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# Evaluation of Non-fumigant Pesticides as Methyl Bromide Alternatives for Managing Weeds in Vegetables

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Additional information is available at the end of the chapter

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## Abstract

The phase out of methyl bromide (MBr) challenged vegetable growers' abilities to control weeds in low-density polyethylene (LDPE) mulch production systems. The herbicides halosulfuron, fomesafen, S-metolachlor, and clomazone are needed as part of the pesticide program in LDPE vegetable production to control weeds including *Cyperus* species. Experiments were conducted during the spring and autumn of 2012, evaluating *Cyperus rotundus*, bell pepper, and cucumber response to these herbicides applied to soil immediately prior to LDPE laying. Halosulfuron, fomesafen, S-metolachlor, and clomazone applied to soil under LDPE mulch did not negatively impact stand and growth of bell pepper in spring or autumn experiments, or cucumber in spring trials. However, there was significantly less growth in the autumn experiment as halosulfuron, S-metolachlor plus clomazone plus halosulfuron or fomesafen, reduced vine length. *Cyperus rotundus* suppression and control was achieved with halosulfuron alone and when used in combinations with S-metolachlor plus clomazone, and combinations of S-metolachlor plus clomazone plus fomesafen. These herbicides provided weed control that were comparable to MBr plus chloropicrin (MBrR-C). Using herbicides for control and suppression of *Cyperus rotundus* in combination with safety for pepper and cucumber will allow growers to implement new control strategies into their vegetable production systems.

**Keywords:** Crop tolerance, clomazone, fomesafen, halosulfuron, S-metolachlor

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## 1. Introduction

Effective weed control in fresh market production of vegetable crops is challenging due to the elimination of the preplant soil fumigant methyl bromide (MBr). Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) are the most common and troublesome weeds in fresh

market vegetable production throughout the southeastern US [1]. The sharp tips of the emerging purple nutsedge shoots readily pierce low-density polyethylene (LDPE) mulch and lead to an exclusive nutsedge infestation (Figure 1), proliferating rapidly as vegetables are supplemented with water and nutrients via drip irrigation from tubes inserted at the time LDPE mulch is laid. Purple and yellow nutsedge are perennial with erect growth and triangular stems. Newly developing nutsedge rhizomes are indeterminate stems sheathed in scaled leaves surrounding pointed meristems [2]. Nutsedge rhizomes, in the absence of light, remain in a heterotrophic growth phase that allows the stem internodes to continue to elongate [3]. The continued lengthening of the rhizomes is responsible for forcing nutsedge leaves through the plastic and into the light, where photomorphogenic cues that lead to leaf formation and expansion are triggered [3]. The use of black polyethylene mulch may alter the environmental characteristics of the cropping system to the benefit of nutsedge species. Research by Webster [4] demonstrated that black LDPE mulch promoted the growth of purple nutsedge plants, relative to a mulch-free check. Under black-opaque LDPE mulch, a single purple nutsedge tuber multiplied to 3,440 shoots covering an area of 22.1 m<sup>2</sup> in 60 weeks. Herbicides that could be incorporated into vegetable systems using LDPE mulch must be effective on *Cyperus* and other weed species. Halosulfuron, fomesafen, clomazone, and S-metolachlor provide residual activity toward weed species with control often extending for many weeks or months after applications [5]. In this region, with MBr no longer a weed control option, herbicides are now used to maintain fresh market vegetable production.

## 2. Importance

The use of LDPE mulch with fumigation to manage weeds, plant pathogens, and nematodes is standard for production of vegetables in the southeastern US [6–10]. Most LDPE mulch is laid for spring vegetable production followed by a second crop in the autumn and potentially a third crop the following spring [7]. Spring vegetables grown after LDPE mulch fumigation include watermelon [*Citrullus lanatus* (Thunb.) Matsum and Nak.], bell pepper (*Capsicum annuum* L.), tomato (*Lycopersicon esculentum* Mill.), squash (*Cucurbita pepo* L.), and eggplant (*Solanum melongena* L.). A second autumn crop often includes cabbage (*Brassica oleracea* L.), eggplant, cucumber (*Cucumis sativus* L.), or squash. This second crop is often transplanted directly into the existing LDPE mulch-covered beds [7, 10] in order to grow two crops in 1 year, minimizing expenses associated with polyethylene mulch and drip tape irrigation by spreading costs over multiple crops. Weed control is critical as bell peppers may be more sensitive to nutsedge interference than other vegetable crops. Gilreath et al. [11] reported that nutsedge densities of approximately 5.4 plant m<sup>-2</sup> occurring during crop fruit set reduced bell pepper yield by 31%. Motis et al. [12] noted that severe nutsedge infestations of greater than 30 plants m<sup>-2</sup> could reduce bell pepper yields from 54% to 74%. Therefore, season-long weed control is essential. Residual herbicides will be an integral part of continued fresh market vegetable production. By applying residual herbicides to the soil surface at the time LDPE mulch is laid, weed control could be improved, while also maintaining and extending productive use of the LDPE mulch for subsequent crops.



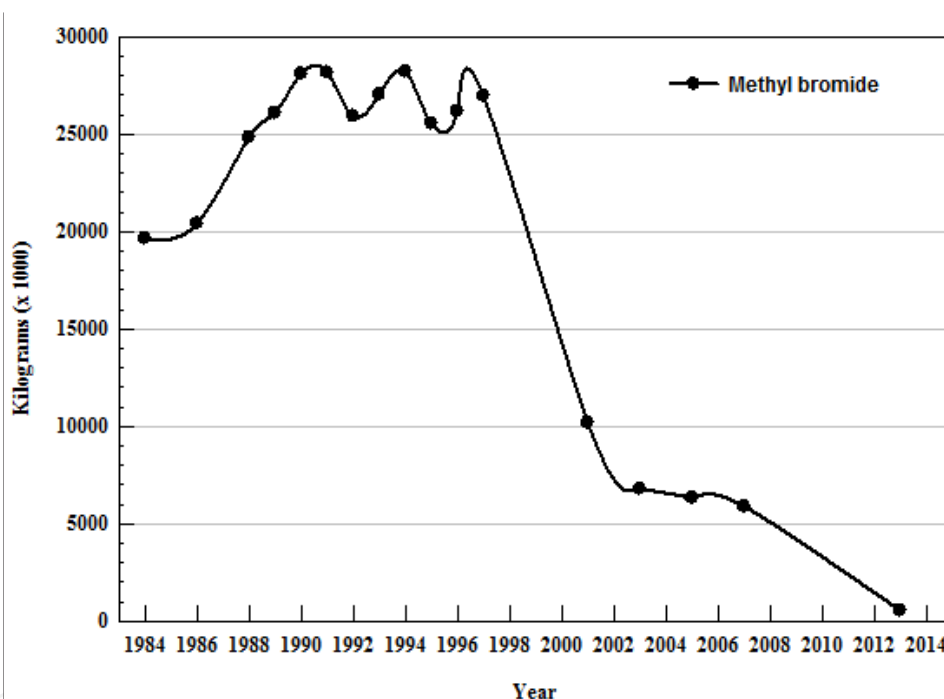
**Figure 1.** Purple nutsedge (*Cyperus rotundus*) piercing low-density polyethylene mulch (photo by Sidney Cromer).

### 3. Background information on LDPE mulch weed control

Methyl bromide was first used as a soil fumigant in France in the 1930s and was tested for nematode control beginning in the 1940s [13], and then used to sterilize soil in the 1950s [14]. It became the standard for broad-spectrum pest control in fresh market vegetable production through the 1990s [15–18]. Herbicides with soil persistence were first used for preemergence (PRE) weed control in agronomic crops beginning in the 1940s [19]. However, there was no need to incorporate herbicides into LDPE mulch fresh market vegetable production, as MBr was effective and consistent in control of multiple pests including most weed species. With the increasing awareness of MBr as an ozone-depleting compound, efforts to decrease its use began in earnest in the early 1990s. Data from the US Environmental Protection Agency (EPA) fact sheets, sales, and usage information indicated the rapid decline in MBr use in the US from greater than 28,000,000 kg in 1991 to less than 2.2% of that baseline level in 2013 (Figure 2), due to restrictive use goals set at the Montreal Protocol in 1991 [7]. In the interim, MBr was often combined with chloropicrin as a means to reduce MBr usage [11]. The goal is to be at less than 0.01% of the 1991 baseline MBr use by 2017 in the US [20]. With the loss of MBr for weed control, herbicide alternatives were immediately considered, as there were several registrations already in place for bare soil production methods. For example, halosulfuron was registered for use in tomato in multiple US states in April 2004 as a pre- and postemergence application. Halosulfuron is now registered for use as a soil preemergence application prior to LDPE mulch laying [21]. While herbicide options are available in LDPE mulch scenarios, crop tolerance and weed control are often a concern and require additional research. There are several herbicides that should be considered as alternatives to MBr in LDPE mulch systems, but the critical factors for their success involve their effectiveness in controlling nutsedges and the level of crop tolerance.

### 3.1. Halosulfuron

Halosulfuron is a sulfonylurea herbicide that inhibits branched-chain amino acid synthesis [5] with good to excellent control of nutsedges [22, 23]. When soil applied in vegetables, halosulfuron was applied to soil for vegetable growth, its adsorption to soil colloids was highly correlated with soil organic carbon content and inversely related to soil pH. Halosulfuron degradation increases with temperature and lower soil pH, with soil moisture content and soil type further affecting soil persistence. Soil dissipation is primarily by chemical hydrolysis and microbial degradation [5]. Halosulfuron half-life ( $DT_{50}$ ) ranges from 6 to 98 days, depending on soil moisture and temperature regimes [8, 24] and exhibit hysteresis [25]. Injury from halosulfuron carryover to rotational crops has occurred as a result of its variable soil behavior [26]. This variability in the literature suggests that further evaluation of halosulfuron for weed control using LDPE is needed.



**Figure 2.** Methyl bromide use in the US (Environmental Protection Agency 2015). The phase out of methyl bromide. Available at <http://www.epa.gov/ozone/mbr/index.html>.

### 3.2. Fomesafen

Fomesafen, a member of the diphenyl ether herbicide family, is registered for postemergence application for control of dicot species in agronomic crops. However, it does have soil residual activity [27–29] with a half-life ranging from 6 to 12 months under aerobic conditions [30]. In contrast, fomesafen degradation under anaerobic conditions was less than 3 weeks [5]. Rauch et al. [31] reported fomesafen field  $DT_{50}$  varied between 28 and 66 days. Fomesafen has been the focus of several research studies to determine its potential preemergence soil residual activity in vegetables, with testing in tomato for control of American black nightshade (*Solanum*



*americanum* Miller) [32], cucurbits for *Amaranthus* spp. and other weeds [33], and crop tolerance in cantaloupe [34] and pepper [35, 36]. When used in combination with other herbicides in tomato production, fomesafen applied to soil prior to laying virtually impermeable film (VIF) mulch provided improved purple nutsedge control compared to fomesafen alone [37]. Fomesafen has exhibited soil activity for yellow nutsedge control [38]. While fomesafen has been evaluated in multiple vegetable crops, the literature suggests that further evaluation of fomesafen for bell pepper and cucumber when applied to soil when using LDPE is needed.

### 3.3. S-metolachlor

Metolachlor is a chloroacetamide herbicide, and its dissipation from soil has been extensively investigated [39–44]. Weber et al. [44] reported that metolachlor sorption, mobility, and soil retention were related to organic matter, clay content, and surface area. As soil organic matter concentration increases, adsorption of metolachlor increases. Metolachlor mobility was inversely related to soil organic matter and clay content. Other studies came to similar conclusions, indicating that metolachlor binding was by physical forces between metolachlor molecules and soil constituent surfaces [44]. Half-life of metolachlor varies with soil temperature, moisture, and organic matter content [5, 45]. S-metolachlor is registered for use in pumpkin (*Cucurbita pepo* L.) (POST), bell pepper (PRE), and tomato (PRE) for LDPE mulch production [21]. However, combinations with other herbicides have not been evaluated.

### 3.4. Clomazone

Clomazone inhibits photosynthesis and carotenoid biosynthesis in higher plants, and application to sensitive species results in bleaching or whitening of photosynthetic tissues, chlorosis, and death [46]. Clomazone is microencapsulated (ME) due to volatility issues [47]. As a soil-applied herbicide, clomazone is currently registered for use in certain US states for cabbage, cantaloupe, cucumber, squash, and watermelon (*Citrullus lanatus* L.) [21]. Field studies have indicated that clomazone provides full-season preemergence weed control in selected cucurbits [48, 49]. As clomazone inhibits carotenoid biosynthesis, chlorosis or “bleaching” of sensitive plants, such as squash, is predicted. Bleaching of squash increased with increasing rates when clomazone was applied either preplant incorporated (PPI) or PRE in bare soil situations [50]. Incorporation of clomazone PPI into the root zone enhances uptake and increases bleaching [50]. Therefore, application sensitivity must be considered when using with LDPE mulch for peppers and cucumbers, but this has not been evaluated.

## 4. Research

Cucumber and bell pepper production are now more reliant on herbicide combinations applied at the time of LDPE mulch laying when MBr alternative fumigants are either not available or not considered due to worker safety issues. Herbicides must provide residual weed control with minimal potential for vegetable crop injury. Weed control for comparing residual herbicides in vegetables has been performed for multiple crops and scenarios [7, 10,

37]. However, when applied to the soil surface prior to laying, LDPE mulch has not been fully researched. Therefore, this chapter will emphasize herbicide combinations for nutsedge control and response in bell pepper (Table 1) and cucumber (Table 2). Methyl bromide plus chloropicrin (MBR-C) was included as a standard along with a nontreated control.

Herbicide	Rate <sup>a</sup>	2011 test		Timing <sup>c</sup>	
				Spring	Autumn
	kg a.i. ha <sup>-1</sup>				
Clomazone ME <sup>b</sup> + fomesafen	0.42 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + fomesafen	0.80 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + fomesafen + clomazone ME	0.80 + 0.28 + 0.42	Spring	Autumn	1 wk PRE	1 wk PRE
Methyl bromide + chloropicrin (50:50)	196 + 196	Spring	Autumn	3 wk PRE	3 wk PRE

<sup>a</sup>Abbreviations: a.i., active ingredient; ME, microencapsulated; PRE, preemergence.

<sup>b</sup>Broadcast rate applied to the soil surface to 91-cm-wide bed as LDPE mulch was laid.

<sup>c</sup>Timing prior to transplanting into LDPE mulch-covered soil.

**Table 1.** Herbicide, rates, and timing of applications for evaluating purple nutsedge control and bell pepper growth response when applied to soil prior to laying of low-density polyethylene (LDPE) mulch in Georgia.

Herbicide	Rate <sup>a</sup>	2011 test		Timing <sup>c</sup>	
				Spring	Autumn
	kg a.i. ha <sup>-1</sup>				
Halosulfuron	0.04	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + clomazone ME + halosulfuron	0.80 + 0.42 + 0.04	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + clomazone ME + fomesafen	0.80 + 0.42 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
Methyl bromide + chloropicrin (50:50)	196 + 196	Spring	Autumn	3 wk PRE	3 wk PRE

<sup>a</sup>Abbreviations: a.i., active ingredient; ME, microencapsulated; PRE, preemergence.

<sup>b</sup>Broadcast rate applied to the soil surface to 91-cm-wide bed as LDPE mulch was laid.

<sup>c</sup>Timing prior to transplanting into LDPE mulch-covered soil.

**Table 2.** Herbicide, rates, and timing of applications for evaluating purple nutsedge control and cucumber vine growth response when applied to soil prior to lying of low-density polyethylene (LDPE) mulch in Georgia.

#### 4.1. Field studies

Field studies conducted to evaluate herbicide replacement of MBr-C had two distinct research objectives. However, all experiments were conducted similarly. Herbicide application, bed formation, and laying of 32- $\mu$ m-thick (1.25 mil) LDPE mulch occurred simultaneously. All studies were conducted on Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandudults) with 86–88% sand, 8% silt, 4–6% clay, 0.5–1.3% organic matter, and pH ranging from 6.3 to 6.9. Experiments were conducted in the spring and autumn of 2011. The soil was moldboard-plowed 25–30 cm deep, then disk-harrowed. Single beds (0.82 m wide, 22.9 m long,

and 20 cm high) were established with a bed shaper. All herbicide treatments were applied as laying of LDPE mulch occurred (Tables 1 and 2). Herbicides were applied with a CO<sub>2</sub>-pressurized sprayer calibrated to deliver 187 L/ha at 210 kPa to the bed as it was being prepared. This was in combination with the immediate cover with the LDPE mulch. A single drip irrigation tube with emitters spaced 30 cm apart with a flow rate of 30 ml/min was placed in the center of the bed under the LDPE mulch for application of water and fertilizer. Two separate tests were conducted with bell pepper (Table 1) and cucumber (Table 2). All tests had experimental designs of a randomized complete block with 5 or 12 replications. Treated plots included two rows of bell pepper or cucumber, with in-row spacing based on University of Georgia recommendations for vegetables. Commercial cucumber and bell pepper cultivars commonly grown in the southeastern US during the spring and autumn were selected. Transplanted cucumber “Thunder” and bell pepper “Camelot” were used. Cucumber and bell pepper were then established in the field by hand transplanting (7.5 cm deep into soil). The final comparisons for stand were based on the nontreated control. Irrigation was applied as needed through drip tape, and fertilizer was applied similarly based on University of Georgia recommendations for vegetables. Insects and plant diseases were monitored and sprayed when necessary.

Temperature data used for growing-degree-day (GDD) calculation were collected off-site at the Georgia Weather Monitoring Network, located within 5 km of the experiment [51]. Growing degree days were calculated by using daily minimum and maximum air temperature. Previous studies used a base temperature of 10.4°C for purple nutsedge [52, 62]. Growing degree days provide a more biologically meaningful measure of crop growth compared with time after planting [53, 63].

Crop stand counts, height, and vine length measures were evaluated multiple times after transplanting. Purple nutsedge stand counts were made multiple times during the season on the entire length of the bed. Data were not combined for analysis due to differences in the time of year when the experiments were conducted. Plant height, vine lengths, and vegetable and purple nutsedge stand counts were subjected to analysis of variance (ANOVA) in SAS 9.2 (SAS Institute, 2012). Linear regression models, using the equation,

$$y = b + mx \quad (1)$$

were assessed to determine associations between herbicide treatment and all dependent variables using the REG Procedure in SAS 9.2 with respect to growing degree days. Treatment means are presented for clarity. Mean separation of 95% asymptotic confidence intervals for comparison of parameter estimates was then used to compare each treatment to MBr-C.

## 5. Purple nutsedge and crop response

Bell pepper, cucumber, and purple nutsedge were measured periodically over time. In spring 2011, greater than 500 GDD were accumulated, over the 2 months the experiment was



conducted. In autumn 2011, greater than 550 GDD were accumulated for the 2 months the experiment was conducted.

### 5.1. Bell pepper

There were no significant differences in crop population density (stand) (data not shown) or plant height response in bell pepper for treatment combinations containing clomazone, fomesafen, or *S*-metolachlor and the nontreated control relative to MBr-C (Tables 3 and 4, Figures 3 and 4). The rate of bell pepper growth ( $b$ ) was less in spring, ranging from 0.056 to 0.062, compared to autumn at 0.071–0.074 cm GDD<sup>-1</sup>. The  $y$ -intercepts were also similar for all treatments. These data indicate that bell pepper was very tolerant of these combinations of herbicides, offering an alternative to fumigants, such as chloropicrin, where use is constrained by various buffer zones [52, 62]. Bell pepper has previously shown tolerance to fomesafen in bare soil production [35], but the combination of fomesafen plus *S*-metolachlor with LDPE mulch had variable effects on height and fresh market yield [36]. Fomesafen, *S*-metolachlor, and clomazone are all registered for use with LDPE mulch in Georgia [21].

### 5.2. Purple nutsedge control in bell pepper

Populations of purple nutsedge varied between the two experiments ranging from 0 to 40 plant m<sup>-2</sup> at 0–530 GDD after trial initiation (Tables 5 and 6, Figures 5 and 6). This level of purple nutsedge population density has been shown to cause reductions in bell pepper shoot dry weight and fresh market yield [53, 63]. Control of purple nutsedge by combinations of *S*-metolachlor plus fomesafen plus clomazone was similar to MBr-C for the 2011 autumn test (Figure 6). While it was significantly different in the spring from MBr-C, this same herbicide trio provided greater purple nutsedge control than any other tandem combination of clomazone plus fomesafen or *S*-metolachlor plus fomesafen in both experiments (Figures 5 and 6). This supports Florida research where fomesafen plus *S*-metolachlor provided greater control than either herbicide alone [36, 37]. The herbicide trio of *S*-metolachlor plus fomesafen plus clomazone has not been previously described for weed control in vegetables using LDPE mulch. Further research to validate the potential of this trio of herbicides in benefiting bell pepper growers is needed.

### 5.3. Cucumber

Relative to MBr-C, there were no significant differences in cucumber stand among halosulfuron alone, or combinations containing clomazone, fomesafen, *S*-metolachlor, halosulfuron, and the nontreated control (data not shown). There were no differences among any treatment in the spring experiment for cucumber vine growth rate ( $b$ ), ranging from 0.073 to 0.104 cm GDD<sup>-1</sup> (Table 7, Figure 7). In contrast, there was variability in the rate of cucumber vine growth in the autumn experiment as all three herbicide treatments had significantly less growth as compared to MBr-C (Table 8, Figure 8). Previous research indicated that cucumber exhibited biomass variability with respect to injury in response to halosulfuron PRE applied in a greenhouse experiment [54]. Halosulfuron is registered for use in cucumber grown with LDPE mulch in Georgia, but injury can occur if proper precautions are not followed during use [21].

S-metolachlor plus clomazone plus halosulfuron, or fomesafen, all had response curves similar to halosulfuron alone (Table 8, Figure 8). Metolachlor has caused reduction in cucumber seedling biomass [55, 56], and is not recommended for use in LDPE mulch systems now due to injury issues. Therefore, these trios of herbicides (S-metolachlor plus clomazone plus either fomesafen or halosulfuron) will be too injurious to use with cucumber.

#### 5.4. Purple nutsedge control in cucumber

Similar to the bell pepper experiments, the populations of purple nutsedge varied between the two cucumber tests, ranging from 0 to 32 plant m<sup>-2</sup> at 0–600 GDD after trial initiation (Tables 9 and 10, Figures 9 and 10). Variability of purple nutsedge control was observed with halosulfuron alone, and the trios of herbicides applied in combination with each other. For the spring experiment (Table 9, Figure 9), all herbicide treatments were different from MBr-C with the rate of purple nutsedge growth of 0.009–0.016 shoots per m<sup>2</sup> GDD<sup>-1</sup>. In comparison, the rate of purple nutsedge growth for the nontreated control was 0.017 shoots per m<sup>2</sup> GDD<sup>-1</sup>. For the autumn experiment, halosulfuron provided control similar to MBr-C with *b* values of 0.022 versus 0.018 shoots per m<sup>2</sup> GDD<sup>-1</sup>, respectively (Table 10, Figure 10). Halosulfuron is registered for use in cucumber [21] and is an effective herbicide that controls purple nutsedge and also reduces the number of new tubers produced [23]. However, variability in nutsedge control has been noted in multiple vegetable crops in bare soil [57–59] and soil under LDPE mulches [37, 60, 61]. Control of purple nutsedge by the trio herbicides combinations was not effective in either experiment (Tables 9 and 10, Figures 9 and 10). These data indicate the variability that can often occur when using herbicides in LDPE mulch systems.

## 6. Discussion

The complexity and difficulty of managing nutsedge species in vegetable crops have increased with the elimination of methyl bromide. Successful management of nutsedge will require diligent control programs utilizing LDPE mulches along with residual herbicides prior to crop planting, during the cropping season, and between crops (spring and autumn), in order to extend the use of LDPE mulches and reduce costs. This research indicated that combining multiple herbicides could provide control of purple nutsedge in bell pepper and cucumber LDPE mulch production. But variability in purple nutsedge control was observed, which indicates the need for further development as growers incorporate this strategy. Spring and autumn soil-applied residual herbicide treatments prior to LDPE mulch lying did not reduce bell pepper growth. Bell pepper was tolerant of herbicide combinations not previously considered as options for nutsedge control. However, cucumber injury to S-metolachlor was unacceptable. Other registered herbicide options should be considered when cucumber is to be grown. Future research should be conducted with the currently evaluated herbicides for other solanaceous and cucurbit crops. Purple nutsedge control was attainable with herbicide applications, but variability was an issue in this research. This should be considered as an area for future research efforts in vegetable production using LDPE mulches.

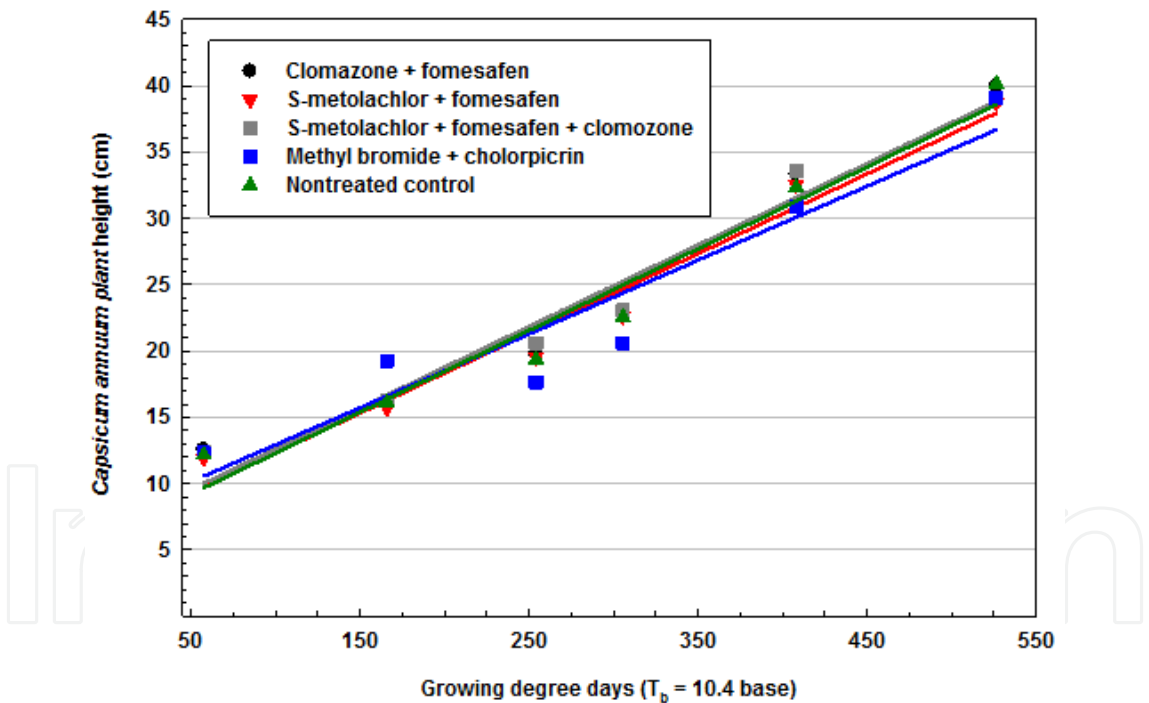
Rate of bell pepper growth <sup>b</sup>						
Treatment	$y_0^c$		SE	$b$		SE
Clomazone + fomesafen	6.13	NS <sup>a</sup>	±1.24	0.062	NS	±0.0038
S-metolachlor + fomesafen	7.35	NS	±1.83	0.056	NS	±0.0057
S-metolachlor + fomesafen + clomazone	6.48	NS	±0.67	0.062	NS	±0.0021
Methyl bromide + chloropicrin	6.30	NS	±0.63	0.060	NS	±0.0019
Nontreated	6.48	NS	±0.67	0.062	NS	±0.0021

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for general linear model (GLM) was used for mean separation with 95% asymptotic confidence interval (CI) in SAS 9.2.

<sup>b</sup>Rates of bell pepper growth ( $b$ ) were calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , bell pepper rate of growth; NS, not significant.

**Table 3.** Rate of bell pepper growth ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD).



Spring

**Figure 3.** Pepper height growth response as affected by herbicide treatment when applied to soil surface as low-density polyethylene mulch was laid in spring 2011. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Clomazone + fomesafen;  $y = 6.13 + 0.062x$ ;  $R^2 = 0.88$  ;  $P = 0.975$  S-metolachlor + fomesafen;  $y = 7.35 + 0.056x$ ;  $R^2 = 0.73$  ;  $P < 0.0001$  S-metolachlor + fomesafen + clomazone;  $y = 6.48 + 0.062x$ ;  $R^2 = 0.93$  ;  $P = 0.0635$  Methyl bromide;  $y = 6.30 + 0.060x$ ;  $R^2 = 0.93$ ; ;  $P = 0.527$  Nontreated;  $y = 6.48 + 0.062x$ ;  $R^2 = 0.93$ ; ;  $P = 0.0635$

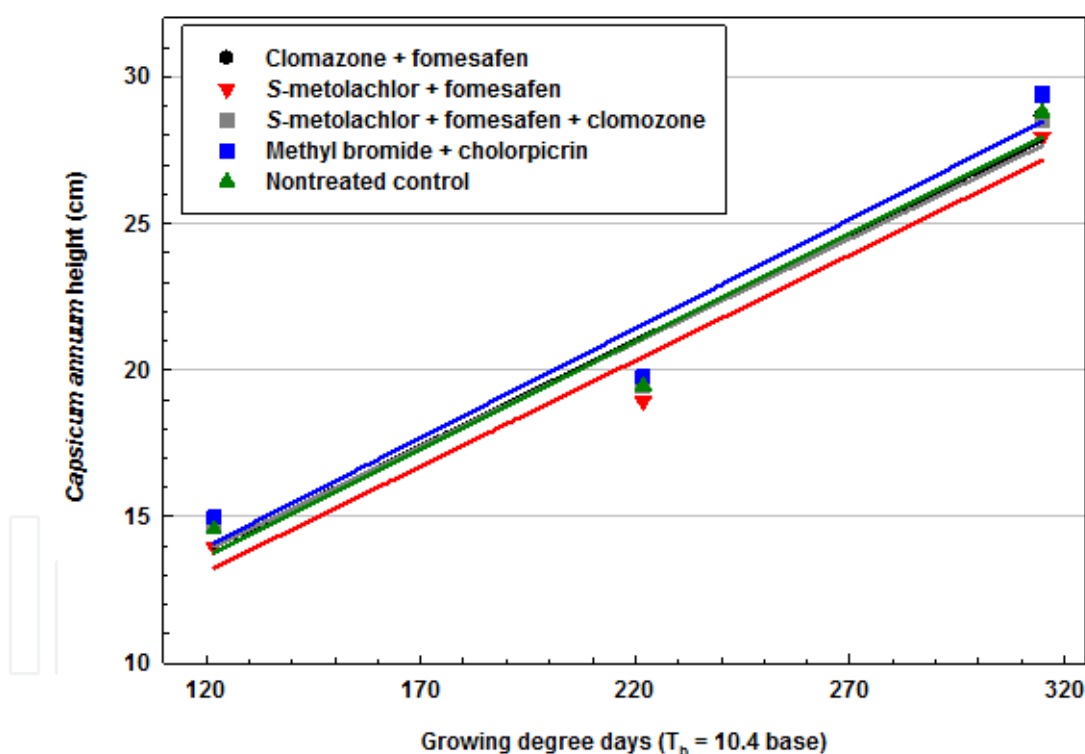
Treatment	Rate of bell pepper growth <sup>b</sup>					
	$y_0^c$		SE	$b$		SE
Clomazone + fomesafen	4.82	NS <sup>a</sup>	±3.68	0.073	NS	±0.0158
S-metolachlor + fomesafen	5.04	NS	±1.64	0.074	NS	±0.0070
S-metolachlor + fomesafen + clomazone	5.35	NS	±1.33	0.071	NS	±0.0057
Methyl bromide + chloropicrin	4.48	NS	±1.50	0.072	NS	±0.0064
Nontreated	5.20	NS	±1.65	0.072	NS	±0.0071

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rates of bell pepper growth ( $b$ ) were calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , bell pepper rate of growth; NS, not significant.

**Table 4.** Rate of bell pepper growth ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD).



Autumn

**Figure 4.** Pepper height growth response as affected by herbicide treatment when applied to soil surface as the low-density polyethylene mulch was laid in autumn 2011. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Clomazone + fomesafen;  $y = 4.82 + 0.073x$ ;  $R^2 = 0.55$ ;  $P = 0.147$  S-metolachlor + fomesafen;  $y = 5.04 + 0.074x$ ;  $R^2 = 0.87$ ;  $P = 0.619$  S-metolachlor + fomesafen + clomazone;  $y = 5.35 + 0.071x$ ;  $R^2 = 0.81$ ;  $P = 0.0073$  Methyl bromide;  $y = 4.48 + 0.072x$ ;  $R^2 = 0.78$ ;  $P = 0.846$  Nontreated;  $y = 5.20 + 0.072x$ ;  $R^2 = 0.75$ ;  $P = 0.233$

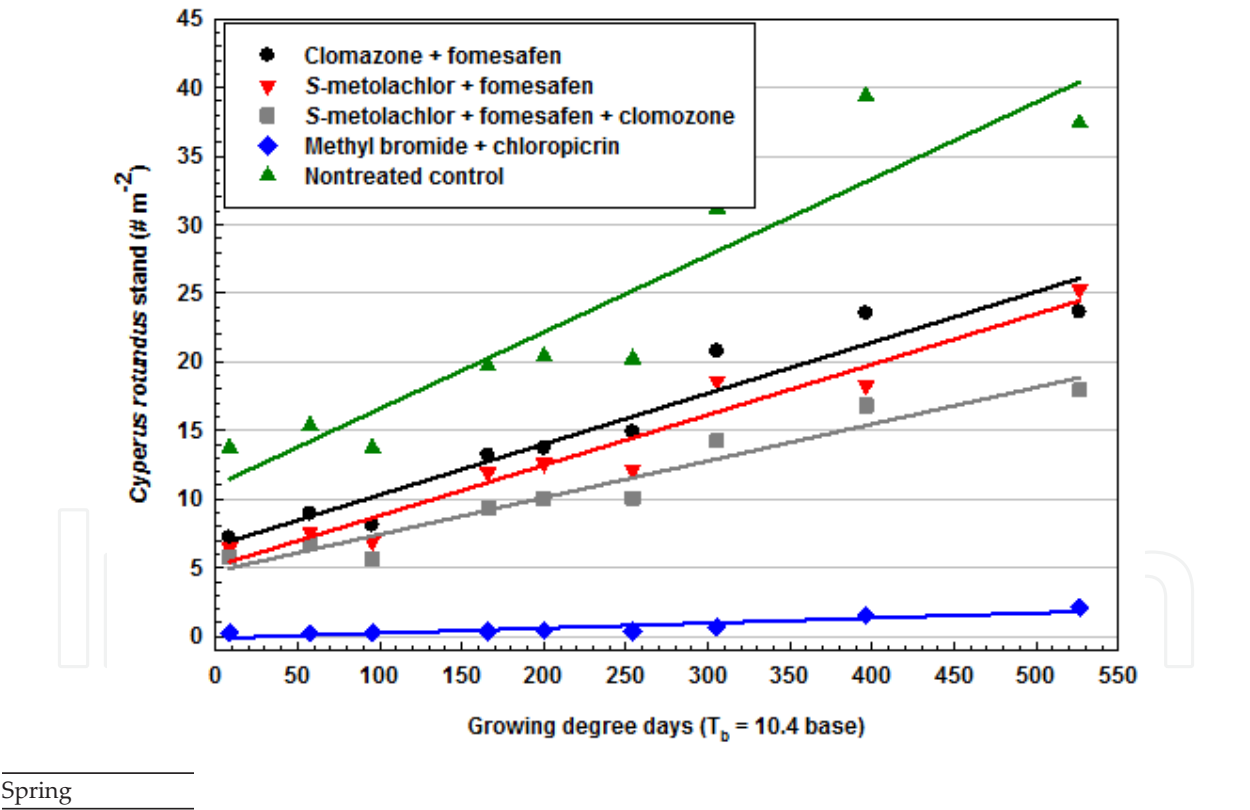
Treatment	Purple nutsedge population <sup>b</sup>				
	$y_0^c$		SE	$b$	SE
Clomazone + fomesafen	6.61	$b^a$	±1.33	0.037	$b$ ±0.0049
S-metolachlor + fomesafen	5.73	$b$	±1.43	0.032	$b$ ±0.0062
S-metolachlor + fomesafen + clomazone	3.89	$b$	±1.28	0.033	$b$ ±0.0042
Methyl bromide + chloropicrin	0.0	$a$	±1.88	0.004	$a$ ±0.0069
Nontreated	11.0	$b$	±1.88	0.056	$b$ ±0.0069

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of purple nutsedge growth ( $b$ ) was calculated by linear regression of the herbicide treatments with respect to time, GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , purple nutsedge rate of growth.

**Table 5.** Purple nutsedge population ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD) in bell pepper.



**Figure 5.** Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011 with bell pepper as a crop. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Clomazone + fomesafen;  $y = 6.61 + 0.037x$ ;  $R^2 = 0.38$ ;  $P < 0.0001$  S-metolachlor + fomesafen;  $y = 5.73 + 0.032x$ ;  $R^2 = 0.28$ ;  $P < 0.0001$  S-metolachlor + fomesafen + clomazone;  $y = 3.89 + 0.033x$ ;  $R^2 = 0.26$ ;  $P < 0.0001$  Methyl bromide;  $y = 0.00 + 0.004x$ ;  $R^2 = 0.22$ ;  $P = 0.0002$  Nontreated;  $y = 11.0 + 0.056x$ ;  $R^2 = 0.40$ ;  $P < 0.0001$



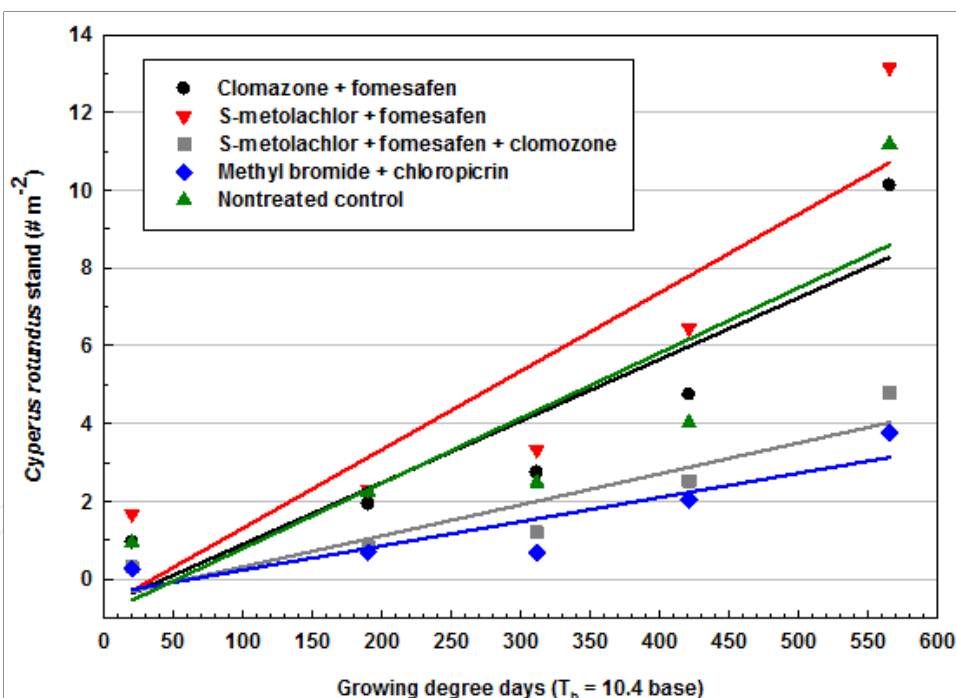
Purple nutsedge population <sup>b</sup>						
Treatment	$y_0^c$		SE	$b$		SE
Clomazone + fomesafen	-0.68	$b^a$	±1.13	0.016	$b$	±0.0032
S-metolachlor + fomesafen	-0.71	$b$	±1.83	0.020	$b$	±0.0002
S-metolachlor + fomesafen + clomazone	-0.48	$a$	±0.63	0.008	$a$	±0.0018
Methyl bromide + chloropicrin	-0.39	$a$	±0.89	0.006	$a$	±0.0025
Nontreated	-0.88	$b$	±2.48	0.017	$b$	±0.0070

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of purple nutsedge growth ( $b$ ) was calculated by linear regression of the herbicide treatments with respect to time, GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , purple nutsedge rate of growth.

**Table 6.** Purple nutsedge population ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in bell pepper.



Autumn

**Figure 6.** Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011 with bell pepper as a crop. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Clomazone + fomesafen;  $y = -0.68 + 0.016x$ ;  $R^2 = 0.29$ ;  $P < 0.0001$  S-metolachlor + fomesafen;  $y = -0.71 + 0.020x$ ;  $R^2 = 0.20$ ;  $P = 0.0002$  S-metolachlor + fomesafen + clomazone;  $y = -0.48 + 0.008x$ ;  $R^2 = 0.24$ ;  $P < 0.0001$  Methyl bromide;  $y = -0.39 + 0.006x$ ;  $R^2 = 0.15$ ;  $P = 0.0195$  Nontreated;  $y = -0.88 + 0.017x$ ;  $R^2 = 0.14$ ;  $P = 0.0232$

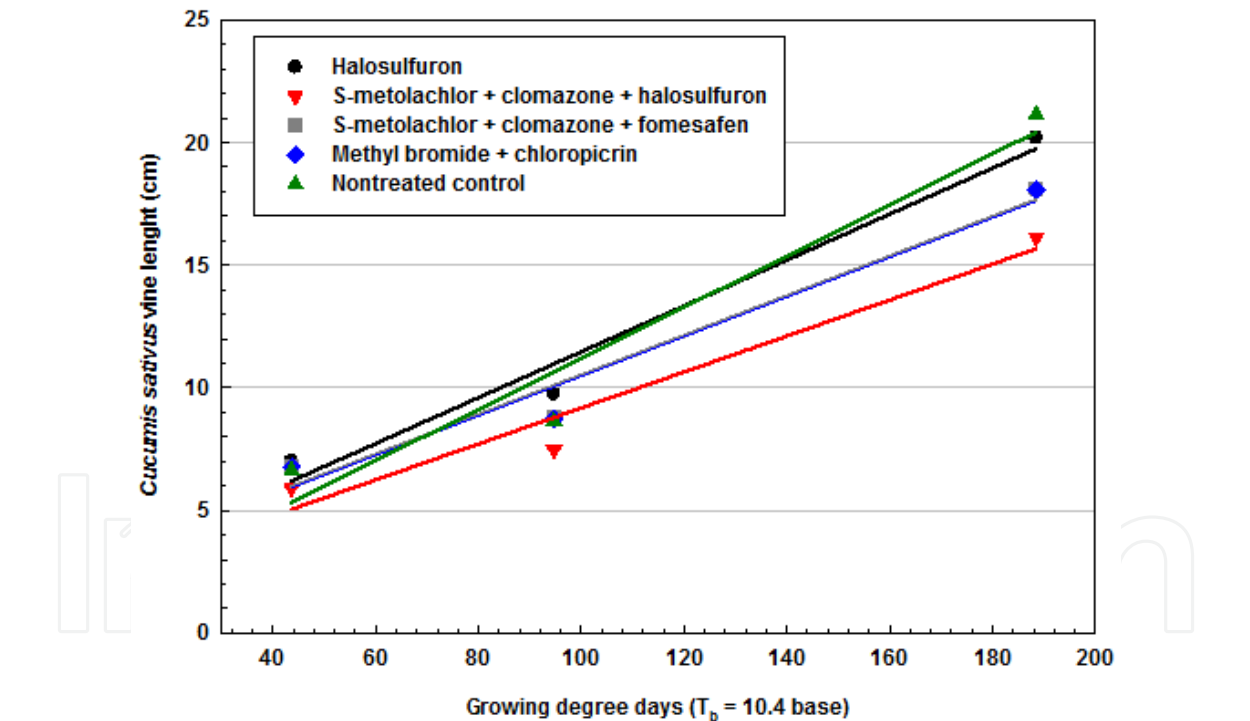
Treatment	Rate of cucumber vine growth <sup>b</sup>					
	$y_0^c$		SE	$b$		SE
Halosulfuron	2.12	NS <sup>a</sup>	±0.88	0.094	NS	±0.0071
S-metolachlor + clomazone + halosulfuron	1.85	NS	±0.85	0.073	NS	±0.0068
S-metolachlor + clomazone + fomesafen	2.44	NS	±0.83	0.081	NS	±0.0067
Methyl bromide + chloropicrin	2.40	NS	±1.05	0.081	NS	±0.0084
Nontreated	0.79	NS	±1.91	0.104	NS	±0.015

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of cucumber vine growth ( $b$ ) was calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , cucumber vine rate of growth; NS, not significant.

**Table 7.** Rate of cucumber vine growth ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD).



Spring

**Figure 7.** Cucumber vine length growth response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Halosulfuron;  $y = 2.12 + 0.094x$ ;  $R^2 = 0.83$ ;  $P = 0.116$  S-metolachlor + clomazone + halosulfuron;  $y = 1.85 + 0.073x$ ;  $R^2 = 0.77$ ;  $P = 0.0004$  S-metolachlor + clomazone + fomesafen;  $y = 2.44 + 0.081x$ ;  $R^2 = 0.80$ ;  $P = 0.831$  Methyl bromide;  $y = 2.40 + 0.081x$ ;  $R^2 = 0.84$ ;  $P = 0.720$  Nontreated;  $y = 0.79 + 0.104x$ ;  $R^2 = 0.72$ ;  $P = 0.013$

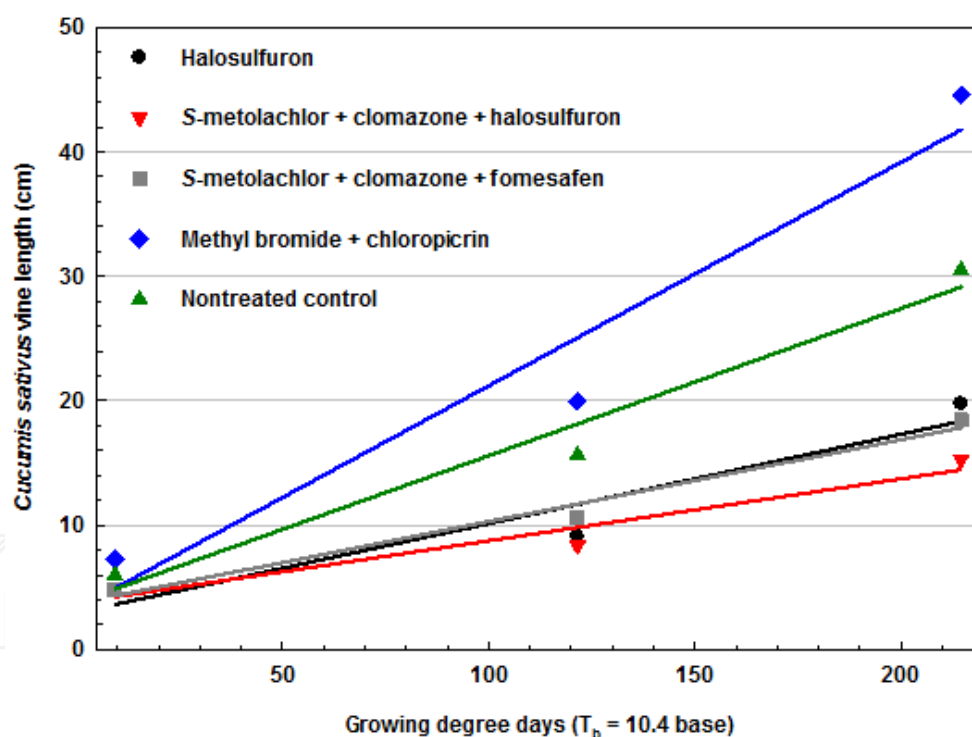
Treatment	Rate of cucumber vine growth <sup>b</sup>					
	$y_0^c$		SE	$b$		SE
Halosulfuron	2.49	NS <sup>a</sup>	±0.88	0.072	<i>b</i>	±0.0062
S-metolachlor + clomazone + halosulfuron	3.77	NS	±0.97	0.050	<i>b</i>	±0.0068
S-metolachlor + clomazone + fomesafen	3.70	NS	±1.09	0.066	<i>b</i>	±0.0076
Methyl bromide + chloropicrin	3.24	NS	±5.01	0.180	<i>a</i>	±0.0352
Nontreated	3.76	NS	±2.32	0.118	<i>b</i>	±0.016

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of cucumber vine growth ( $b$ ) was calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , cucumber vine rate of growth; NS, not significant.

**Table 8.** Rate of cucumber vine growth ( $b$ ) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD).



Autumn

**Figure 8.** Cucumber vine length growth response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Halosulfuron;  $y = 2.49 + 0.072x$ ;  $R^2 = 0.79$ ;  $P = 0.216$  S-metolachlor + clomazone + halosulfuron;  $y = 3.77 + 0.050x$ ;  $R^2 = 0.60$ ;  $P < 0.0001$  S-metolachlor + clomazone + fomesafen;  $y = 3.70 + 0.066x$ ;  $R^2 = 0.68$ ;  $P < 0.0001$  Methyl bromide;  $y = 3.24 + 0.104x$ ;  $R^2 = 0.60$ ;  $P = 0.557$  Nontreated;  $y = 3.76 + 0.118x$ ;  $R^2 = 0.75$ ;  $P < 0.0001$

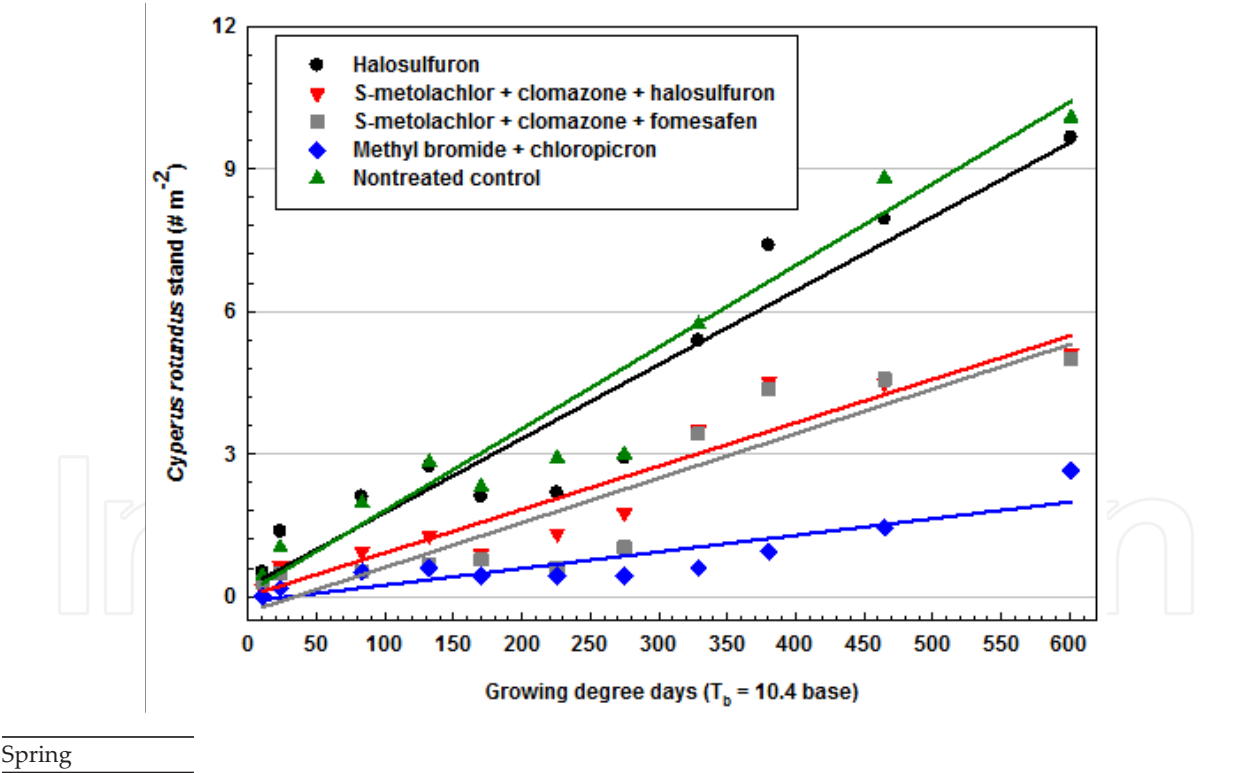
Treatment	Rate of purple nutsedge growth <sup>b</sup>					
	$y_0^c$		SE	$b$		SE
Halosulfuron	0.21	$b^a$	$\pm 0.55$	0.016	$b$	$\pm 0.0018$
S-metolachlor + clomazone + halosulfuron	0.00	$b$	$\pm 0.55$	0.009	$b$	$\pm 0.0018$
S-metolachlor + clomazone + fomesafen	-0.33	$b$	$\pm 0.55$	0.009	$b$	$\pm 0.0018$
Methyl bromide + chloropicrin	-0.11	$a$	$\pm 0.77$	0.004	$a$	$\pm 0.0026$
Nontreated	0.09	$b$	$\pm 0.77$	0.017	$b$	$\pm 0.0026$

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of purple nutsedge growth ( $b$ ) calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , purple nutsedge rate of growth.

**Table 9.** Purple nutsedge population ( $b$ ) growth as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in cucumber.



**Figure 9.** Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011 with cucumber as a crop. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Halosulfuron;  $y = 0.21 + 0.016x$ ;  $R^2 = 0.16$ ;  $P < 0.0001$  S-metotachlor + clomazone + halosulfuron;  $y = 0.00 + 0.009x$ ;  $R^2 = 0.41$ ;  $P < 0.0001$  S-merolachlor + clomazone + fomesafen;  $y = -0.33 + 0.009x$ ;  $R^2 = 0.47$ ;  $P < 0.0001$  Methyl bromide;  $y = -0.11 + 0.004x$ ;  $R^2 = 0.10$ ;  $P < 0.0001$  Nontreated;  $y = 0.09 + 0.017x$ ;  $R^2 = 0.46$ ;  $P = 0.0305$

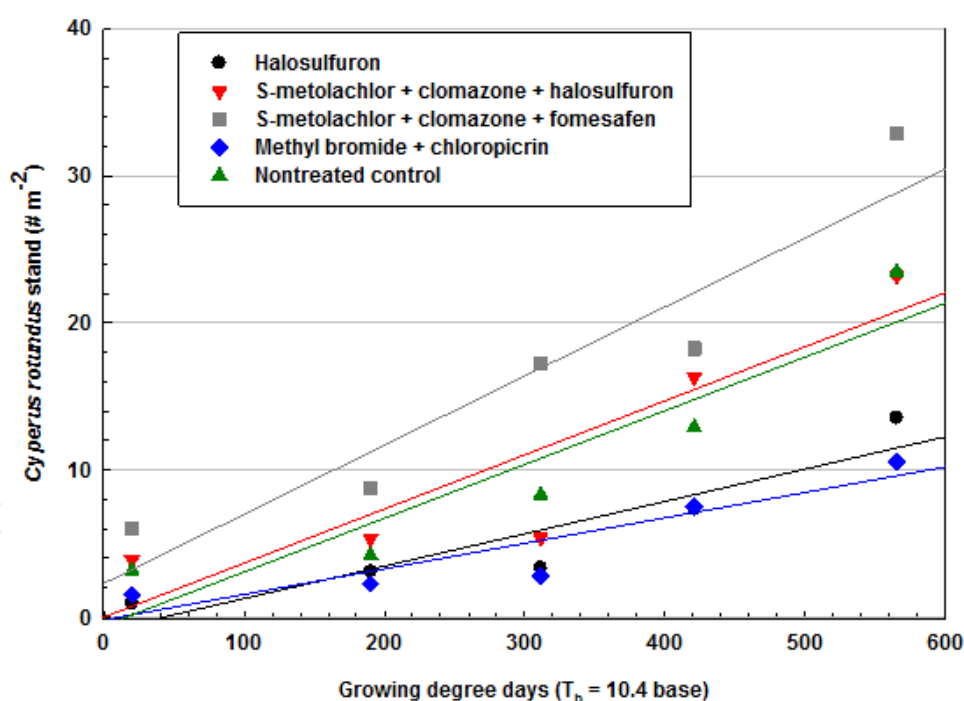
Treatment	Rate of purple nutsedge growth <sup>b</sup>					
	$y_0^c$		SE	$b$		SE
Halosulfuron	-0.92	$a^a$	±3.27	0.022	$a$	±0.0091
S-metolachlor + clomazone + halosulfuron	0.0015	$b$	±3.27	0.037	$b$	±0.0091
S-metolachlor + clomazone + fomesafen	2.94	$b$	±3.66	0.034	$b$	±0.0101
Methyl bromide + chloropicrin	-0.23	$a$	±3.25	0.018	$a$	±0.0092
Nontreated	-0.57	$b$	±3.27	0.037	$b$	±0.0091

<sup>a</sup>For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ( $P \leq 0.05$ ) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

<sup>b</sup>Rate of purple nutsedge growth ( $b$ ) calculated by linear regression of the herbicide treatments with respect to time in GDD.

<sup>c</sup>Abbreviations:  $y_0$ ,  $y$ -intercept; SE, standard error;  $b$ , purple nutsedge rate of growth.

**Table 10.** Purple nutsedge population ( $b$ ) growth as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in cucumber.



Autumn

**Figure 10.** Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011 with cucumber as a crop. The line represents the linear regression equation with adjusted  $R^2$ . Data points are the means of replications: Halosulfuron;  $y = -0.92 + 0.022x$ ;  $R^2 = 0.43$ ;  $P = 0.0002$  S-metolachlor + clomazone + halosulfuron;  $y = 0.015 + 0.037x$ ;  $R^2 = 0.23$ ;  $P = 0.0084$  S-metolachlor + clomazone + fomesafen;  $y = 2.94 + 0.034x$ ;  $R^2 = 0.22$ ;  $P = 0.0224$  Methyl bromide;  $y = -0.23 + 0.018x$ ;  $R^2 = 0.38$ ;  $P = 0.0006$  Nontreated;  $y = -0.57 + 0.037x$ ;  $R^2 = 0.42$ ;  $P = 0.0003$



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