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Methyl bromide alternatives for nematode and *Cyperus* control in bell pepper (*Capsicum annuum*)

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Abstract

Three field trials were conducted to determine the efficacy of fumigant and herbicide combinations on nematode and *Cyperus* control in bell pepper (*Capsicum annuum* L.). Various in-bed, broadcast and drip-applied fumigants were combined with napropamide, trifluralin, and a non-herbicide treated control. Results indicated that during all the three bell pepper seasons, metham sodium plus chloropicrin (MNa + Pic), and both the gas and emulsifiable formulations of 1,3-dichloropropene (1,3-D) plus Pic provided equal or better *Meloidogyne* control than methyl bromide (MBr) plus Pic. For *Heterodera* and *Belonolaimus* control, MNa + Pic and both formulations of 1,3-D + Pic were equally effective as MBr + Pic during the three bell pepper trials. For *Cyperus* control, the herbicides failed to improve weed control. For the fumigants, MBr + Pic consistently controlled the weed better than the others. However, most of the MBr alternatives reduced *Cyperus* populations with respect to the non-fumigant control. For bell pepper yield, the application of MNa and MNa + Pic provided similar fruit weight as for MBr + Pic in two of the three seasons.

Keywords: 1,3-dichloropropene; Chloropicrin; Metham sodium; Napropamide; Trifluralin

1. Introduction

Nematode and weed pressure in bell pepper (*Capsicum annuum* L.) is one of the most challenging situations faced by growers throughout the world. *Meloidogyne*, *Heterodera*, and *Belonolaimus* are among the most common nematode genera found affecting bell pepper fields in the USA, causing significant root damage and consequently yield reduction. Likewise, *Cyperus rotundus* L. and *C. esculentus* L. are the most troublesome weeds in polyethylene-mulched bell pepper. These two *Cyperus* species grow in mixed stands, and penetrate plastic mulch and compete with the crop, reducing bell pepper yields up to 73% (Morales-Payan et al., 1998).

In contrast with broad acre field crops, there are few herbicides registered in the USA for season-long weed control in bell pepper (Stall and Gilreath, 2002). The combined use of polyethylene mulch, broad-spectrum fumigants, and herbicides has been the main pest management alternative in bell pepper production (Maynard et al., 2003). However, there are no herbicides available to control these weeds in the crop (Stall and Gilreath, 2002). The most common nematode and *Cyperus* management strategy has been in-bed fumigations with methyl bromide (MBr). However, MBr is listed as a significant ozone-depleting agent, affecting the upper atmosphere. In compliance with the USA Clean Air Act and provisions of the Montreal Protocol Agreement, MBr is being phased-out from the market,

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leading to research efforts to find suitable replacements for agricultural production (Watson et al., 1992).

Previous studies have indicated the potential of different broad-spectrum fumigants, such as the nematicide 1,3-dichloropropene (1,3-D) combined with the fungicide chloropicrin (Pic) (Gilreath et al., 1994; Jones et al., 1995). However, *Cyperus* management continues to be a major challenge in the crop. 1,3-D plus Pic is sold either as a gas formulation for soil injection with chisels or similar equipment, or as an emulsifiable concentrate (EC), which can be applied through the microirrigation lines.

The broadcast application of 1,3-D plus Pic has been presented as a potential method to increase pest exposure to the fumigant gases (Gilreath et al., 2002). An effective dosage of a fumigant is a combination of a specific fumigant concentration over an extended duration of exposure. Currently, there are deep-injectors available in the market, such as the Yetter Avenger coulter applicator (Yetter Farm Equipment, Colchester, Illinois, USA), which applies at a depth of 30 cm in non-bedded soil. The large coulters and rear sealing wheels on the Yetter rig cut through strings, old plastic mulch, and other residue, which normally would hang on gas knives, reducing fumigant volatilization.

Another fumigant, metham sodium (MNa), has been the subject of research in cucumber (*Cucumis sativus* L.) and tomato (*Lycopersicon esculentum* Mill.). In these two crops, this fumigant has shown to be effective against *Meloidogyne* root galling (Gilreath et al., 2004a, b, c). However, MNa has been inconsistent against *Cyperus* (Locascio et al., 1997; Gilreath and Santos, 2004a; Gilreath et al., 2004c). Because of this inconsistency, adding a preplant incorporated herbicide, such as pebulate, before fumigant injection has been tested and successfully controlled *Cyperus* in tomato (Gilreath and Santos, 2004b; Gilreath et al., 2004d). However, pebulate is injurious to bell pepper and is no longer registered for use in the USA. Therefore, other herbicide options in combination with fumigants must be explored in an attempt to improve *Cyperus* control. The objective of this research was to determine the efficacy of fumigant and herbicide combinations on nematode and *Cyperus* control in bell pepper.

2. Materials and methods

Three field trials were conducted in consecutive seasons—during fall 2001, and spring and fall 2002 at the Gulf Coast Research and Education Center in Bradenton, Florida, USA. Research plots were located on an EauGallie fine sand spodosol, with pH 6.3 and organic matter content <2%. The experimental site has a history of heavy nematode and *Cyperus* infestations. Based on previous soil analysis and crop nutritional requirements, the fields received a broadcast application of 285 kg/ha of 15N-0P-25 K as starter fertilizer (Maynard et al., 2003). Prior to treatment establishment, the plots were disked twice before planting bed formation.

Fumigant treatments were: (a) non-treated control, (b) in-bed applied MBr plus Pic (67:33 v/v) at a dose of 400 kg/ha, (c) the gas formulation of 1,3-D plus Pic broadcast-applied at 330 L/ha, (d) the EC formulation of 1,3-D plus Pic drip-applied at 330 L/ha, (e) drip-applied MNa at 710 L/ha, and (f) broadcast-applied Pic at 150 kg/ha followed by drip-applied MNa at 710 L/ha. Herbicide treatments were napropamide at a dose of 2.3 kg ai/ha, trifluralin at 7.1 kg ai/ha, and a non-treated control. All the treatments were arranged in a split-plot design with six replications, in which fumigants were the main plots.

Planting beds were 80 cm wide at the base, 70 cm wide at the top, 20 cm high, and spaced 150 cm apart on centers. On the day of fumigant injection, planting beds were formed and the herbicides were applied on the bed surfaces and incorporated 20 cm below the surface with a tractor-powered rototiller. All herbicides were sprayed using a tractor mounted three-nozzle boom with 8004 flat fan nozzles. Spraying volume was 430 L/ha, and the application lines were pressurized with CO_2 at 240 kPa. MBr plus Pic, and Pic were injected 15 to 20 cm deep into the finished bed using a N-propelled fumigation rig with three chisels per bed. Each chisel was spaced 30 cm apart. Broadcast 1,3-D plus Pic application was achieved with a Yetter coulter rig delivering the fumigant at 20 cm below the soil surface. The drip-applied fumigants were delivered with an irrigation flow of approximately 5.6 L/min/100 m of row (T-Tape Systems®, San Diego, California, USA). The fumigant dosages were achieved by mixing the given amount of the product in a delivery volume of 100 m^3 water.

Immediately after herbicide and fumigant application, beds were pressed and covered with low-density polyethylene film (0.038 mm thick; Pliant Corp., Schaumburg, Illinois, USA). Two drip irrigation lines were placed 30 cm apart under the mulch film and buried 2.5 cm deep. Emitters were spaced every 30 cm. Drip irrigation was provided daily and additional N and K were supplied to the crop by daily injections of approximately 2.8 and 2.2 kg/ha of N and K, respectively. Besides drip irrigation, continuous subsurface irrigation maintained the water table at 45 cm deep in order to reduce water stress. 'Admiral' bell pepper seedlings at the four-true-leaf stage were transplanted 3 weeks after treatment into the pressed beds. According to local pepper recommendations, insecticides and fungicides were applied as necessary beginning 3 weeks after transplanting (Maynard et al., 2003).

Nematode populations were determined between 12 and 14 weeks after treatment by extracting soil samples with a soil probe (2.5 cm wide by 20 cm deep) from the rhizosphere of 20 bell pepper plants per plot, and the nematodes were separated and counted from 100 cm^3 soil using a standard sieving and centrifugation procedure (Jenkins, 1964). In all the bell pepper seasons, the *Cyperus* population on the top of each bed was counted at 6 weeks after treatment. Additionally, weed counts were made at 14 weeks after treatment in the two fall seasons. Marketable pepper fruits (mature, green or red) were harvested two to three times each season. Fruit weight for each harvest was determined and added to obtain season total marketable yield. Treatment and season effects, and bell pepper marketable fruit weight were analyzed with ANOVA ($P = 0.05$). Both nematode by genus and *Cyperus* populations were examined with Friedman's non-parametric test (SAS Institute, 1999).

3. Results and discussion

There were significant season by treatment interactions, therefore each bell pepper season will be discussed separately.

Fall 2001: There were no significant herbicide, and herbicide by fumigant effects on nematode populations. Thus, only the fumigant treatments affected the populations of *Meloidogyne*, *Heterodera*, and *Belonolaimus*. At the end of the bell pepper cropping season, the non-fumigant control had higher *Meloidogyne*, *Heterodera*, and *Belonolaimus* counts than the average nematode populations for all the fumigants (Table 1). For *Meloidogyne* populations, 1,3-D + Pic EC and MNa + Pic were more effective controlling *Meloidogyne* spp. than MBr + Pic. However, there was no difference between 1,3-D + Pic and MBr + Pic, whereas MNa alone failed to reach the control level of MBr + Pic. When comparing the two 1,3-D + Pic formulations, the EC resulted in lower *Meloidogyne* counts than the gas formulation. The addition of Pic to the MNa injection improved MNa performance against *Meloidogyne. Heterodera* was equally controlled by all fumigants. For *Belonolaimus*, the application of MNa alone failed to improve control of this nematode in comparison with either MBr + Pic or MNa + Pic. There was no difference on *Belonolaimus* control between MBr + Pic and either 1,3-D + Pic, MNa + Pic, or 1,3-D + Pic EC.

At both 6 and 14 WAT, *Cyperus* densities were affected by both the fumigant and the herbicides. However, the fumigant by herbicide interactions were not significant. There was considerable weed pressure in the non-fumigated control, where *Cyperus* densities reached 75 and 379 plants/m^2, 6 and 14 WAT, respectively. At 6 WAT, the highest *Cyperus* density occurred in the non-fumigant control (Table 2). All the fumigants, except the gaseous formulation of 1,3-D + Pic, were equal to MBr + Pic for weed control. There were no differences on *Cyperus* counts between the two MNa treatments. However, 1,3-D + Pic EC was more effective than 1,3-D + Pic for weed control. At 14 WAT, *Cyperus* densities had a similar trend as that examined at 6 WAT, except that MNa had a lower weed density than MBr + Pic. For the herbicides, both trifluralin and napropamide had lower weed densities than the control, reducing *Cyperus* densities by 43% at 14 WAT. However, average densities of 41 and 110 plants/m^2 at 6 and 14 WAT in the herbicide-treated plots of 41 and 110 plants/m^2 are considered excessive for commercial bell pepper production.

The fumigants and herbicides independently influenced total bell pepper weight. However, the interaction of both factors was not significant. The addition of any of the fumigants increased fruit weight in comparison with the non-fumigated control. All fumigants, except 1,3-D + Pic, had equal fruit weight as MBr + Pic (Table 2). The emulsifiable formulation of 1,3-D + Pic had yields 18% higher than 1,3-D + Pic. The addition of Pic to MNa resulted in no significant change in bell pepper fruit weight. There was no yield difference between the untreated plot and the napropamide-sprayed treatments. Trifluralin application resulted in approximately 21% increase on bell pepper fruit weight.

Spring 2002: Soil fumigants affected the populations of all three nematode genera. However, the interaction between fumigant and herbicide was not significant. At the end of the cropping season, 1,3-D + Pic reduced the *Meloidogyne* population by more than 60% compared with MBr + Pic. For this nematode genus, there were no control differences between MBr + Pic and either 1,3-D + Pic EC, MNa, and MNa + Pic (Table 1). The gas formulation of 1,3-D + Pic decreased the *Meloidogyne* population by 67% in relation to the emulsifiable formulation of the same fumigant. For *Heterodera*, there were no differences between the fumigants, which resulted in average populations of <0.5 juveniles/100 mL. A similar situation occurred with *Belonolaimus*, with the exception of MNa, which failed to reach the control level of the other fumigants.

At 6 WAT, only the fumigants had a significant effect on *Cyperus* densities. The application of MBr + Pic was the most effective reducing the weed density (3 plants/m^2), whereas the other fumigants failed to reach this control level, with densities ranging from 69 to 136 plants/m^2 (Table 2). There was no improvement in *Cyperus* control when Pic was added to MNa, with an average density of 111 plants/m^2. Likewise, both 1,3-D + Pic formulations resulted in the same weed densities.

There was no significant fumigant by herbicide interaction or herbicide effect on bell pepper fruit weight. Only the fumigants had significant effect on yield. For the fumigants, MBr + Pic resulted in the same fruit yield as 1,3-D + Pic, MNa, and MNa + Pic, with

Table 1
Effect of soil fumigants on *Meloidogyne*, *Heterodera*, and *Belonolaimus* populations in bell pepper trials[a]

Treatments[b]	Dose per ha	Fall 2001			Spring 2002			Fall 2002		
		Meloidogyne	*Heterodera*	*Belonolaimus*	*Meloidogyne*	*Heterodera*	*Belonolaimus*	*Meloidogyne*	*Heterodera*	*Belonolaimus*
		number/100 mL soil								
Non-fumigant control	—	1418	1.8	1.4	1283	12.5	17.0	35	1.2	11.1
MBr + Pic	400 kg	366	0.2	0.0	1013	0.1	0.0	1	0.0	1.8
1,3-D + Pic	330 L	450	0.7	0.3	404	0.6	0.0	1	0.0	1.1
1,3-D + Pic EC	330 L	52	0.6	0.0	1221	0.1	0.0	2	0.1	0.0
MNa	710 L	502	0.4	1.5	796	0.2	6.3	11	0.2	0.0
MNa + Pic	710 L + 150 kg	69	0.0	0.0	1078	0.1	1.5	2	0.1	0.0
Fumigant single degree-of-freedom orthogonal contrasts										
Non-fumigant vs. fumigants		*	*	*	*	*	*	*	*	*
MBr + Pic vs. 1,3-D + Pic		NS	NS	NS	*	NS	NS	NS	NS	NS
MBr + Pic vs. 1,3-D + Pic EC		*	NS	NS	NS	NS	NS	NS	NS	NS
MBr + Pic vs. MNa		*	NS	*	NS	NS	*	*	NS	NS
MBr + Pic vs. MNa + Pic		*	NS	NS	NS	NS	NS	NS	NS	NS
1,3-D + Pic vs. 1,3-D + Pic EC		*	NS	NS	*	NS	NS	NS	NS	NS
MNa vs. MNa + Pic		*	NS	*	NS	NS	*	*	NS	NS

[a]Nematode populations analyzed with Friedman's non-parametric test. Data obtained between 12 and 14 weeks after treatment.
[b]Abbreviations: MBr = methyl bromide; Pic = chloropicrin; 1,3-D = 1,3-dichloropropene; EC = emulsifiable concentrate; MNa = metham sodium; NS = non-significant effect ($P > 0.05$).
* = significant effect ($P \leqslant 0.05$).

Table 2
Effect of soil fumigants on *Cyperus* densities and total marketable bell pepper fresh weight[a]

Treatments[b]	Dose per ha	Fall 2001			Spring 2002		Fall 2002		
		Cyperus		Weight t/ha	*Cyperus*	Weight t/ha	*Cyperus*		Weight t/ha
		6 WAT plants/m^2	14 WAT plants/m^2		6 WAT plants/m^2		6 WAT plants/m^2	14 WAT plants/m^2	
Non-fumigant control	—	75	379	24.0	135	11.2	165	303	6.0
MBr + Pic	400 kg	26	160	32.6	3	37.4	3	4	18.8
1,3-D + Pic	330 L	152	97	26.5	69	39.6	79	170	14.5
1,3-D + Pic EC	330 L	11	51	32.4	107	29.4	117	251	13.5
MNa	710 L	30	74	31.4	136	42.6	156	326	10.6
MNa + Pic	710 L + 150 kg	12	65	32.7	85	38.6	95	173	13.7
Non-herbicide control	—	72	194	28.0	187	31.0	107	209	12.0
Napropamide	2.3 kg	42	110	27.1	168	33.1	106	209	12.3
Trifluralin	7.1 kg	40	110	34.8	191	35.2	94	195	14.2
Fumigant single degree-of-freedom orthogonal contrasts									
Non-fumigant vs. fumigants		*	*	*	*	*	*	*	*
MBr + Pic vs. 1,3-D + Pic		*	*	*	*	NS	*	*	*
MBr + Pic vs. 1,3-D + Pic EC		NS	NS	NS	*	*	*	*	*
MBr + Pic vs. MNa		NS	*	NS	*	*	*	*	*
MBr + Pic vs. MNa + Pic		NS	NS	NS	*	NS	*	*	*
1,3-D + Pic vs. 1,3-D + Pic EC		*	*	*	NS	*	*	NS	NS
MNa vs. MNa + Pic		NS	NS	NS	NS	NS	*	*	*
Herbicide single degree-of-freedom orthogonal contrasts									
Non-herbicide vs. napropamide		*	*	NS	NS	NS	NS	NS	NS
Non-herbicide vs. trifluralin		*	*	*	NS	NS	NS	NS	NS
Napropamide vs. trifluralin		NS	NS	*	NS	NS	NS	NS	NS

[a] *Cyperus* densities analyzed with Friedman's non-parametric test.
[b] Abbreviations: MBr = methyl bromide; Pic = chloropicrin; 1,3-D = 1,3-dichloropropene; EC = emulsifiable concentrate; MNa = metham sodium; NS = non-significant effect ($P > 0.05$).
* = significant effect ($P \leqslant 0.05$), WAT = weeks after treatment.

values ranging between 37.4 and 42.6 t/ha, whereas the emulsifiable formulation of 1,3-D + Pic produced 21 and 26% less fruit weight than MBr + Pic, and 1,3-D + Pic, respectively (Table 2). The addition of Pic to MNa failed to improve fruit yield.

Fall 2002: There were significant fumigant effects on *Meloidogyne*, *Heterodera*, and *Belonolaimus* populations. At the end of the cropping season, all fumigants, except MNa, effectively controlled *Meloidogyne*, with $\leqslant 2$ juveniles/100 mL (Table 1). The addition of Pic to MNa improved the control of this nematode. There was no difference between the two 1,3-D + Pic formulations. All fumigants had excellent performance against *Heterodera* and *Belonolaimus*, with average populations of < 0.1 and < 1 juveniles/100 mL, respectively.

Weed pressure in the non-fumigated control was high, with densities of 165 and 303 plants/m^2 at 6 and 14 WAT, respectively. At 6 WAT, *Cyperus* densities were only affected by the fumigants. MBr + Pic had the lowest weed densities (3 plants/m^2) (Table 2). MNa alone had 64% more *Cyperus* plants than MNa + Pic. When comparing the two 1,3-D + Pic formulations, the gas formulation had 32% less *Cyperus* plants than the emulsifiable formulation. These same trends were observed at 14 WAT, excepting that no significant weed control difference was observed between the two 1,3-D + Pic formulations.

Only fumigants affected bell pepper fruit weight (Table 2). All MBr alternatives resulted in lower yield than MBr + Pic. Those treatments had fruit weights between 10.6 and 14.5 t/ha, which were in average 30% less than MBr + Pic (18.8 t/ha). There was no fruit weight difference between the two 1,3-D + Pic formulations. The addition of Pic to MNa improved bell pepper yield by 29%.

In summary, during all the three bell pepper seasons, MNa + Pic and both formulations of 1,3-D + Pic provided equal or better *Meloidogyne* control than MBr + Pic. In two of the three cropping seasons, adding Pic to MNa improved the performance against this nematode. For *Heterodera* and *Belonolaimus* control, MNa + Pic and both formulations of 1,3-D + Pic were equally effective as MBr + Pic in all the trials. Although MNa performed better than the non-fumigant control, this product failed to reach the control levels of the other fumigants in two of the seasons. Throughout the study, the gas formulation of 1,3-D + Pic resulted in the same nematode populations as for the emulsifiable formulation of this fumigant. For *Cyperus*, the herbicides failed to improve control, although in one season napropamide and trifluralin showed some activity. However, the resulting weed populations were still commercially unacceptable for bell pepper production. As a result, there were no differences in bell pepper fruit yield between napropamide and the non-herbicide control in all three trials, and between the control and trifluralin in two of the bell pepper seasons. For the fumigants, MBr + Pic consistently controlled the weed better than the others. Nevertheless, most of the MBr alternatives reduced *Cyperus* populations with respect to the non-fumigant control. For bell pepper yield, the application of MNa and MNa + Pic provided similar fruit weight as for MBr + Pic in two of the three seasons.

These results indicate that MNa and MNa + Pic could be considered potential MBr + Pic replacements in bell pepper production systems, based on their overall nematode and weed control levels. It has been suggested that the efficacy of 1,3-D + Pic, regardless of the formulation, could be increased by using thicker polyethylene films, such as virtually impermeable films, which increase fumigant retention in contrast with the standard low-density polyethylene mulch (Hochmuth et al., 2002; Wang et al., 1998; Yates et al., 1998). Therefore, further research should be conducted with more retentive type of polyethylene films to improve 1,3-D + Pic performance on *Cyperus* and nematodes.

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