for weed control (Bangarwa 2010). Plots were separated by cutting LDPE mulch at end of each plot and covering the cut ends with soil. The final size of each plot was 4.5 m long and 0.75 m wide at the top of bed. After the treatment application, drip tape was attached to the irrigation system, and field was irrigated to incorporate and activate the pre-transplant herbicides.

At 1 wk after pre-transplant herbicides and MeBr application, holes were punched in the LDPE mulch for transplant establishment. At 3 d after punching transplanting holes, 'Amelia' tomato transplant (four- to six-leaf stage), produced from seed (Seedway LLC, Hall, NY) was transplanted in a single row at 0.6 m in-row spacing. Plots were regularly fertigated and managed with standard practices recommended for plasticulture tomato production (Holmes and Kemble 2010). Weeds emerging in the alleys between plastic-mulched beds were controlled all season by a hooded-sprayer application of *S*-metolachlor and paraquat. At 4 WATP, each pre-transplant herbicide was fb trifloxysulfuron (Envoke 75 DG, Syngenta Crop Protection, Greensboro, NC) at 0.008 kg ai ha^{-1} plus halosulfuron at 0.027 kg ai ha^{-1} (Sandea 75 DG; Gowan Co., Yuma, AZ) post-transplant over the top of tomato. Post-transplant treatments included 0.25% (v/v) nonionic surfactant (Induce; Helena Chemical Company, Memphis, TN). These herbicides were chosen because of their effectiveness against yellow nutsedge and purple nutsedge when applied separately in tomato (Bangarwa et al. 2010).

Parameters evaluated included crop injury, weed control, hand-weeding time, marketable fruit yield, and yellow nutsedge tuber density. Plots were rated visually for crop injury and weed control (Palmer amaranth, large crabgrass, and yellow nutsedge) at 2, 4, 6, and 8 WATP. Crop injury and weed control ratings were made on a 0 to 100% scale, where 0 = no crop injury or no weed control and 100 = complete death of crop or complete weed control. Weed-free plots were hand weeded biweekly, and hand-weeding times were recorded. Hand-weeding times from all the weeks were added and converted to hours per hectare to determine the total hand-weeding time for the season. Marketable tomato fruit was hand picked and graded manually into jumbo, extra large, large, medium, and small according to the USDA grades (USDA 1997). There were six and five harvests in 2010 and 2011, respectively, and fruit weight from each harvest was recorded for each grade. Yield from all the harvests were added to determine marketable tomato yield according to USDA grades and total yield. At the end of season, five soil core samples, each 0.1 m diam and 0.15 m deep, were taken from each tomato plot. Core samples were washed to obtain yellow nutsedge tubers. Number of yellow nutsedge tubers for each plot was based on firm tubers collected from core sample.

PROC GLM procedure was used in Statistical Analysis Software (version 9.2, SAS Institute Inc, Campus Drive, Cary, NC 27513) for data analysis. Treatment-by-year interaction was nonsignificant for weed control, yellow nutsedge tubers, and tomato yield; therefore, data from 2 yr were averaged for analysis. Before analysis, data were tested for normality with the use of PROC UNIVARIATE and transformed upon requirement. Weed control, yellow nutsedge tuber, and tomato yield data were arcsine, square root, and $\log_{10}$ transformed, respectively, and analyzed. Means were separated by Fisher's protected LSD ($P \leq 0.05$).

Economics of each herbicide program relative to the standard MeBr treatment and weed-free control was evaluated for fresh-market tomato production in the LDPE-mulched system. Differential costs of inputs versus returns were calculated for each herbicide program. The method used for economic analysis was similar to previous economic studies conducted by Bangarwa et al. (2010) and Sydorovych et al.

Table 1. Effect of pre-transplant imazosulfuron and *S*-metolachlor followed by (fb) post-transplant trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on Palmer amaranth and large crabgrass control in tomato, averaged over 2010 and 2011.

			Weed control[bc]					
			Palmer amaranth			Large crabgrass		
Treatment	Rate	Timing	4 WATP	6 WATP	8 WATP	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}		%					
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.112 0.008 0.027	PRE POST	40 c	43 b	14 bc	59 c	67 c	53 c
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.224 0.008 0.027	PRE POST	46 c	47 b	8 c	63 bc	73 bc	64 bc
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.336 0.008 0.027	PRE POST	56 b	55 b	19 b	72 b	82 b	71 b
S-metolachlor fb trifloxysulfuron + halosulfuron	1.6 0.008 0.027	PRE POST	95 a	91 a	89 a	90 a	94 a	88 a
Methyl bromide + chloropicrin	261 129	PRE	97 a	96 a	94 a	95 a	95 a	91 a

[a] Pre-transplant herbicides applied at 1 wk before transplanting, and post-transplant treatment applied at 4 wk after transplanting tomato.

[b] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on arcsine-transformed data.

[c] Palmer amaranth and large crabgrass control presented at 4, 6, and 8 wk after transplanting tomato.

(2008). Preharvest cost, weed management cost, and harvesting and marketing cost accounted for the total cost of a particular treatment. Preharvest cost included all inputs (except weed management) required for tomato production. Preharvest cost was calculated based on the planning budgets developed for tomato production by the Department of Agricultural Economics, Mississippi State University (Hood et al. 2011), and appropriate adjustments were made in the budget according to the input used in the current study. Fertilizer cost was estimated based on the drip-applied fertilizer and added to the cost of lime. Machinery cost was based on implements and tractors used for raised-bed formation, laying LDPE mulch, and spraying pesticides. Labor cost was estimated by summation of the cost for hand and operator labor.

Input prices were based on the price for vegetable production in 2011. Labor cost was calculated based on \$8.97 and \$11.59 hr^{-1} for hand labor and machine operator labor. The fuel cost for machinery was calculated based on \$0.9 L^{-1}. The interest on operating capital was calculated based on annual interest rate of 6% and calculated for 6 mo for tomato production. Weed management cost accounted for the cost of LDPE mulch and herbicides for each herbicide program; cost of LDPE mulch and MeBr for the MeBr treatment; cost of LDPE mulch and hand-weeding labor for the weed-free control; and cost of LDPE mulch for the nontreated control. Harvesting and marketing cost consisted of harvesting labor, material (buckets and packing boxes), grading and packing labor, hauling, and transportation to the terminal market. For calculation of harvesting and marketing cost a fixed charge of \$5.36 per 11.36-kg box of tomato was estimated.

Gross return for tomato was calculated by adding returns from each grade yield. Returns for each grade of tomato were calculated based on market price of \$15.6, 14.1, 13.1, 12.7, and 12.0 per box of jumbo, extra large, large, medium, and small grades of tomato, respectively, obtained from the Dallas Terminal Market report for August 2011 (USDA Agriculture Marketing Services 2011). As price per box for small grade of tomato was not listed in the Dallas Terminal Market report, price for this grade were assumed to be \$12.0 per box for calculating the returns. Net returns were calculated for each treatment by subtracting total cost from gross return. In addition, net return relative to the MeBr treatment was calculated for each treatment by subtracting net return of MeBr from the respective treatment.

Results and Discussion

There was no treatment-by-year interaction for Palmer amaranth, large crabgrass, and yellow nutsedge control. Similarly, the treatment-by-year interaction was nonsignificant for yellow nutsedge tuber density, crop injury, and marketable yield in tomato. Therefore, data were averaged over years and presented accordingly. LSD comparison for weed control and yield are based on arcsine and $\log_{10}$ transformed data, respectively. However, untransformed numeric means are presented for results and discussion.

Palmer Amaranth Control. Pre-transplant treatments differed ($\alpha = 0.05$) for Palmer amaranth control in LDPE-mulched tomato. Palmer amaranth control from imazosulfuron pre-transplant at 0.112, 0.224, and 0.336 kg ha^{-1} were $\leq$ 56% which were lesser comparable to control with MeBr at 4 WATP (Table 1). The highest rate of imazosulfuron controlled 56% of the Palmer amaranth population compared to the nontreated control at 4 WATP. In previous studies, there are mixed results on the activity of imazosulfuron PRE for broadleaf weed control in bare soil conditions. Riar and Norsworthy (2011) reported 29 to 79% control of hemp sesbania (*Sesbania exaltata* Raf.) with imazosulfuron PRE at 0.224 to 0.336 kg ha^{-1}; whereas Godara et al. (2012) reported 86 to 89% hemp sesbania control with imazosulfuron PRE at $\geq$ 0.168 kg ha^{-1} in drill-seeded rice (*Oryza sativa* L.). Soil temperature and pH have been reported to influence the activity of imazosulfuron (Moricca et al. 2001).

After the post-transplant trifloxysulfuron plus halosulfuron, Palmer amaranth growth ceased temporarily (for about 1 to 2 wk), but control did not increase significantly (Table 1). This might be attributed to the Palmer amaranth size at post-transplant herbicide application. Palmer amaranth plants ranged from 15 to 30 cm tall at post-transplant herbicide application, so the herbicide mixtures applied at 4 WATP were not effective against Palmer amaranth. Singh and Singh (2004) reported greater redroot pigweed control from trifloxysulfuron POST at the four-leaf than at the six-leaf stage. Norsworthy and Meister (2007) found that post-transplant halosulfuron was ineffective against Palmer amaranth regardless of plant size, and halosulfuron applied post-transplant to 7.5- and 15-cm-tall Palmer amaranth provided only 28 and 10% control, respectively. In current study, imazosulfuron-containing herbicide programs controlled $\leq$ 19% of Palmer amaranth at 8 WATP, whereas control with MeBr was 94%. Bangarwa et al. (2010) reported that post-transplant trifloxysulfuron at 0.008 kg ha^{-1} or halosulfuron at 0.027 kg ha^{-1} applied at 4 WATP controlled Palmer amaranth $\leq$ 55 and $\leq$ 37%, respectively, at 8 WATP in LDPE-mulched tomato. In the present study, trifloxysulfuron and halosulfuron were tank-mixed; however, there was no apparent additive effect of the post-transplant herbicide mixture for Palmer amaranth control.

S-metolachlor applied pre-transplant at 1.6 kg ha^{-1} was more effective than imazosulfuron and controlled Palmer amaranth 95%, comparable to MeBr at 4 WATP (Table 1). Bangarwa et al. (2010) reported higher control of Palmer amaranth from pre-transplant *S*-metolachlor than from pre-transplant halosulfuron. Likewise, *S*-metolachlor pre-transplant at 1.14 kg ha^{-1} was most effective in maintaining low broadleaf weed density (2 plants m^{-2}) compared to weed density ($>$ 7 plants m^{-2}) with napromide, pebulate, and trifluralin in direct-seeded tomato (Santos et al. 2008). Application of post-transplant herbicides after *S*-metolachlor pre-transplant maintained Palmer amaranth control ($\geq$ 89%) through 8 WATP. The effective Palmer amaranth control is because of the pre-transplant efficacy of *S*-metolachlor early in the season fb the post-transplant control of newly emerged Palmer amaranth by trifloxysulfuron plus halosulfuron.

Large Crabgrass Control. Large crabgrass control differed with the increased rate of pre-transplant imazosulfuron in LDPE-mulched tomato at 4 WATP (Table 1). However, imazosulfuron applied pre-transplant at 0.112, 0.224, and 0.336 kg ha^{-1} did not control large crabgrass effectively in LDPE-mulched tomato production. At 4 WATP, large crabgrass control from the highest rate of imazosulfuron was 72%, which was lower than the 95% control with MeBr. In a previous study, imazosulfuron applied pre-transplant fb clomazone preflood in drill-seeded rice showed variable control (51 to 100%) of grass weeds at 2 wk after the preflood application (Riar and Norsworthy 2011).

After the post-transplant application of trifloxysulfuron plus halosulfuron, large crabgrass control percentages increased numerically at 6 WATP over the control at 4 WATP; however, large crabgrass control in pre-transplant imazosulfuron plots was still not comparable to control with MeBr (Table 1). At the last rating, imazosulfuron-containing herbicide programs did not control large crabgrass effectively, and control ($<$ 71%) was not comparable with MeBr (91%). Lower control of large crabgrass with post-transplant herbicides is because the applications were made to well-established large crabgrass plants with tillers and adventitious roots. Chernicky et al. (1984) reported better control of large crabgrass at early rather than later growth stages. Hartzler and Foy (1983) observed poor large crabgrass control with post-transplant herbicides applied to 8- to 10-cm-tall large crabgrass with adventitious roots in the nodes. In another study, halosulfuron applied post-transplant at 0.035 kg ha^{-1} to two- to three-leaf (2.5 to 5 cm) large crabgrass provided little or no reduction on large crabgrass dry weight (Kammler et al. 2010).

S-metolachlor applied pre-transplant controlled large crabgrass comparable to the control with MeBr in LDPE-mulched tomato (Table 1). At 4 WATP, large crabgrass control was 90% from pre-transplant *S*-metolachlor, a control level similar to that with MeBr. This result is in agreement with findings of Bangarwa et al. (2009), who reported 85% large crabgrass control with pre-transplant *S*-metolachlor at 1.6 kg ha^{-1} in plasticulture tomato. Likewise, post-transplant trifloxysulfuron plus halosulfuron maintained large crabgrass control in pre-transplant *S*-metolachlor plots equivalent to the control in MeBr plots at 6 and 8 WATP. At 8 WATP, the *S*-metolachlor–containing herbicide program controlled large crabgrass 88%, similar to large crabgrass control (91%) from MeBr.

Yellow Nutsedge Control. Pre-transplant imazosulfuron did not control yellow nutsedge effectively in LDPE-mulched tomato. Analysis of variance illustrated the difference in yellow nutsedge control with the various rates of pre-transplant imazosulfuron; however, imazosulfuron treatments did not control yellow nutsedge comparable to MeBr (Table 2). Pre-transplant imazosulfuron even at the highest rate (0.336 kg ha^{-1}) controlled yellow nutsedge only 65% at 4 WATP, and control was lower than with MeBr. In another study, pre-transplant imazosulfuron at 0.224 and 0.336 kg ha^{-1} provided variable yellow nutsedge control (22 to 99%) in drill-seeded rice (Riar and Norsworthy 2011). After the post-transplant application of trifloxysulfuron plus halosulfuron, yellow nutsedge control increased in the tomato plots treated with pre-transplant herbicides. At 8 WATP, yellow nutsedge control from the imazosulfuron fb trifloxysulfuron plus halosulfuron herbicide program was $\leq$ 77%, which was 14% lower control than control from MeBr.

Yellow nutsedge control with pre-transplant *S*-metolachlor was about 10% lower than control from MeBr at 4 WATP (Table 2). In another study, yellow nutsedge control was 67% with the pre-transplant *S*-metolachlor in plasticulture tomato (Bangarwa et al. 2009). After post-transplant application of

Table 2. Effect of pre-transplant imazosulfuron and *S*-metolachlor followed by (fb) post-transplant trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on yellow nutsedge control and tuber density in tomato, averaged over 2010 and 2011.

Treatment	Rate	Timing[a]	Yellow nutsedge control[bc] 4 WATP	6 WATP	8 WATP	Yellow nutsedge tuber density[de]
	kg ai ha^{-1}		%			tubers m^{-2}
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.112 0.008 0.027	PRE POST	45 e	61 d	66 c	60 b
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.224 0.008 0.027	PRE POST	52 d	67 c	71 c	49 bc
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.336 0.008 0.027	PRE POST	65 c	75 b	77 b	43 bc
S-metolachlor fb trifloxysulfuron + halosulfuron	1.6 0.008 0.027	PRE POST	84 b	92 a	90 a	41 bc
Methyl bromide + chloropicrin	261 129	PRE	93 a	92 a	91 a	29 c
Weedy check	–	–	–	–	–	177 a

[a] Pre-transplant herbicides applied at 1 wk before transplanting, and post-transplant treatment applied at 4 wk after transplanting tomato.

[b] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on arcsine transformed data.

[c] Yellow nutsedge control presented at 4, 6, and 8 wk after transplanting tomato.

[d] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on square root transformation.

[e] Tuber density (tubers m^{-2}) determined from five soil cores (0.1-m diameter by 0.15-m depth) pulled from each tomato plot.

trifloxysulfuron plus halosulfuron, yellow nutsedge control increased in the pre-transplant *S*-metolachlor treatment, and control was comparable to MeBr. At the end of season, yellow nutsedge control was 90% from the *S*-metolachlor–containing herbicide program. Adock et al. (2008) also reported that pre-transplant *S*-metolachlor fb post-transplant halosulfuron was an effective treatment for yellow nutsedge control in polyethylene-mulched tomato. Furthermore, pre-transplant *S*-metolachlor fb post-transplant halosulfuron reduced 44 and 29% of yellow nutsedge biomass and plastic punctures, respectively, in polyethylene-mulched tomato (Adock et al. 2008).

Yellow Nutsedge Tuber Density. Yellow nutsedge tuber density did not differ among herbicide programs and MeBr treatment in LDPE-mulched tomato (Table 2). Later in the season, imazosulfuron-treated plots were covered densely with Palmer amaranth plants that were greater than 2 m tall with widespread branches and dense foliage. Because of the height and wider canopy, Palmer amaranth overtook yellow nutsedge plants reducing plant stand, growth, and tuber production in plots treated with imazosulfuron herbicide programs. Patterson (1982) reported a decrease from 33 to 10 shoots and 75 to 9 tubers when yellow nutsedge was transferred from full light condition (at 30 d after planting) to 85% shade in the later season. Similarly, Santos et al. (1997) reported a linear relationship between shading and reduction in shoot and tuber dry weight of yellow nutsedge.

In plots treated with the *S*-metolachlor–containing herbicide program, yellow nutsedge tubers were fewer because of the effective control of yellow nutsedge (Table 2). At the end of the season, pre-transplant *S*-metolachlor fb post-transplant trifloxysulfuron plus halosulfuron reduced yellow nutsedge tuber density by 77% compared to the tuber density in the weedy check (Table 2). Kelly and Renner (2002) have reported > 80% reduction in yellow nutsedge tuber density with post-transplant halosulfuron at 0.035 kg ha^{-1}.

Tomato Injury. Among pre-transplant treatments, only imazosulfuron at 0.336 kg ha^{-1} injured tomato. At 2 WATP, imazosulfuron at the highest rate injured tomato up to 11% (data not shown), but injury was transient and the crop recovered. Pre-transplant *S*-metolachlor at 1.6 kg ha^{-1} was safe for LDPE-mulched tomato at all evaluations. After post-transplant application of trifloxysulfuron plus halosulfuron, tomato injury was 13 to 17% at 6 WATP. However, the crop recovered, and by 8 WATP, tomato injury was $\leq$ 8% from all herbicide programs. In a previous study, tomato injury was 6% at 6 WATP with post-transplant trifloxysulfuron or halosulfuron in the plasticulture system (Bangarwa et al. 2009). In this study, greater injury to tomato was likely because of trifloxysulfuron and halosulfuron application in a mixture.

Tomato Yield. Early-season tomato yield was lower with imazosulfuron-containing herbicide programs compared to MeBr (Table 3). In contrast, early-season yield with *S*-metolachlor herbicide program was equivalent to the MeBr treatment. Although there was tomato injury after the post-transplant application of trifloxysulfuron plus halosulfuron, injury did not affect early-season tomato yield in *S*-metolachlor–containing herbicide program. The early-season harvest contributed about 23% for the total marketable yield for the *S*-metolachlor–containing program.

Marketable tomato yield was lower with pre-transplant imazosulfuron fb post-transplant herbicide programs com-

Table 3. Effect of pre-transplant imazosulfuron and *S*-metolachlor followed by (fb) post-transplant trifloxysulfuron plus halosulfuron, and methyl bromide plus chloropicrin on marketable tomato yield, averaged over 2010 and 2011.[a]

Treatment	Rate	Timing[b]	Early season yield[c]	Yield according to grade and total yield[d]					
				Jumbo	Extra large	Large	Medium	Small	Total yield[e]
	kg ai ha^{-1}		ton ha^{-1}						
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.112 0.008 0.027	PRE POST	2.2 d	4.4 b	2.3 b	2.0 c	1.6 b	1.6 b	11.9 b
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.224 0.008 0.027	PRE POST	2.6 bcd	2.3 b	1.2 b	1.2 c	1.6 b	1.7 b	8.1 b
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.336 0.008 0.027	PRE POST	2.2 d	4.6 b	2.5 b	2.4 bc	1.8 b	1.7 b	13.0 b
S-metolachlor fb trifloxysulfuron + halosulfuron	1.6 0.008 0.027	PRE POST	5.2 ab	8.6 a	4.4 a	3.8 ab	3.1 a	3.2 a	23.1 a
Methyl bromide + chloropicrin	261 129	PRE	5.1 abc	11.8 a	5.9 a	5.0 a	4.6 a	3.8 a	31.1 a
Weed free control	–	–	5.3 a	12.5 a	6.2 a	5.2 a	3.9 a	3.8 a	31.6 a
Weedy check	–	–	2.4 cd	2.9 b	1.6 b	1.7 c	1.5 b	2.0 b	9.8 b

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$. Mean separation based on Log_{10} transformation.

[b] Pre-transplant herbicides applied at 1 wk before transplanting, and post-transplant herbicides applied at 4 wk after transplanting tomato.

[c] Early-season yield determined by summation of first and second harvests from 2010 and 2011, respectively.

[d] Marketable tomato yield according to the U.S. Department of Agriculture A grade and the total yield.

[e] Total yield determined by summation of all tomato grades yield from six and five harvests in 2010 and 2011, respectively.

pared to the yield with MeBr treatment (Table 3). Moreover, marketable tomato yield did not increase with increased rate of imazosulfuron because weed control was similar in the plots treated with different imazosulfuron rates. In a previous study, Dittmar et al. (2012) reported that yield did not increase significantly in relation to increased rate of imazosulfuron when applied post-transplant in watermelon (*Citrullus lanatus* Thunb.).

Herbicide programs consisting of pre-transplant *S*-metolachlor fb post-transplant trifloxysulfuron plus halosulfuron yielded total marketable tomato fruit comparable to that treated with MeBr. There was a variation in number of Palmer amaranth plant within *S*-metolachlor herbicide program and MeBr treatment. In the small-plot field study, a difference of a single Palmer amaranth per plot could cause a considerable difference in yield. Meyers et al. (2010) reported that season-long Palmer amaranth interference at 0.5 plants m^{-1} of crop row reduced yield 36% in sweet potato. Likewise, redroot pigweed at one or two plants m^{-1} row reduced bell pepper yield 7% in one year; whereas 38 and 68% with one or two plants m^{-1} row, respectively, in other year (Fu and Ashley 2006). Among the different grades of tomato fruit, jumbo-grade fruit yield contributed the highest percentage (38%) of the total marketable yield in the *S*-metolachlor–treated plots (Table 3). Likewise, extra-large–, large-, medium-, and small-grade tomato yields contributed 19, 17, 13, and 13% of the total marketable tomato yield. The total marketable tomato yield (23.1 ton ha^{-1}) in *S*-metolachlor–treated plots was 2.3 times greater than yield (9.8 ton ha^{-1}) in weedy check. Likewise, tomato treated with post-transplant trifloxysulfuron at 0.007 kg ha^{-1} or halosulfuron at 0.04 kg ha^{-1} yielded total marketable fruit 98% greater than nontreated weedy check plots in a study conducted in North Carolina (Jennings 2010).

Economic Evaluation

Preharvest Cost. Costs of all the variable inputs required for tomato production, except for weed control costs (which are presented separately), were included in the preharvest cost (Table 4). Preharvest cost for the LDPE production system was \$11,349.65 ha^{-1}. Total preharvest variable cost was estimated as \$9,895.77 ha^{-1} and total preharvest fixed cost was estimated at \$1,453.88 ha^{-1}; these costs were the same for all treatments.

Weed Management Cost. Weed management cost is the summation of various inputs that are directly related to weed control and are presented accordingly for tomato production (Table 5). For herbicide programs, weed management cost is the sum of LDPE mulch and herbicides applied for weed control. The cost of LDPE mulch, \$720.25 ha^{-1}, is a common cost for all treatments irrespective of the herbicide program. The total weed management cost for the herbicide program containing pre-transplant imazosulfuron fb post-transplant trifloxysulfuron plus halosulfuron ranged from \$831.65 to 877.91 ha^{-1}. Likewise, weed management cost for the *S*-metolachlor–containing herbicide program was \$858.94 ha^{-1}. MeBr cost was highest among treatments, with total weed management cost of \$5,782.45 ha^{-1}. The cost for the MeBr treatment was \$5,062.20 ha^{-1} (MeBr cost \$12.98 kg^{-1}). In the weed-free control, hand-weeding time was recorded as 225 hr ha^{-1} and labor cost (labor charge \$8.97 hr^{-1}) was \$2,018.87 ha^{-1}. Labor cost was added to the cost of

Table 4. Estimated preharvest cost based on input for tomato production in low-density polyethylene–mulched system.[a]

Production inputs[b]	Cost
	$ ha^{-1}
Variable costs	
Mulch cleanup	332.33
Lime and fertilizer	809.83
Machinery (raise bed, mulch laying, spraying pesticide)	262.50
Fuel (diesel)	197.84
Drip tape	435.00
Seed/transplant	1,220.15
Labor	
Hand labor (transplanting, fertigation, staking, tying, unallocated labor)	587.25
Operator labor (tractor, implement)	411.43
Irrigation	1,111.65
Insecticide	623.15
Fungicide	431.13
Herbicide for row middles	72.57
Stakes and string	2,913.60
Repair and maintenance	
Implements	182.40
Tractor	16.72
Interest on operating capital	288.22
Total preharvest variable cost (A)	9,895.77
Fixed costs	
Implements	339.47
Tractor	102.55
Irrigation setup	1,011.86
Total preharvest fixed cost (B)	1,453.88
Total preharvest cost (A + B)	11,349.65

[a] Preharvest cost includes all input cost except weed management and marketing and harvesting cost.

[b] Preharvest costs consist inputs required for plasticulture tomato and production input are adopted from traditional vegetables 2012 planning budgets developed by Department of Agricultural Economics at Mississippi State University.

LDPE mulch to estimate the total weed management cost of \$2,739.12 ha^{-1} in the weed-free control. In the weedy check, weed management cost was the cost of LDPE mulch alone.

Harvesting and Marketing Cost. Harvesting and marketing cost for tomato production is calculated based on the total yield and irrespective of tomato grades (Table 6). A fixed charge of \$5.36 per box (weighed 11.36 kg per box) of tomato was estimated for calculating harvesting and marketing cost. Harvesting and marketing cost are also higher for the treatments that produced higher yield. In tomato production, the weed-free control, MeBr treatment, and *S*-metolachlor–containing herbicide program yielded higher, and harvesting and marketing costs were \$13,624.17, \$13,396.18, and \$9,945.71 ha^{-1}, respectively. Conversely, imazosulfuron-treated plots and nontreated plots had lower yields, resulting in harvesting and marketing cost of $\leq$ \$5,593.81 ha^{-1}.

Gross Returns and Net Returns. Gross returns in tomato production were estimated by adding returns from jumbo, extra-large, large, medium, and small grades. Among the different grades of tomato, returns were highest from jumbo grade (data not shown) because this category yield contributed the highest percentage of total yield. Tomato plots treated with the imazosulfuron-containing herbicide programs provided gross returns ranging from \$8,746 to \$14,543.60 ha^{-1} (Table 6). With these gross returns, there was loss of \$3,277.76 to \$6,916.96 ha^{-1} in net return with the imazosulfuron-containing programs. Furthermore, losses in net return relative to MeBr treatment ranged from \$7,707.88 to \$11,347.08 ha^{-1} from imazosulfuron-containing programs. Gross returns were estimated to be \$35,668.80, \$34,958.40, and \$25,912.80 ha^{-1} for the weed-free control, MeBr treatment, and *S*-metolachlor–containing herbicide program, respectively. Moreover, there was a gain in net returns from

Table 5. Estimated weed management cost for pre-transplant imazosulfuron and *S*-metolachlor followed by (fb) post-transplant trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene–mulched tomato production.

Treatments	Rate	Cost[a]			
		Chemical[b]	LDPE mulch[c]	Labor[d]	Total[e]
	kg ai ha^{-1}	$ ha^{-1}			
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.112	23.12	720.25	0	831.65
	0.008	37.64			
	0.027	50.64			
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.224	46.25	720.25	0	854.78
	0.008	37.64			
	0.027	50.64			
Imazosulfuron fb trifloxysulfuron + halosulfuron	0.336	69.38	720.25	0	877.91
	0.008	37.64			
	0.027	50.64			
S-metolachlor fb trifloxysulfuron + halosulfuron	1.6	50.41	720.25	0	858.94
	0.008	37.64			
	0.027	50.64			
Methyl bromide + chloropicrin	390	5,062.20	720.25	0	5,782.45
Weed-free control	–	0	720.25	2,018.87	2,739.12
Weedy check	–	0	720.25	0	720.25

[a] Weed management cost includes the cost of all the inputs applied for weed control.

[b] Chemical cost is the cost of herbicides or methyl bromide. In weed-free and nontreated control plots, chemicals were not applied.

[c] LDPE mulch cost is the cost of low-density polyethylene mulch.

[d] Labor cost is the cost of hand weeding in weed-free control plots. Hand weeding was done only in weed-free control plots.

[e] Total cost is the summation of chemical, LDPE mulch, and labor costs required for weed management.

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Table 6. Estimated total cost, gross return, net return, and net return relative to methyl bromide for pre-transplant imazosulfuron and *S*-metolachlor followed by (fb) post-transplant trifloxysulfuron plus halosulfuron, methyl bromide, and weed-free control in low-density polyethylene–mulched tomato production.

Treatment	Preharvest cost	Weed management cost	Harvesting and marketing cost[a]	Total cost[b]	Gross return[c]	Net return[d]	Net return relative to methyl bromide[e]
	$\$ ha^{-1}$						
Imazosulfuron (0.112) fb trifloxysulfuron + halosulfuron	11,349.65	831.65	5,123.60	17,304.90	13,349.60	−3,955.30	−8,385.41
Imazosulfuron(0.224) fb trifloxysulfuron + halosulfuron	11,349.65	854.78	3,458.53	15,662.96	8,746.00	−6,916.96	−11,347.08
Imazosulfuron (0.336) fb trifloxysulfuron + halosulfuron	11,349.65	877.91	5,593.81	17,821.37	14,543.60	−3,277.76	−7,707.88
S-metolachlor fb trifloxysulfuron + halosulfuron	11,349.65	858.94	9,945.71	22,154.30	25,912.80	3,758.50	−671.61
Methyl bromide + chloropicrin	11,349.65	5,782.45	13,396.18	30,528.28	34,958.40	4,430.116	0
Weed-free control	11,349.65	2,739.12	13,624.17	27,712.94	35,668.80	7,955.86	3,525.75
Weedy check	11,349.65	720.25	4,190.86	16,260.76	10,657.60	−5,603.15	−10,033.27

[a] Harvesting and marketing cost includes the cost of harvesting labor, materials for harvesting, grading and packing labor, hauling, and transportation to the terminal market. Harvesting and marketing cost was calculated based on a fixed charge of $5.36 per 11.23-kg box of tomato, therefore, harvesting and marketing cost differed with the varying yield.

[b] Total cost is the summation of preharvest cots, weed management cost, and harvesting and marketing cost.

[c] Gross return is the summation of returns from all the tomato grades.

[d] Net return is the difference between gross return and total cost.

[e] Net return relative to methyl bromide for a treatment was calculated by subtracting net return of methyl bromide from net return of a particular treatment.

these treatments, and they were profitable treatments. Hand-weeded plots had the highest net return with $7,955.86 ha^{-1}. Likewise, net returns were $4,430.11, and 3,758.50 ha^{-1} for the MeBr and *S*-metolachlor–containing program, respectively. When comparing with the MeBr, only the weed-free control showed a gain in net return of $3,525.75 ha^{-1}. With the *S*-metolachlor–containing program, there was a loss of $671.61 ha^{-1} in net return relative to MeBr.

In conclusion, pre-transplant imazosulfuron did not provide effective weed control. Weeds emerged in the early weeks following transplanting established rapidly in the imazosulfuron-treated plots because of favorable growing conditions in the polyethylene-mulched production system. Because weeds grew vigorously, they were too large for post-transplant trifloxysulfuron plus halosulfuron to control in the imazosulfuron-treated plots. This study demonstrates that a pre-transplant imazosulfuron fb post-transplant trifloxysulfuron plus halosulfuron herbicide program is not an effective alternative to MeBr for weed management in LDPE-mulched tomato. However, pre-transplant *S*-metolachlor fb post-transplant trifloxysulfuron plus halosulfuron is an effective alternative for Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched tomato production. Moreover, the *S*-metolachlor program provided total marketable tomato yield comparable to the MeBr treatment.

Hand weeding at 2, 4, 6, and 8 WATP provided highest yield and net return in the current study. However, in the absence of labor, hand-weeding for multiple times in a growing season might not be a practical option for large acreage tomato production. Moreover, repeated hand weeding affects the durability of LDPE mulch (because of the splitting and tearing of the mulch during weed pulling) for multiseason use from single mulch application. In this regard, herbicide application fb by hand weeding (one or two times per season) might be an effective weed control option in commercial tomato production. However, further study should evaluate the effectiveness and efficacy of herbicide application fb hand weeding compared to MeBr for weed control in LDPE-mulched tomato. Among the herbicide programs, the current study illustrates *S*-metolachlor-containing herbicide program as the most feasible alternative to MeBr. Hence, pre-transplant *S*-metolachlor fb post-transplant trifloxysulfuron plus halosulfuron is suggested as a MeBr alternative for weed management in LDPE-mulched tomato production.

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