**Placement of metam potassium in combination with dimethyl disulfide, chloropicrin, and
1,3-dichloropropene for *Cyperus rotundus* L. and broadleaf weed control in tomato
(*Solanum lycopersicum* L.)**

Running Title: Weed control with fumigants in tomato

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Abstract

Registered fumigants tend to provide poor or inconsistent *Cyperus rotundus* L. and broadleaf weed control. Dimethyl disulfide (DMDS) is generally considered more effective on *Cyperus* species than chloropicrin (Pic) or 1,3-dichloropropene (1,3-D) whereas metam potassium is generally considered more effective on broadleaf weeds. The objective of the experiment was to determine if the use of metam potassium in conjunction with other fumigants would enhance *C. rotundus* and broadleaf weed control in tomato. 1,3-D+Pic caused low level crop damage in spring 2014, increased crop height in fall 2014, and had no effect on crop growth in spring 2015. In every case, differences in crop damage or height did not result in yield differences. The most effective *C. rotundus* control was achieved with 131 kg ha⁻¹ 1,3-D + 200 kg ha⁻¹ Pic, 340 kg ha⁻¹ of DMDS + 90 kg ha⁻¹ Pic, or 392 kg ha⁻¹ of DMDS + 195 kg ha⁻¹ metam potassium. Metam potassium improved *C. rotundus* control when applied alone or in conjunction with DMDS but not when applied in conjunction with DMDS+Pic or 1,3-D+Pic. All fumigants evaluated reduced broadleaf weed density compared with non-fumigated treatments. No consistent differences in total revenues or net benefit were observed among fumigants when applied without metam potassium. The use of metam potassium increased costs per hectare although DMDS+metam potassium was cheaper than 1,3-D+Pic but not DMDS+Pic. DMDS+Pic had the lowest estimated total cost of the three best *C. rotundus* treatments.

Keywords: fumigation, weeds, nutsedge, vertical management zones

1. Introduction

Commercial vegetable and strawberry production in Florida relies on the use of soil fumigation for control or suppression of soil-borne pathogens, nematodes and weeds. Growers historically relied on methyl bromide and chloropicrin combinations for pest control primarily because methyl bromide volatilized rapidly, moved readily through the soil, and controlled a broad spectrum of pests across a wide range of environmental conditions (Duniway, 2002; Gilreath et al., 2005; Locascio et al., 1997; Noling and Becker, 1994). It was classified as an ozone depleting chemical in 1993 under the Montreal Protocol and subsequent production in the U.S. was phased out by January 2005. The loss of methyl bromide resulted in the need and extensive search for alternative pest management programs.

Several alternative fumigants have been identified and registered including chloropicrin (Pic), 1,3-dichloropropene (1,3-D), dimethyl disulfide (DMDS) and MITC generators such as metam potassium. These fumigants can be used alone but are more frequently applied in combination or as sequential applications. Nematode, pathogen and weed control achieved with these products has been promising in some studies (Desaeger et al., 2008; Fennimore et al., 2003; Santos et al., 2006) but it is generally acknowledged that they provide poor or inconsistent weed control. Chloropicrin is typically used in mixtures with 1,3-D and DMDS because it is effective on fungi and insects but not on nematodes and weeds (Hutchinson et al., 2000). 1, 3-D is generally effective on nematodes and soil-borne insects but less effective on fungi and weeds (Noling and Becker, 1994). DMDS controls a range of pests but has been evaluated primarily for its efficacy on nutsedge (McAvoy and Freeman, 2013). Metam potassium also controls a broad spectrum of pests but is frequently applied primarily for its herbicidal properties (Santos,

2009). None of the registered fumigants control as broad of spectrum of pests as methyl bromide (Duniway, 2002).

All of the alternatives have a much lower vapor pressure and higher boiling point than methyl bromide (Ajwa et al., 2003). As a result, they do not volatilize as rapidly nor do they move through the soil as extensively. Metam potassium, for example, may only treat a 10 cm sphere from the injection point (Ajwa et al., 2003). The lack of efficacy frequently observed in commercial fields may not be solely due to the products inability to kill the pest but rather a result of the fumigants not coming in contact with the pest. Efficacy may be improved if the appropriate fumigant is injected within the correct management zone where the pest of interest is located. This approach has proven effective when supplemental Pic was applied to previously nontreated zones to prevent fusarium infection of tomato roots (Jacoby et al. 2015) and when fumigants were placed beneath soil compaction zones for control of nematodes (Noling, 2015). The concept of management zones should also apply to weed control. Shallow fumigant injections should have the greatest efficacy on broadleaf weeds given that the majority of broadleaf species emerge from the top 4 cm of the soil (recruitment zone), (Boyd and Van Acker, 2003; du Croix Sissons et al., 2000). The recruitment zone for *Cyperus* spp. may be much deeper but it is likely that the majority of shoots emerge from tubers that sprout at relatively shallow depths due to the temperature fluctuation required to promote tuber sprouting (Sun and Nishimoto, 1997). Total weed control with fumigants should improve when the fumigants are applied to the recruitment zone of the weed species present within a field.

Weeds are consistently highlighted as one of the most significant pest management issues faced by Florida vegetable growers (Snodgrass et al., 2013). *Cyperus rotundus* L. and *C. esculentus* L. are two of the most problematic weeds across the southern United States. They

93 compete with crops for light, water, and nutrients (Webster, 2005). Previous research has shown
94 that large *Cyperus* populations reduce pepper yield by 70-73% (Morales-Payan et al., 1998;
95 Motis et al., 2003) and that even low densities (less than 5 nutsedge/m²) can reduce pepper yields
96 by 10%. Tomato yield can also be reduced as much as 50% with high *Cyperus* densities
97 (Gilreath and Santos, 2004). Many of the methyl bromide alternatives do not adequately control
98 nutsedge populations. This is especially true of *C. rotundus* which tends to be more tolerant to
99 many of the methyl bromide alternatives (Culpepper and Langston, 2004; Stall, 2000). Grass and
100 broadleaf weeds are also problematic. They emerge in the planting holes in plasticulture
101 production systems and compete with the crop for resources. The application of fumigants to
102 manage weeds within the recruitment zone may increase overall efficacy.

103 The objectives of this research were to: (1) compare the efficacy of metam potassium,
104 DMDS, DMDS + chloropicrin, and 1,3-D + chloropicrin on purple nutsedge (2) determine if
105 metam potassium applied in conjunction with other fumigants improves weed control, and (3)
106 determine if metam potassium placement improves efficacy on purple nutsedge and broadleaf
107 weeds.

110 **2. Materials and methods**

111 Experiments were conducted in the spring and fall of 2014 and the spring of 2015 at the Gulf
112 Coast Research and Education Center in Balm, FL, (27°N, 82°W) to evaluate multiple fumigant
113 combinations and placement for weed control and crop growth and yield. Soil type at the
114 research center is a Myakka fine sand (Sandy, Siliceous Hyperthermic Oxyaquic Alorthod). The
115 spring 2014 and spring 2015 site had a pH of 6.0, 1.5% organic matter and the soil was

composed of 98% sand, 1% silt, and 1% clay. The fall 2014 site had a pH of 6.8, 1% organic matter and the soil was composed of 95% sand, 4% silt, and 1% clay.

All three experiments were conducted as a randomized complete block design with four blocks with a 4 x 4 factorial treatment arrangement. The first factor was the primary fumigant applied with a 3 shank fumigation rig (Kennco Manufacturing, Ruskin, FL) with shanks set to evenly distribute fumigant at the base of the 20 cm tall and 81 cm wide bed. Treatments were 1) no fumigant, 2) 131 kg ha⁻¹ 1,3-D plus 200 kg ha⁻¹ chloropicrin (Pic-Clor 60), 3) 392 kg ha⁻¹ of DMDS (Paladin), and 4) 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin. Fumigants were applied during the bed shaping process. The second factor was the placement of 195 kg ha⁻¹ of metam potassium. Treatments were 1) no metam potassium, 2) metam placement at 30 cm from the bed top, 3) 10 cm from the bed top, and 4) applications at both 10 and 30 cm soil depths. Full rates were applied at both depths for treatment 4. The 30 cm application was made using a Yetter rig with three coulters spaced 20 cm apart on flat ground. The soil was harrowed to distribute the fumigant and the beds were formed immediately afterward. The metam potassium was distributed in approximately 10 cm of soil at the base of the 20 cm tall bed for a maximum depth of 30 cm. The 10 cm metam potassium application was made with a fumigation rig with six equally distributed fumigant shanks set to the appropriate depth. All beds were then covered with totally impermeable film (TIF), (Berry Plastics; spring 2014 and Raven Plastics; fall 2014 and spring 2015) immediately after fumigation.

Plot size was 22.9 m of a single raised bed. Beds were spaced 1.5 m apart and were 81.3 cm wide at the base, 71 cm wide at the top, and 20.3 cm tall. Beds were shaped, and fumigated on February 10 and August 7, 2014 and February 16, 2015. Two rows of drip tape were buried 2.5 cm beneath the soil surface and centered 20 to 23 cm apart down the center of each bed.

Tomatoes were transplanted in the center of the bed with 61 cm spacing between plants on March 11, 2014 (cv. Tygress), September 8, 2014 (cv Florida47), and March 9, 2015 (cv Charger) which corresponds to 29, 32, and 20 days after fumigation, respectively. Tomatoes were irrigated, fertilized, and managed for foliar pests as per industry standards in the region (Vallad et al. 2015).

The height of five tomato plants from the center of each plot was measured monthly. Tomato damage ratings were taken 2, 4, and 8 weeks after transplant using a 0 (no damage) to 100 (complete top kill). The visual damage scale was based on plot averages and represents a percentage of the non-treated control. The number of *C. rotundus* shoots emerging through the TIF mulch and in the planting hole was counted over the entire bed on March 19, April 7, May 7, and May 29 in the Spring 2014, September 23 and November 18 in the fall 2014 and April 19, May 19, March 12 and June 9 in the spring 2015. Ten tomato plants per plot were harvested on June 2 and June 10 for the spring 2014 trial and ten tomato plants per plot were harvested on October 30 and June 2 in the fall 2014 and spring 2015, respectively. All fruit was graded prior to weighing as small (<5.5 cm diameter), medium (5.5 cm < diameter <6.5 cm), large (6.5 cm < diameter <7 cm) or extra large (>7 cm).

Data were analyzed in SAS (version 9.2, SAS Institute Inc.) using the mixed procedure with block as the random factor. Seasons were analyzed separately as they were conducted as separate experiments and weather conditions varied between seasons. Means were compared using the least squares means statement in SAS with the Tukey adjustment. Data were checked for normality and constant variance prior to analysis. Data that were collected over time were analyzed using the repeated statement in SAS.

The partial budgeting method was used to analyze the cost and benefit of fumigation treatments. Partial budgeting only considers changes in revenues and costs attributed to changes in production practices. The change in costs relative to the control was compared with the change in the revenue for each treatment to calculate the net benefit (or loss) due to the changing fumigation practice. Change in revenue was based on yield changes. Non-fumigation inputs such as fertilizer, transplants, and chemicals were assumed to be unaffected by treatments. Fumigant costs were calculated based on market prices as of fall 2015. Tomato revenues were calculated using average spring prices over 2014 and 2015 and average fall prices over the same period at Florida shipping points.

3. Results and discussion

3.1 Tomato growth and yield

In spring 2014, there was a significant time by fumigant interaction ($p=0.0046$) for tomato damage and 1,3-D+Pic caused greater damage 4 weeks after transplant (April 10) than DMDS+Pic which caused greater damage than DMDS or the nontreated control (Fig. 1). The visual injury difference had largely disappeared by 8 weeks after transplant (May 8) but the plants where 1,3-D+Pic was injected had 23-25% fewer flowers per plant 4 weeks after transplant than all other treatments (data not shown). The effect of fumigant on tomato plant height did not differ over time and as a result seasonal averages are presented (Table 1). Tomato height in spring 2014 was unaffected by fumigant type ($p=0.0451$). A similar trend was observed with percent green leaf tissue measured at harvest. Plants had 32% more green leaf tissue that was not affected by southern blight (*Sclerotium rolfsii* Sacc.) when they were growing in soil that had been treated with 1,3-D+Pic compared to the nontreated control (data not shown).

In the same season, there was no difference among treatments in total tomato yield ($p=0.1118$) (Table 2). Our results suggest that 1,3-D or Pic caused minor early season damage that affected damage ratings and flower number but not height. The plants had less disease incidence at season end (data not shown) than the nontreated control and there were no yield differences (Table 2). It is well known that 1,3-D can persist in cool, wet soil conditions as are frequently observed in the spring in Florida and can cause early season phytotoxicity (Desaeger and Csinos, 2005; Desaeger et al., 2008).

The same trends did not occur in fall 2014 and spring 2015. In both cases, no visible tomato damage was observed (data not shown). In fall 2014, there was a significant time by fumigant ($p=0.0367$) and time by metam potassium placement ($p=0.0110$) interaction on tomato height. In both cases, the earliest height measurement did not differ among treatments but approximately one month later plants growing in soil fumigated with DMDS+Pic and 1,3-D+Pic were slightly taller than plants growing in nontreated soils or those fumigated with DMDS (Figure 2). Plants were also slightly taller in soil that was fumigated with shallow applications of supplemental metam potassium versus no supplemental fumigation or placement of the supplemental fumigant at only 30 cm. In spring 2015, there was no time by fumigant interaction ($p=0.3150$) but fumigant had a significant effect on average tomato height ($p=0.0143$). Metam potassium placement did not effect height ($p=0.8982$). As was noted in fall 2014, plants growing where the fumigant combination included Pic tended to be taller than where plants were treated with DMDS alone or the nontreated. In every season, height differences among treatments were small and likely of little biological significance. However, our results across seasons do support previous research that has shown that the addition of Pic can improve overall plant health

(Jacoby et al., 2015) even in situations where early season damage occurs as was the case in spring 2014.

In spring 2014 and 2015, tomato fruit were collected and graded on two dates. In fall 2014, only one harvest was collected due to a severe disease outbreak. In all trials, there were no consistent yield trends in the various grading categories and as a result only the total yield is presented (Table 2). Metam potassium placement had no effect on yield in any season. In spring and fall 2014, none of the treatments differed significantly from the nontreated control. In spring 2015, the 1,3-D+Pic treatment had higher yields than the nontreated control and the DMDS treatment but not the DMDS+Pic. In two of three years all fumigant treatments were not different from the nontreated control in terms of tomato yield. Our results indicate that nutsedge densities present in this study were not adequate to reduce tomato yields.

3.2 *C. rotundus* density

There was a significant interaction between fumigant and metam potassium placement in spring 2014 ($p=0.0012$), fall 2014 ($p=0.0001$), and spring 2015 ($p=0.0122$). In fall 2014 and spring 2015, metam potassium applications at 10 cm with no additional fumigants reduced *C. rotundus* density by 92 and 64% respectively compared to the nontreated control (Table 3). Though not significant, a similar trend was noted in spring 2014. Bielinski and Gilreath (2007) reported similar *C. rotundus* reduction when metam potassium was injected through a drip tape at a similar rate. Metam potassium applications at 30 cm were much less effective in fall 2014 and spring 2015 than 10 cm applications. DMDS tended to be more effective than metam potassium at 30 cm and reduced nutsedge density by 95 and 84% compared to the nontreated control in fall 2014 and spring 2015, respectively. Metam potassium applications at 10 cm

combined with DMDS tended to be more effective than DMDS alone with an 80-100% reduction in *C. rotundus*. Metam potassium applications applied both at 10 and 30 cm did not improve *C. rotundus* control versus a single application at 10 cm.

Combinations of DMDS+Pic, 1,3-D+Pic or DMDS+metam potassium applied at 10 cm were equally effective on *C. rotundus* with an 83 to 100% density reduction. Our results do not support the assumption that DMDS is more effective for *C. rotundus* control than 1,3-D+Pic. It is worth noting that 1,3-D+Pic is not typically applied with TIF and results may have been different had we included a 1,3-D+Pic under VIF. DMDS+metam potassium was as effective as any of the fumigant combinations that included chloropicrin. Supplemental metam potassium added no additional benefit when combined with DMDS+Pic or 1,3-D+Pic within any experimental season.

3.3 Broadleaf weed density

Fumigation significantly reduced broadleaf weeds emerging in the planting holes in fall 2014 ($p=0.0027$) and spring 2015 ($p<0.0001$), (Table 4). In spring 2014, there were no significant differences. Broadleaf weed control in the fall 2014 and spring 2015 ranged from 58 to 100% with no difference among fumigant treatments. Metam potassium applied at 10 cm reduced broadleaf weeds by 79 and 63% in the spring 2014 ($p=0.0010$) and 2015 ($p=0.0002$), respectively. Though only significant in one of three years, our results suggest that shallow (10 cm) metam potassium applications are more effective than deep (30 cm) applications at controlling broadleaf weeds. The research was initiated in part to determine if supplemental metam potassium following Pic, 1,3-D or DMDS would improve weed control as was observed

by Haar et al. (2003). This did not occur and we conclude that, at low weed densities, all of the fumigants evaluated in this study provided equivalent broadleaf weed suppression.

3.4 Costs and benefits

The cost of metam potassium applied alone was substantially less than the other fumigant treatments evaluated in this experiment. Without supplemental metam potassium, 1,3-D+Pic was the most expensive fumigant treatment (\$2,981/ha) followed by DMDS+Pic (\$2,182/ha), (Table 5). The material cost for supplemental metam potassium applications was approximately \$645 ha⁻¹ (Table 5) which is substantially more than the cost for most herbicides used for nutsedge or broadleaf weed control. However, DMDS+metam potassium was as effective in terms of nutsedge control as 1,3-D+Pic and was \$259 ha⁻¹ cheaper.

The total revenue for all fumigant treatments was not significantly different in any season (Table 6). The net benefit in spring 2014 for DMDS, DMDS+pic, 1,3-D+Pic was \$680, -\$6,640, and -\$9,340/ha, respectively, relative to the nontreated control. The net benefit of DMDS was significantly higher than DMDS+pic and 1,3-D+Pic. The same trend did not occur in fall 2014 or spring 2015. In fact, the net benefit for DMDS tended to be lower than all other treatments in fall 2014 and spring 2015.

4. Conclusions

Tomato yields were unaffected by fumigant treatments in two of three seasons. Metam potassium applications reduced *C. rotundus* density but were not as effective as 1,3-D+Pic or DMDS+Pic. Metam potassium reduced *C. rotundus* density when applied with DMDS but not DMDS+Pic or 1,3-D+Pic. All fumigants reduced broadleaf and grass weeds in the plantings

holes and shallow (10 cm) applications of supplemental metam potassium were more effective than deep applications (30 cm). DMDS generated higher net benefit than the other two fumigants used in spring 2014, but it did not outperform other fumigants in other seasons. The use of supplemental metam potassium increased costs by \$787 ha⁻¹ but DMDS with supplemental metam potassium remained cheaper than 1,3-D+Pic but not DMDS+Pic.

Acknowledgments

The authors would like to thank Arkema for providing the fumigant used in this research as well as Mike Sweat, Amy Hays, Fnu Kiran, Nicole Billera and the farm crew at GCREC for assistance with fumigation and data collection. Funding for this project was provided in part by the USDA NIFA Integrated Research, Education, and Extension Competitive Grants Program - Methyl Bromide Transition

References

- Ajwa, A.A., Klose, S., Nelson, S.D., Minuto, A, Gullino, M.L., Lamberti, F., Lopez-Aranda, J.M. 2003. Alternatives to methyl bromide in strawberry production in the United States of America and the Mediterranean region. *Phytopathol. Mediterr.* 42, 220-244.
- Bielinski, M.S., J.P. Gilreath. 2007. Effects of water delivery volume, rates, and concentrations of metam potassium on purple nutsedge emergence in mulched beds. *HortTechnology.* 17, 191-194.

297

298 Boyd, N.S., Van Acker, R.C. 2003. The effect of depth and fluctuationg soil moisture on the
 299 emergence of eight annual and six perennial plant species. *Weed Sci.* 51, 725-730.

300

301 Culpepper, A. S., Langston, D.L. 2004. Methyl bromide alternatives for nutsedge in
 302 pepper. *Proc. South. Weed Sci. Soc.* 57, 142.

303

304 Desaegeer, J.A., Csinos, A. 2005. Phytotoxicity associated with drip-applied 1,3-dichloropropene
 305 and chloropicrin in vegetables produced with plastic mulch. *HortScience.* 40, 700-706.

306

307 Desaegeer, J.A., Seebold, K.W., Csinos, A.S. 2008. Effect of application timing and method on
 308 efficacy and phytotoxicity of 1,3-D, chloropicrin, and metam-sodium combinations in squash
 309 plasticulture. *Pest Manag Sci.* 64, 230-238.

310

311 du Croix Sissons, M.J., Van Acker, R.C., Derksen, D.A., Thomas, A.G. 2000. Depth of
 312 seedling recruitment of five weed species measured in situ in conventional and zero-tillage
 313 fields. *Weed Sci.* 48, 327-332.

314

315 Duniway, J.M. 2002. Status of chemical alternatives to methyl bromide for pre-plant fumigation
 316 of soil. *Phytopathology.* 92, 1337-1343.

317

318 Fennimore, S.A., Haar, M.J., Ajwa, H.A. 2003. Weed control in strawberry provided by shank-
 319 and drip-applied methyl bromide alternative fumigants. *HortScience.* 38, 55-61.

320

321 Gilreath, J.P., Santos, B.M. 2004. Efficacy of methyl bromide alternatives on purple
322 nutsedge control (*Cyperus rotundus*) in tomato and pepper. *Weed Technol.* 18, 141-145.

323

324 Gilreath, J.P., Santos, B.M., Motis, T.M., Noling, J.W., Mirusso, J.M. 2005. Methyl bromide
325 alternatives for nematode and *Cyperus* control in bell pepper (*Capsicum annuum*). *Crop*
326 *Protection.* 24, 903-908.

327

328 Haar M.J., Fennimore, S.A., Ajwa, H.A., Winterbottom, C.Q. 2003. Chloropicrin effect on weed
329 seed viability. *Crop Protection.* 22, 109-115.

330

331 Hutchinson, C.M., McGiffen Jr, M.E., Ohr, H.D., Sims, J.J., Becker, J.O. 2000. Efficacy of
332 methyl iodide and synergy with chloropicrin for control of fungi. *Pest Manag Sci.* 56, 413-418.

333

334 Jacoby, T.J., Vallad, G., Boyd, N.S., Noling, J. 2015. Large-Scale Evaluation of Supplemental
335 Chloropicrin Applications to Manage Fusarium Wilt in Commercial Tomato Production. *Annual*
336 *International Research Conference on Methyl Bromide Alternatives and Emissions Reductions.*
337 *San Diego, CA.*

338

339 Locascio S.J., Gilreath, J.P., Dickson, D.W., Kucharek, T.A., Jones, J.P., Noling, J.W. 1997.
340 Fumigant alternatives to methyl bromide for polyethylene-mulched tomato. *HortScience.* 32,
341 1208-1211.

342

343 McAvoy, T., Freeman, J.H. 2013. Yellow nutsedge (*Cyperus esculentus*) control with reduced
 344 rates of dimethyl disulfide in combination with totally impermeable film. *Weed Technol.* 27,
 345 515-519.
 346
 347 Motis, T.M., Locascio, S.J., Gilreath, J.P., Stall, W.M. 2003. Season-long interference of yellow
 348 nutsedge (*Cyperus esculentus*) with polyethylene-mulched bell pepper (*Capsicum annuum*).
 349 *Weed Technol.* 17, 543-549.
 350
 351 Morales-Payan, J.P., Santos, B.M., Stall, W.M., Bewick, T.A. 1998. Influence of purple nutsedge
 352 (*Cyperus rotundus*) population densities on bell pepper (*Capsicum annuum*) yield as influenced
 353 by nitrogen. *Weed Technol.* 12, 230-234.
 354
 355 Noling, J.W., Becker, J.O. 1994. The challenge of research and extension to define and
 356 implement alternatives to methyl bromide. *J Nematol.* 26, 573-586.
 357
 358 Noling J. 2015. Resolving fumigant performance inconsistencies with vertical management
 359 zones. Annual International Research Conference on Methyl Bromide Alternatives and
 360 Emissions Reductions. San Diego, CA.
 361
 362 Santos, B.M., Gilreath, J.P., Motis, T.N., Noling, J.W., Jones, J.P., Norton, J.A. 2006.
 363 Comparing methyl bromide alternatives for soilborne disease, nematode and weed management
 364 in fresh market tomato. *Crop Protection.* 25, 690-695.
 365

366 Santos B.M. 2009. Drip-applied metam potassium and herbicides as methyl bromide
367 alternatives for *Cyperus* control in tomato. Crop Protection. 28, 68-71.
368

369 Snodgrass C, Ozores-Hampton, M., MacRae, A., Noling, J. 2013. Fumigation practices and
370 challenges among Florida tomato growers: Survey results. The Florida Tomato Proceedings, Pp
371 20-21.
372

373 Stall, W. 2000. Methyl bromide alternatives field day. North Florida Research and
374 Education Center - Suwannee Valley. Live Oak, FL.
375

376 Sun, W.H., Nishimoto, R.K. 1997. Dormancy release of purple nutsedge tuber buds by a single
377 thermal pulse. J Am Soc Hort Sci 122, 306-309.
378

379 Webster T.M. 2005. Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow
380 nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53, 839-845
381

Table 1. Tomato heights following fumigation averaged over time and across metam potassium treatments¹ at the Gulf Coast Research and Education Center in Balm, Florida.

Fumigant	Spring 2014	Fall 2014	Spring 2015
	-----cm-----		
Nontreated Control	80 (1.8) ² b ³	40 (3.9) b	56 (4.8) b
Dimethyl disulfide ⁴	84 (1.8) a	40 (4.1) b	61 (5.9) ab
Dimethyl disulfide + Pic	82 (2.0) ab	42 (4.3) a	60 (5.9) b
1,3-D + Pic	83 (2.2) a	42 (4.3) a	63 (6.3) a
P value	0.0451	0.0014	0.0550

¹Metam potassium treatments were no supplemental metam potassium or 195 kg ha⁻¹

supplemental metam potassium injected at 10 cm, 30 cm, or both depths.

²numbers in brackets are the standard error of the mean.

³means followed by the same letter are not significantly different based on Tukey adjusted mean comparisons at p<0.05.

⁴Fumigant rates were 392 kg ha⁻¹ of dimethyl disulfide (DMDS), 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin (Pic), or 131 kg ha⁻¹ 1,3-dichloropropene (1,3-D) plus 200 kg ha⁻¹ Pic.

Table 2. Total tomato yields based on the harvest of 10 plants per plot that were treated with different fumigants and averaged across metam potassium treatments¹ at the Gulf Coast Research and Education Center in Balm, Florida.

Fumigant	Spring	Fall	Spring
	2014	2014	2015
	-----T ha ⁻¹ -----		
Nontreated Control	31.40 (1.2) ²	12.15 (1.1)	47.03 (2.4) b ³
Dimethyl disulfide ⁴	32.79 (1.1)	12.91 (1.1)	47.18 (2.0) b
Dimethyl disulfide + Pic	30.28 (1.2)	14.65 (1.0)	51.38 (2.2) ab
1,3-D + Pic	28.51 (1.5)	12.98 (1.1)	56.09 (1.8) a
P value	0.1118	0.1784	0.0143

¹Metam potassium treatments were either no supplemental metam potassium or 195 kg ha⁻¹ supplemental metam potassium injected at 10 cm, 30 cm, or both depths.

²numbers in brackets are the standard error of the mean.

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Table 3. *Cyperus rotundus* shoots that emerged through the plastic mulch (based on counts within 9.94 m²) following fumigation treatments averaged across multiple counting dates at the Gulf Coast Research and Education Center in Balm, Florida.

Fumigant	Metam potassium placement	Spring 2014	Fall 2014	Spring 2015
----- <i>C. rotundus</i> shoots ha ⁻¹ -----				
Nontreated Control	None	14,727 a ¹	24,657 a	98,908 a
	10 cm ⁴	9,914 ab	2,071 bc	35,064 bc
	30 cm	9,416 ab	9,248 ab	53,180 ab
	10 & 30 cm	8,582 ab	1,067 c	36,873 bc
Dimethyl disulfide	None	5,793 ab	1,164 c	16,245 ef
	10 cm	1,179 d	0 c	10,000 f
	30 cm	4,243 bc	1,629 c	23,998 cde
	10 & 30 cm	1,000 d	0 c	13,642 ef
Dimethyl disulfide + Pic	None	1,892 cd	0 c	13,733 ef
	10 cm	1,051 d	0 c	11,680 f
	30 cm	1,329 d	586 c	12,197 ef
	10 & 30 cm	1,182 d	0 c	10,000 f
1,3-D + Pic	None	1,173 d	1,840 c	16,996 ef
	10 cm	1,122 d	1,157 c	10,000 f
	30 cm	1,548 cd	658 c	17,621 def
	10 & 30 cm	1,122 d	0 c	11,979 ef
P value		0.0012	<0.0001	0.0122

¹means followed by the same letter within columns are not significantly different based on Tukey adjusted mean comparisons at $p < 0.05$.

²Fumigant rates were 392 kg ha⁻¹ of dimethyl disulfide (DMDS), 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin (Pic), or 131 kg ha⁻¹ 1,3-dichloropropene (1,3-D) plus 200 kg ha⁻¹ Pic.

⁴The metam potassium application rate was 195 kg ha⁻¹. The 10 cm treatment was applied with six equally distributed shanks and the 30 cm treatment was applied prior to bed formation with a Yetter rig with three coulters followed by a single pass with a spring-tine harrow to improve horizontal distribution.

Table 4. Broadleaf weeds¹ that emerged in the planting holes following fumigation at the Gulf Coast Research and Education Center in Balm, Florida in spring 2014, fall 2014, and spring 2015.

Fumigation Treatments	Spring 2014	Fall 2014	Spring 2015
	-----# ha ⁻¹ -----		
<u>Fumigant</u>			
Nontreated Control	1,288	308 a ²	3,144 a
Dimethyl disulfide ³	700	0 b	1,333 b
Dimethyl disulfide + Pic	504	0 b	939 b
1,3-D + Pic	448	0 b	822 b
P value	0.0952	0.0027	<0.0001
<u>Metam Potassium Placement</u>			
None	1,625 a	196	2,226 a
10 cm ⁴	336 b	112	834 b
30 cm	811 b	0	2,139 a
10 & 30 cm	168 b	0	815 b
P value	0.0010	0.1147	0.0002

¹Predominate broadleaf weed species present at all three experimental sites were *Amaranthus* spp., *Eclipta prostrata* (L.) L., *Solanum americanum* P. Mill., *Richardia brasiliensis* (Moq.) Gomez, *Oenothera laciniata* Hill, and *Mollugo verticillata* L.

²means followed by the same letter are not significantly different based on Tukey adjusted mean comparisons at p<0.05.

³Fumigant rates were 392 kg ha⁻¹ of dimethyl disulfide (DMDS), 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin (Pic), or 131 kg ha⁻¹ 1,3-dichloropropene (1,3-D) plus 200 kg ha⁻¹ Pic.

⁴The metam potassium application rate was 195 kg ha⁻¹. The 10 cm treatment was applied with six equally distributed shanks and the 30 cm treatment was applied prior to bed formation with a Yetter rig with three coulters followed by a single pass with a spring-tine harrow to improve horizontal distribution.

Table 5. Estimated costs of materials, labor, and equipment of fumigant treatments applied at the Gulf Coast Research and Education Center in Balm, FL.

Fumigant	Metam potassium placement	Material costs	Labor costs	Equipment costs	Total
-----\$ ha ⁻¹ -----					
Nontreated Control	None	0	0	0	0
	10 cm	645	79	205	929
	30 cm	645	79	205	929
	10 & 30 cm	1,290	158	410	1,858
Dimethyl disulfide	None	1,793	40	103	1,935
	10 cm	2,438	79	205	2,722
	30 cm	2,438	79	205	2,722
	10 & 30 cm	3,083	158	410	3,652
Dimethyl disulfide + Pic	None	2,040	40	103	2,182
	10 cm	2,685	79	205	2,969
	30 cm	2,685	79	205	2,969
	10 & 30 cm	3,330	158	410	3,899
1,3-D + Pic	None	2,839	40	103	2,981
	10 cm	3,484	79	205	3,768
	30 cm	3,484	79	205	3,768
	10 & 30 cm	4,129	158	410	4,698

³Fumigant rates were 392 kg ha⁻¹ of dimethyl disulfide (DMDS), 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin (Pic), or 131 kg ha⁻¹ 1,3-dichloropropene (1,3-D) plus 200 kg ha⁻¹ Pic.

⁴The metam potassium application rate was 195 kg ha⁻¹. The 10 cm treatment was applied with six equally distributed shanks and the 30 cm treatment was applied prior to bed formation with a Yetter rig with three coulters followed by a single pass with a spring-tine harrow to improve horizontal distribution.

Table 6. Tomato total revenues (Total) and net benefits (Net) (\$1,000/ha) in plots treated with different fumigants averaged across metam potassium treatments at the Gulf Coast Research and Education Center in Balm, Florida¹.

Fumigant	Spring 2014		Fall 2014		Spring 2015	
	-----\$1,000 ha ⁻¹ -----					
	Total	Net	Total	Net	Total	Net
Nontreated Control	51.73(2.0) ²	--	20.06 (1.9)	--	57.47(2.9)	--
Dimethyl disulfide ³	53.77 (1.9)	0.68(3.0)a	19.57 (2.0)	-0.28(4.2)	58.33(2.5)	1.69(4.4)
Dimethyl disulfide +Pic	46.69 (3.3)	-6.64(2.5)b	22.31 (1.6)	4.87(3.0)	62.09 (5.0)	6.74(7.7)
1,3-D + Pic	44.80 (3.4)	-9.34 (3.7)b	18.64 (1.9)	-0.57(3.1)	64.68(4.6)	10.42(6.7)
P value	0.2420	0.0250	0.1784	0.5401	0.2581	0.4651

¹net benefits are benefits of different fumigation treatments compared to the nontreated control.

²numbers in brackets are the standard error of the mean.

³means followed by the same letter are not significantly different based on Tukey adjusted mean comparisons at p<0.05.

⁴Fumigant rates were 392 kg ha⁻¹ of dimethyl disulfide (DMDS), 340 kg ha⁻¹ of DMDS plus 90 kg ha⁻¹ of chloropicrin (Pic), or 131 kg ha⁻¹ 1,3-dichloropropene (1,3-D) plus 200 kg ha⁻¹ Pic.

Figure 1. Effect of fumigant type on tomato damage following transplant into fumigated soil in spring 2014 at the Gulf Coast Research and Education Center in Balm, Florida. Error bars represent the standard error of the mean. Means followed by the same letter are not significantly different based on Tukey adjusted mean comparisons at $p < 0.05$.

Figure 2. Effect of fumigant type and the placement depth of metam potassium on tomato height following transplant into fumigated soil in fall 2014 at the Gulf Coast Research and Education Center in Balm, Florida. Error bars represent the standard error of the mean. Means followed by the same letter are not significantly different based on Tukey adjusted mean comparisons at $p < 0.05$.

Figure 1

Figure 2