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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.)

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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 then 1,3-D + Pic but not DMDS + Pic. DMDS + Pic had the lowest estimated total cost of the three best *C. rotundus* treatments.

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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

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(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 volatize 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 compete with crops for light, water, and nutrients (Webster, 2005). Previous research has shown that large *Cyperus* populations reduce pepper yield by 70–73% (Morales-Payan et al., 1998; Motis et al., 2003) and that even low densities (less then 5 nutsedge/m^2) can reduce pepper yields by 10%. Tomato yield can also be reduced as much as 50% with high *Cyperus* densities (Gilreath and Santos, 2004). Many of the methyl bromide alternatives do not adequately control nutsedge populations. This is especially true of *C. rotundus* which tends to be more tolerant to many of the methyl bromide alternatives (Culpepper and Langston, 2004; Stall, 2000). Grass and broadleaf weeds are also problematic. They emerge in the planting holes in plasticulture production systems and compete with the crop for resources. The application of fumigants to manage weeds within the recruitment zone may increase overall efficacy.

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

2. Materials and methods

Experiments were conducted in the spring and fall of 2014 and the spring of 2015 at the Gulf Coast Research and Education Center in Balm, FL, (27°N, 82°W) to evaluate multiple fumigant combinations and placement for weed control and crop growth and yield. Soil type at the research center is a Myakka fine sand (Sandy, Siliceous Hyperthermic Oxyaquic Alorthod). The 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 × 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 20–23 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.

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