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Application and crop safety parameters for soil fumigants

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Abstract

Metam sodium alone and in combination with 1,3-dichloropropene plus 17% chloropicrin (1,3-D + C-17) were evaluated under polyethylene mulch film as alternatives for methyl bromide in tobacco and tomato transplant production for both efficacy against pests and crop safety. Eight different weed species, 10 genera or species of fungi and several agronomic criteria were evaluated at three different sites. In general both the metam sodium alone and in combination with 1,3-D + C-17 were highly efficacious when compared to methyl bromide. Short polyethylene film retention times and short aeration times resulted in poor stands and poor crop vigor while relatively long polyethylene film retention times and long aeration periods at the same rates typically resulted in high stand counts and vigor. Combination treatments were more phytotoxic to germinating seed of tobacco and tomato. Vigor and stand counts of the seedlings were higher as aeration time increased, suggesting phytotoxic residues dissipate with time. Method of application of metam sodium, either injected with chisels or sprayed onto the soil surface and incorporated with a tractor-powered tiller alone or co- applied with 1,3-D + C-17 chisel injected, did not affect the efficacy of the treatments. Caution regarding phytotoxicity must be exercised when seeding into soil fumigated with metam sodium alone or combined with 1,3-D + C-17. Additional work will be required to establish safety periods required prior to transplanting crops into fumigated soil.

Keywords: Metam sodium; Chloropicrin; 1,3-dichloropropene; Tobacco; Tomato

1. Introduction

The production of tobacco (*Nicotiana tabacum* L.) and tomato (*Lycopersicon esculentum* Miller) requires vigorous pest-free transplants. In Georgia the majority of tobacco transplants, and to a lesser degree tomato and pepper transplants, are produced in methyl-bromide-fumigated soil beds. However, the use of methyl bromide will be phased out by 2005 in the USA, with scheduled reductions in the interim (USDA, 1999) as its use is implicated in the depletion of the stratospheric ozone layer. Since methyl bromide is a relatively safe broad spectrum biocide, it has become the industry standard for the last 50 years (Koch, 1951; Martin et al., 1955; Todd and Lucas, 1956). No other single pesticide is available that has a wide spectrum of activity and has been cost effective.

Drip irrigation application of 1,3-dichloropropene plus 32% chloropicrin and metam sodium (MS) provided good yield responses over the untreated control, when *Verticillium dahliae*, *Pythium* spp., and weeds were the primary pests (Ajwa and Trout, 1999). Poor nematode control with combinations of chloropicrin and metam sodium in tomato have been reported by Dickson et al. (1999). However, Csinos et al. (1997) have reported good activity for pest control, vigor and yield with combinations of 1,3-dichloropropene plus chloropicrin and metam sodium. Studies on polyethylene-mulched tomatoes in Florida indicated good to variable results with combinations of 1,3-D, chloropicrin and pebulate (Locascio et al., 1997).

Csinos et al. (2000) further defined rates of materials used in combinations and explored activity on an expanded pest range. Their work indicated that data collected from plots treated with metam sodium or methyl bromide (+2% chloropicrin) were not significantly different from each other for 76 of 79 parameters evaluated. However, metam sodium and 1,3-D + C-17

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combinations were equal or better in 77 of the 79 parameters evaluated.

Methyl iodide has been evaluated on a limited scale by several researchers (Sims et al., 1999; Noling and Gilreath, 1995; Becker et al., 1998; Webster et al., 2001; Zhang et al., 1998; Ohr et al., 1996). Its activity is comparable to methyl bromide but is not considered an ozone depleter. However, its relative cost may prohibit its commercial development. This study further evaluates combinations of fumigants, application techniques and polyethylene film retention and aeration intervals to maximize activity against pests and establish crop safety limits.

2. Methods and materials

2.1. General

The work was conducted at the University of Georgia, Coastal Plain Experiment Station, Tifton, GA, USA on a fuquay loamy sand (88% sand, 8% silt, 4% clay; pH 5.5–6.0; $<2\%$ organic matter; loamy, siliceous thermic Arenic Plinthic Paleudults). Randomized complete block designs were used with five or six replications depending on the tests. Plots were 1.82 m wide and 3.8 or 7.6 m long, with a 1.2–1.8 m wide non-treated space between treatments and a 4.6 m wide alley between replications. Metam sodium was applied to the soil surface via a spray boom with nozzles mounted in front of a tractor-powered rototiller, and incorporated to a depth of 15–20 cm. The 1,3-D + C-17 was applied through six chisels 30.5 cm apart into the soil to a depth of 20 cm. In combinations, the chiseled-in treatments were applied first, followed by the sprayer–rototiller for the MS application, unless otherwise noted. All plots were covered with polyethylene film as soon after chemical application as possible (1–2 min). The MeBrC was injected under the polyethylene film using 0.45 kg cans (McCarter et al., 1976). Applications were started and terminated in the alleys and plots established in the center of the treated area. Plots were fertilized with 0.5–0.8 kg m^{-2} of 6–12–6 (N–P_2O_5–K_2O) plant–bed–fertilizer prior to treatment. Plots were top dressed during the season with 16–0–0 as required and water was applied as required with overhead irrigation to promote germination and plant growth. Tobacco seedbed management was consistent with recommendations of the Georgia Cooperative Extension Service (Moore, 1999). All plots, including the non-treated controls, were covered with 25 mm (3 mil) polyethylene film immediately following treatment.

An Onset® temperature probe was placed under the polyethylene film at a depth of 7.5 cm during the trials to record soil temperature.

2.2. 1997–1998 Plot A

Plot area A was planted in tobacco the previous crop year. In Plot A all fumigants were applied on 5 November 1997 as indicated in Table 1. Each treatment was replicated five times in a randomized complete block design.

Plots were seeded on five dates, namely 16 November, 17 November, 21 November, 3 December and 7 December 1997 to establish different combinations of period covered with a polyethylene mulch and subsequent aeration period prior to seeding as shown in Table 1. Methyl-bromide-treated plots were covered with polyethylene film for 6 days and aerated for 7 days prior to seeding.

After treatment, but just prior to covering the plots with polyethylene film, oat grain cultures of *Rhizoctonia solani* AG-4 placed in polyethylene mesh bags, were buried to a depth of 2–3 cm below the surface of the soil.

Twenty soil cores (2.5 cm diameter × 15 cm depth) were collected from plots just prior to treatment and when the polyethylene film was removed after fumigation. The soil was assayed for populations of *Pythium* spp. (P_5 ARP agar) (Jeffers and Martin, 1986), *R. solani* AG-4 (tannic acid–benomyl agar) (Henis et al., 1978; Sumner et al., 1978; Sumner and Bell, 1982), *Fusarium* spp., (Papavizas, 1967) and plant-parasitic nematodes. Nematodes were extracted from 150 cm^3 soil subsample by the centrifuge sugar flotation method (Jenkins, 1964).

The polyethylene mesh bags were removed to assay for viability of *R. solani* following removal of the polyethylene film. Oat kernels were plated onto tannic acid–benomyl agar and percentage of viable *R. solani* cultures recovered were determined. Plots were rototilled, shaped into beds for preparation for seeding. Tomato (*L. esculentum* Miller), variety Heinz H8704 was seeded at 18.6 seed m^{-1} and tobacco (*N. tabacum* L.) Cultivar Coker 371 Gold was seeded at 66.7 seed m^{-1} in four rows on each of the 1.84 m wide beds. Beds were irrigated and covered with polyethylene film immediately after seeding to retain moisture and protect seeds from adverse weather. Soil air samples were taken at seeding using the Sensidyne, Gastec® air sampler, from a 2.5 cm diameter core, 15 cm deep made by a soil probe. The #139 mini tubes for the detection of 1,2-dichloroethylene were used to estimate residual 1,3-D in the soil in parts per million. The #139 tube can be used to measure 1,3-D by multiplying the readings by 2 with one pump stroke (Zefon International, St Petersburg, FL).

Since seeding dates depended on polyethylene covered-aeration scenarios, stand counts for tobacco and tomato were made on 10 December 1997, 15 December 1997, 5 January 1998, and 21 January 1998 on 3 m of row in the center of the plot. Vigor ratings were made on 10 March 1998 based on a scale of 1–10, where 1 is dead plants and 10 is most vigorous. Weed ratings were made

Table 1
Influence of fumigation time and aeration time of metam sodium alone, and with 1,3-D + C-17, on stand counts, vigor and 1,3-D soil residue, 1997–1998 (Plot A)

Treatment[a]	Polyethylene coverage[b] (days)	Aeration time[c] (days)	Stand[d] (plants 3 m^{-1})		Lettuce[e] (% germ)	Air[f] sample	Vigor rating[g] (1–10 scale)	
			Tobacco	Tomato			Tobacco	Tomato
Metam sodium	6	5	96 a–d	34 ab	—	—	6.5 bcd	4.3 bcd
Metam sodium	6	10	142 ab	41 a	—	—	9.5 ab	8.5 ab
Metam sodium	15	1	58 def	5 d	—	—	7.2 abc	3.6 cd
Metam sodium	15	6	130 ab	33 ab	—	—	9.5 ab	7.5 abc
Metam sodium	29	3	134 ab	22 bc	—	—	9.3 ab	7.3 abc
Metam sodium	29	7	147 a	32 ab	—	—	10.0 a	9.0 a
1,3-D + C-17 + MS	6	5	35 ef	2 d	87 a	11 a	6.0 cd	4.0 bcd
1,3-D + C-17 + MS	6	10	73 cde	8 cd	72 b	6 bc	6.5 bcd	5.8 abc
1,3-D + C-17 + MS	15	1	8 f	0 d	90 a	12 a	3.8 de	1.0 d
1,3-D + C-17 + MS	15	6	90 bcd	10 cd	87 a	7 b	9.8 ab	6.8 abc
1,3-D + C-17 + MS	29	3	114 abc	21 bc	88 a	3 c	9.5 ab	5.0 a–d
1,3-D + C-17 + MS	29	7	147 a	42 a	91 a	5 bc	10.0 a	7.0 abc
Methyl bromide	6	7	100 a–d	45 a	83 a	—	7.6 abc	6.0 abc
Nontreated	—	—	110 a–d	39 a	—	—	1.0 e	1.0 d

[a] Plots were treated on 5 November 1997. The combination treatment of 1,3-D + C-17 at 93 l ha^{-1} and metam sodium at 349 l ha^{-1} were injected and sprayed onto the soil, respectively, and mixed together with a tractor-powered rototiller and plots covered with 3 mil polyethylene film. The metam sodium treatment was sprayed on the soil surface and incorporated into the soil with a tractor-powered rototiller and covered with polyethylene film.

[b] Time in days the plots remained covered with polyethylene film.

[c] Aeration time was from when the polyethylene film was removed to when crops were seeded.

[d] Tomato variety H8704 seeded at 18.6 seed m^{-1} and tobacco (Coker 371 Gold) was seeded at 66.7 seed m^{-1}. Stand count is number of plants 3 m^{-1} of row.

[e] Twenty-five seed of lettuce seeded into soil from plots at seeding date. Data are % germination.

[f] Air sample noted as parts per million 1,2-dichloroethylene as detected by Sensidyne Gastec® air sampler, tube #139. Numbers should be multiplied by 2.0 convert to 1,3-D in parts per million.

[g] Vigor ratings on a scale of 1–10 for tobacco and tomato made on 10 March 1998.

on 16 March 1998 by visually comparing weed growth relative to the non-treated control.

2.3. 1997–1998 Plot B

Plot B was planted to peanut (*Arachis hypogaea*) the previous crop year. All fumigant treatments except the methyl bromide treatment were made on 5 November 1997. Methyl bromide at the rate of 650 kg ha^{-1} was injected under the polyethylene plastic on 6 November 1997 (McCarter et al., 1976).

Metam sodium, methyl bromide and 1,3-D + C-17 were applied as noted in Section 2.1. This test was a randomized complete block design with six replications.

Polyethylene mesh bags containing three media-impregnated toothpicks infested with *Phytophthora parasitica* var *nicotianae* (Breda de Haan) Tucker were buried 2–3 cm below the soil surface just after treatment, but prior to covering plots with polyethylene film. Media-impregnated toothpicks were prepared as previously described (Csinos and Bertrand, 1994). These mesh bags were recovered when the polyethylene film was removed prior to seeding and bioassayed for living fungus by inserting toothpicks into stems of tobacco seedlings. Soil samples were collected as described for Plot A and assayed for fungi as described for Plot A.

On 11 December 1997, plots were seeded with Coker 371 Gold tobacco and Heinz H8704 tomato as described for Plot A. Plots were watered and covered with polyethylene film on 12 December 1997. Stand counts were made on 21 January 1998 for 3 m of row for each plot. The primary weeds present are listed in Table 6. Other weeds present at low densities were (*Doctyloctenium aegyptium* (L.) wild.), Bermuda grass (*Cynodon dactylon* (L.) pers.), Texas panicum (*Panicum texanum* Buckl.), carpet weed (*Mollugo Verticillate* L.), southern crabgrass (*Digitaria Ciliaris* (Ret2.) Koel.), smallflower morning glory (*Jacquemontia tannifolia* (L.) Griseb), florida parsley (*Richardia Scabara* L.), and jimsonweed (*Datura Stramonium* L.). Weed control data were collected on 16 March 1998. Plant height data were collected on 1 m of row, by measuring each plant from the soil line to the top of the longest leaf on 16 April 1998. Plant vigor, based on a scale of 1–10 where 1 is dead plants and 10 is the most vigorous plant, was recorded on 16 April 1998.

2.4. 1999–2000

The plot area was planted to peanuts during the crop year 1999. Metam sodium, methyl bromide and 1,3-D + C-17 were applied as described in Section 2.1.

Plots were covered with polyethylene film mulch, uncovered and seeded to establish the following scenarios: 7 days polyethylene covered (poly)/1 day aeration; 7 days poly/7 days aeration; 7 days poly/14 days aeration; 14 days poly/1 day aeration; 14 days poly/7 days aeration; and 14 days poly/16 days aeration. MeBrC-treated plots were covered with polyethylene film for 7 days and aerated for 1 day. Each treatment was replicated five times in a randomized complete block design.

Plots were rototilled, shaped and seeded according to the poly/aeration scenarios. Each plot was seeded with a Stanhay® planter with two rows of tomatoes, 'Heinz H8704' at 18.6 seeds m^{-1} and two rows of tobacco, 'Coker 371 Gold' at 59.4 seeds m^{-1}. Germination of the tomato and tobacco in the laboratory were 82% and 90%, respectively. Soil samples were collected as previously described just prior to fumigation and at seeding. Beds were irrigated and covered with polyethylene film immediately after seeding to retain moisture and protect seeds from adverse weather. Stand counts (plants emerged) were made 3 and 5 weeks post-seeding for tobacco and 5 weeks post-seeding for tomato. Vigor ratings based on a scale of 1–10, where 1 was dead plants and 10 was most vigorous, were made on 18 February 2000 and 14 March 2000 on tobacco. Weed control ratings were made on 17 February and 20 March 2000.

2.5. Data analysis

Data were analyzed by ANOVA or GLM procedures of SAS (1985). Data for soil populations were transformed as necessary (square root transformation for small numbers [<100] and log 10 for large numbers [>100] for statistical analysis) but all data are reported as non-transformed values. Significant differences among treatment means were determined by Fisher's protected least significant difference test (FLSD), Duncan's multiple range test, or Waller–Duncan ratio t-tests at $P = 0.05$ (Steel and Torrie, 1960; Waller and Duncan, 1969).

3. Results and discussion

3.1. 1997–1998 Plot A

The fall of 1997 was one of the wettest on record with a total of 39 cm of rain from 1 November until 31 December. Some plots were lost to potential contamination through flooding. This was a concern in previous research studies in Georgia, (McCarter et al., 1976) since fumigation soil is easily recolonized post-fumigation. Soil temperature at 7.6 cm below the soil surface under the polyethylene film ranged from a high of 24°C to a low of 7°C during the test.

Air samples analyzed just prior to the aeration period using the Sensidyne air sampler ranged from a low of 3 to a high of 12 ppm of the 1,3-D degradation product using the #139 tube. This number should be multiplied by 2 to estimate 1,3-D ppm. Plots registering the highest level were plots which had the lowest stand counts and vigor (Table 1). Soil samples taken at the same time were used to germinate lettuce seeds, in petri plates in the laboratory at 27°C. Soil from all plots except one germinated lettuce seed as well as soil from methyl bromide plots (Table 1), even though some plots had high 1,3-D residue according to the air samples. This would suggest to us that Sensidyne Gastec® sampling of air from 1,3-D-fumigated plots may be a better measure of potential crop phytotoxicity than the use of lettuce seed germination bioassay.

Stand counts and vigor ratings of tobacco and tomato were the highest in plots which had the longest polyethylene coverage and aeration times. In many cases where the combinations of 1,3-D + C-17 and metam sodium were used, stand and vigor data were significantly lower than the non-treated control or where metam sodium alone, or methyl bromide was used (Table 1).

All treatments except metam sodium at the 6 days poly/10 days aeration scenario reduced viability of *R. solani* on artificially infested oat kernels (Table 2) relative to the non-treated plots. Only the methyl bromide treatment did not reduce *Pythium* spp. and total *Fusarium* spp. in plots. All treatments reduced populations of *Fusarium solani*, *Aspergillus* spp. and Zygomycetes. Populations of *Penicillium* spp. and *Paecilomyces* spp. and total fungi were high and variable and did not appear to respond consistently to any treatment.

All of the treatments provided weed control similar to methyl bromide for cutleaf evening primrose, cudweed and red sorrel (Table 3). All of the treatments controlled Carolina geranium better than methyl bromide. Metam sodium at 29 days poly/7 days aeration did not provide as good general weed control as methyl bromide. Control of henbit was lower for 1,3-D + C-17 + MS at the 29 days poly/3 days aeration scenario than methyl bromide. Control of catchweed bedstraw was lower in plots treated with metam sodium at the 15–6 and 29–3 poly/aeration scenario than plots treated with methyl bromide. We suspect some of the variability in control could be attributed to wet soil conditions encountered during the test.

Table 2
Effect of soil fumigation application rates and methods on populations and viability of fungi in soil, 1997–1998 (Plot A)

Treatment[a]	Polyethylene coverage[b] (days)	Aeration time[c] (days)	*R. solani*[d]	*Pythium* spp.	*F. solani*	Total *Fusarium* spp.	*Aspergillus* spp.	*Penicillium* spp. + *Paecilomyces* spp.	Zygo-mycetes	Total fungi × 1000
Metam sodium	6	5	61 b[e]	1 b	0 c	63 cd	420 bc	129,800 cde	0 b	132 cd
Metam sodium	6	10	63 ab	1 b	0 c	42 cd	0 c	276,900 cde	0 b	278 a–d
Metam sodium	15	1	17 c	0 b	0 c	68 bcd	0 c	97,400 a–e	0 b	99 bcd
Metam sodium	15	6	0 b	0 b	0 c	304 bc	0 c	183,300 a–e	0 b	185 a–d
Metam sodium	29	3	0 d	42 b	372 b	423 bcd	680 b	314,900 b–e	0 b	318 a–d
Metam sodium	29	7	0 d	7 b	17 bc	355 bcd	20 bc	664,600 abc	0 b	668 abc
1,3-D + C-17 + MS	6	5	59 b	0 b	0 c	106 bcd	0 c	904,400 cde	0 b	906 bcd
1,3-D + C-17 + MS	6	10	46 b	0 b	0 c	63 cd	0 c	130,200 a–d	420 b	132 a–d
1,3-D + C-17 + MS	15	1	0 d	0 b	0 c	34 cd	0 c	79,100 de	0 b	79 cd
1,3-D + C-17 + MS	15	6	5 cd	0 b	0 c	34 d	0 c	944,700 a–e	0 b	945 a–d
1,3-D + C-17 + MS	29	3	0 d	17 b	0 c	34 cd	0 c	468,800 e	0 b	471 a–d
1,3-D + C-17 + MS	29	7	0 d	2 b	0 c	34 cd	0 c	1,210,600 a–e	0 b	1,238 a–d
Methyl bromide	6	7	62 b	89 a	63 bc	338 ab	420 bc	951,700 ab	420 b	954 ab
Non-treated	—	—	77 a	262 a	994 a	3,805 a	1,270 a	871,400 a	1,270 a	935 a

[a] Plots were treated on 5 November 1997. The combination treatment of 1,3-D + C-17 at 93 l ha^{-1} and MS at 349 l ha^{-1} were injected and sprayed onto the soil, respectively, and mixed together with a tractor-powered rototiller and plots covered with 3 mil polyethylene film. The metam sodium treatment was sprayed on the soil surface and incorporated into the soil with a tractor-powered rototiller and covered with polyethylene film.

[b] Time in days the plots remained covered with polyethylene film.

[c] Aeration time was from when the polyethylene film was removed to when crops were seeded.

[d] The percentage viability in colonized oat kernels buried at fumigation. Populations of other fungi are in cfu g^{-1} of oven-dried soil. Three plots were lost because of water erosion; only colonized oat kernels were collected in those plots.

[e] Numbers within columns followed by different letters are different according to *t*-tests (FLSD), $P<0.05$. Data for soil fungal populations were transformed as necessary (square root transformations for small numbers <100 and $\log_{10}$ for large numbers >100 for statistical analyses) but all data are reported as non-transformed values.

Table 3
Effect of soil fumigant application rates and methods on weed populations, 1997–1998 (Plot A)

Treatment[a]	Polyethylene coverage[b] (days)	Aeration time[c] (days)	Percent weed control	Percent control by weed species[d]						
				GERCA[e]	OEOLA	GNAPU	RAPRA	LAMAM	RUMAA	GALAP
Metam sodium	6	5	87 a	100 a	85 a	75 abc	100 a	100 a	100	100 a
Metam sodium	6	10	78 ab	100 a	73 ab	58 c	100 a	100 a	100	95 a
Metam sodium	15	1	91 a	96 a	90 a	85 abc	100 a	100 a	100	98 a
Metam sodium	15	6	78 ab	100 a	77 ab	76 abc	100 a	100 a	100	76 bc
Metam sodium	29	3	80 ab	96 a	86 a	63 bc	100 a	100 a	100	73 c
Metam sodium	29	7	65 b	100 a	58 b	78 abc	95 b	100 a	98	85 abc
1,3-D + C-17 + MS	6	5	97 a	100 a	97 a	94 a	100 a	100 a	100	99 a
1,3-D + C-17 + MS	6	10	96 a	98 a	96 a	92 a	100 a	100 a	100	96 a
1,3-D + C-17 + MS	15	1	99 a	100 a	98 a	98 a	100 a	100 a	100	100 a
1,3-D + C-17 + MS	15	6	95 a	99 a	97 a	97 a	100 a	100 a	100	94 a
1,3-D + C-17 + MS	29	3	84 ab	96 a	93 a	90 ab	100 a	88 b	100	93 ab
1,3-D + C-17 + MS	29	7	95 a	100 a	95 a	90 ab	100 a	100 a	100	98 a
Methyl bromide	6	7	88 a	75 b	79 ab	85 abc	100 a	100 a	98	95 a

[a] Plots were treated on 5 November 1997. The combination treatment of 1,3-D + C-17 at 93 l ha^{-1} and MS at 349 l ha^{-1} were injected and sprayed onto the soil, respectively, and mixed together with a tractor-powered rototiller and plots covered with 3 mil polyethylene film. The metam sodium treatment was sprayed on the soil surface and incorporated into the soil with a tractor-powered rototiller and covered with polyethylene film.

[b] Time in days the plots remained covered with polyethylene film.

[c] Aeration time was time from when the polyethylene film was removed to when crops were seeded.

[d] Weed control was estimated visually using a scale of 0 (no control) to 100 (complete weed control) based on non-treated control plots.

[e] GERCA = Carolina geranium (*Geranium carolinianum* L.), OEOLA = cutleaf evening primrose (*Oenothera laciniata* Hill), GNAPU = purple cudweed (*Gnaphalium purpureum* L.), RAPRA = wild radish (*Raphanus raphanistrual* L.), LAMAM = henbit (*Lamium amplexicauce* L.), RUMAA = red sorrel (*Rumex acetosella* L.), GALAP = catchweed bedstraw (*Galium aparine* L.).

Table 4
Effect of soil fumigant application rates and methods on tobacco height, stand, and vigor on tobacco and tomato, 1997–1998 (Plot B)

Treatments[a]	Method[b]	Tobacco height[c]	Tobacco[d] vigor	Tomato vigor	Stand counts[e] (plants m^{-1})	
					Tobacco	Tomato
1,3-D + C-17 + MS	Inject + spray rototill	22.3 a	7.0 a[f]	6.7 a	59.2 a	10.5 abc
MS + 1,3-D + C-17	Spray rototill + inject	22.0 a	8.2 a	6.8 a	51.5 a	10.3 abc
1,3-D + C-17 + MS	Inject + inject	20.7 ab	5.8 a	6.3 a	47.0 ab	10.3 abc
Metam sodium	Spray rototill	19.2 ab	6.2 a	6.5 a	55.5 a	12.0 ab
Metam sodium	Inject	20.2 ab	6.0 a	5.7 a	55.7 a	13.2 a
Methyl bromide (650 kg ha^{-1})	Inject	21.9 a	7.8 a	6.3 a	46.7 ab	9.7 bc
Metam sodium (698 l ha^{-1})	Inject	23.3 a	7.7 a	6.8 a	55.2 a	11.5 ab
Metam sodium (698 l ha^{-1})	Spray rototill	19.9 ab	5.8 a	6.0 a	49.5 ab	12.8 a
Diphenamid 80WP (8.1 kg ha^{-1})	Spray on	17.2 b	2.7 b	2.0 b	36.3 bc	5.5 d
Non-treated	—	No plants	1.0 b	1.0 b	31.2 c	8.0 cd

[a] All 1,3-D + C-17 treatments were injected at 93 l ha^{-1} through six chisels per bed to a depth of 15–20 cm on 5 November 1997. Metam sodium treatments were applied at 349 l ha^{-1} (unless otherwise noted) using a tractor-operated sprayer and rototiller or injected through six chisels per bed as noted on 5 November 1997. All plots were covered with polyethylene film mulch immediately after treatment. Diphenamid 80WP was applied via a sprayer prior to seeding on 10th of December.

[b] Method describes how chemicals were applied and the order in which they were applied.

[c] Plant heights were measured on 16 April 1998 in centimeters.

[d] Vigor rating based on a scale of 1–10, where 1 is dead plants and 10 is most vigorous.

[e] Tomato, variety H8704 was seeded at 18.6 seed m^{-1} and tobacco, Coker 371 Gold was seeded at 66.7 seed m^{-1}. Counts were made on 1 m of row on 21 January 1998.

[f] Means followed by the same letter are not significantly different according to Duncan's multiple range test, $P = 0.05$.

3.2. 1997–1998 Plot B

Since Plot B was located just 100 m from Plot A, environmental data described for plot A would be similar for Plot B. All fumigant treatments both the combination of 1,3-D + C-17 + MS, metam sodium alone and methyl bromide produced abundant high-quality tobacco and tomato plants and all had vigor ratings higher than both the diphenamid and non-treated controls (Table 4). Tobacco stand counts were greater in all treatments than in the diphenamid and non-treated control. However, only metam sodium treatments had higher tomato stands than the non-treated controls (Table 4). Both treatments with 1,3-D + C-17 + MS, methyl bromide and metam sodium at 698 l ha^{-1} injected had taller tobacco plants than the diphenamid control. No tobacco plants survived in the non-treated control by the end of the trial.

All fumigant treatments reduced soil populations of *Pythium* spp., *F. solani* total *fusarium* spp., *Trichoderma* spp., *Aspergillus* spp., *Penicillium* spp. + *Paecilomyces* spp. and *Phoma* spp. compared to the diphenamid and non-treated control (Table 5). Low populations of *R. solani* AG-4 were present and differences among treatments were not detected. Viable *P. parasitica* var. *nicotianae* was recovered from both controls at 100% and at 17% from the combination of 1,3-D + C-17 (injected) and metam sodium (spray rototilled) and from metam sodium at 349 l ha^{-1} spray rototilled treatment plots.

Weeds present in the plot area were Carolina geranium, cutleaf evening primrose, cudweed, dog fennel and a low level of other weeds (Table 6). All of the fumigant treatments provided weed control over the non-treated plots and provided significant control over the diphenamid-treated plots. The fumigation treatments caused a shift in weed species composition as compared to the non-treated control. The primary weed species in the non-treated control was common chickweed. Other weeds present were cudweed, cutleaf evening primrose, red sorrel, shepherd's purse, bed straw, and Carolina geranium. Carolina geranium was the dominant weed species in the fumigated plots.

3.3. 1999–2000

The environmental conditions for the fall of 1999, were in direct contrast to those of the fall of 1997. Only 9.9 cm of rain fell from 1 November to 31 December 1999, and the days were mostly sunny and clear during the fumigation period. Soil temperature at 8 cm below the soil under the polyethylene film ranged from a high of 31°C to 3.3°C during the test.

Stand counts for tobacco and tomato ranged from 0 to 33, and 0 to 19 plants m^{-1} of row, respectively (Table 7). The fumigation aeration scenarios of 7 days poly/1 day aeration for metam sodium alone and with 1,3-D + C-17 and methyl bromide resulted in lower stand counts than the non-treated control for both tobacco and tomato. In addition, the 14 days poly/1 day aeration scenario for 1,3-D + C-17 + MS resulted in the tomato stands to be lower than the non-treated control. Vigor ratings mirrored stand counts and the 7 day poly/1 day aeration scenario for metam sodium alone and

Table 5
Effect of soil fumigation application rates and methods on populations and viability of fungi in soil, 1997–1998 (Plot B)

Treatment[a]	Methods	*R. solani*[b]	*Pythium* spp.	*F. solani*	*Total fusarium* spp.	*Trichoderma* spp.	*Aspergillus* spp.	*Penicillium* spp. + *Paecilomyces* spp.	*Phoma* spp.	Total fungi × 100	Infected plants[c] # of 12 test plants
1,3-D + C-17 + MS	Inject + spray rototill	0[d]	15.0 b	0 c	30 cd	0 c	570 b	0 b	0 b	120 b	2
MS + 1,3-D + C-17	Inject + spray rototill	0	0.0 b	0 c	100 c	0 c	290 b	0 b	0 b	586 b	0
1,3-D + C-17 + MS	Inject + inject	0	0.7 b	0 c	30 cd	0 c	0 b	0 b	0 b	11 b	0
Metam sodium (349 l ha^{-1})	Spray rototill	1.1	3.6 b	29 bc	70 c	0 c	0 b	0 b	0 b	11 b	2
Metam sodium (349 l ha^{-1})	Inject	0	18.6 b	100 b	470 b	0 c	1430 b	0 b	0 b	63 b	0
Methyl bromide (650 kg ha^{-1})	Inject	0	9.3 b	0 c	70 cd	2280 b	0 b	0 b	570 b	71 ab	0
Metam sodium (698 l ha^{-1})	Inject	0	0.0 b	43 bc	300 c	0 c	0 b	290 b	0 b	20 b	0
Metam sodium (698 l ha^{-1})	Spray rototill	0	0.7 b	0 c	0 d	0 c	0 b	290 b	0 b	9 b	0
Diphenamid 80WP (8.1 kg ha^{-1})	Spray on	1.1	67.1 a	814 a	6940 a	7140 a	3140 a	3710 a	4000 a	817 a	12
Non-treated	—	1.1	72.1 a	986 a	7600 a	5430 a	1140 a	7430 a	5710 a	817 a	12

[a] Plots were fumigated on 5 November 1997. Soil was collected on 8 December 1997.
[b] cfu 100 g^{-1} of soil with *R. solani* AG-4 and per gram of soil in all other fungi.
[c] *P. parasitica* var *nicotianae* infested toothpicks recovered from fumigated plots (two per plot—total 12 per treatment) were used to inoculate tobacco seedlings. Numbers are number of positive disease responses for each treatment.
[d] Numbers in columns followed by the same letter are not significantly different according to Duncan's multiple range test, $P = 0.05$. No letters indicates no significant differences.

with 1,3-D + C-17 reduced vigor of tobacco, while metam sodium alone for the same scenario reduced vigor of tomato.

All treatments controlled weeds as well as methyl bromide (Table 8) rated on 17 February. However, metam sodium in a 14 day poly/16 day aeration scenario did not control dog fennel as compared to methyl bromide on 20 March.

No significant differences in soil fungal populations were detected among treatments, possibly due to the dry soil conditions encountered during the fall of 1999 as compared to 1997. Similarly, a very low level of nematodes were detected in this test and no differences among treatments in either nematode numbers or root gall indices was detected (data not presented).

The fall of 1997 and 1999 were very different environmentally. In 1997 almost four times as much rain fell as in 1999 for the 2-month period of November and December. November of 1999 was near ideal for the fumigation process while 1997 was excessively cloudy and wet. The data collected from both years suggest that the fumigants were efficacious under both sets of conditions. However, longer aeration times were required to maintain high stand and vigor in 1997 as compared to 1999 when fumigation conditions were ideal.

The aeration time influenced the crops stand count and vigor of the seedlings more than polyethylene film mulch retention time, especially at low coverage times in 1997. As the poly time increased, aeration times had lesser effects on both stand counts and vigor. In 1999 this was not as evident, probably due to the better aeration conditions encountered that year.

These results support earlier work that demonstrated the efficacy of both metam sodium alone and with 1,3-D + C-17 (Csinos et al., 1997, 2000). Although the efficacy on pests evaluated here demonstrated performance similar to methyl bromide, phytotoxicity may occur evidenced by stand counts and vigor ratings on emerging crops. Air samples taken to evaluate residual 1,3-D in one study support these findings. The level of 1,3-D residue was related inversely to the stand and vigor of tobacco and tomato.

The use of metam sodium and 1,3-D with combinations of chloropicrin under polyethylene film mulch represent a good alternative to methyl bromide for soil fumigation. However, caution must be exercised in allowing sufficient time for both the polyethylene film retention time and subsequent aeration to dissipate phytotoxic residual materials. Whereas in this study tobacco and tomato were seeded into the fumigated soil, very little is known about the relative phytoxicity of these fumigants to transplanted crops. Plots were fumigated for 10–14 days and aerated for 5 days and pepper plants were not adversely affected whether the fumigant was applied through chisels or through drip

Table 6
Effect of soil fumigant application rates and methods on weed populations, 1997–1998 (Plot B)

Treatment	Method[a]	Percent[b] weed control	Percent weed species composition				
			[c]GERCA	OEOLA	GNAPU	EUPCP	Other[d]
1,3-D + C-17 + MS	Inject + spray rototill	77 a	68	4	2	16	10
MS + 1,3-D + C-17	Spray rototill + inject	72 a	82	7	0	8	3
1,3-D + C-17 + MS	Inject + inject	58 a	78	3	1	13	5
Metam sodium	Spray rototill	71 a	53	12	2	31	2
Metam sodium	Inject	56 a	44	3	2	43	8
Methyl bromide (650 kg ha^{-1})	Inject	65 a	60	1	2	29	8
Metam sodium (698 l ha^{-1})	Injected	63 a	77	1	17	0	5
Metam sodium (698 l ha^{-1})	Spray rototill	68 a	77	6	8	0	8
Diphenamid 80WP (8.1 kg ha^{-1})	Spray on	30 b	10	5	80	0	5
Non-treated	—	—	5	10	5	0	80

[a] 1,3-D + C-17, and metam sodium (349 l ha^{-1} unless noted otherwise) were injected using six chisels spaced 30.5 cm apart, set at 15–20 cm depth. Tractor-mounted spray–rototill operations were performed with a sprayer–rototiller, applied to a depth of about15 cm, and covered with polythene film mulch. Methyl bromide was manually injected under the film mulch by puncturing cans of methyl bromide and dispensing under the film mulch.

[b] Means followed by the same letter are not significantly different according to Duncan's multiple range study, $P = 0.05$. Weed ratings were made on 18 March 1998. Weed control was estimated visually using a scale of 0 (no control) to 100 (complete weed control) based on non-treated control plots.

[c] GERCA = Carolina geranium (*G. carolinianum* L.), OEOLA = cutleaf evening primrose (*O. laciniata* Hill), GNAPU = purple cudweed (*G. purpureum* L.), and EUPCP = dog fennel (*Eupatorium capillifolium* (Lam.) Small).

[d] All other weeds include: crowfoot grass, Bermuda grass, Texas panicum, carpetweed, crabgrass, smallflower morning glory, Florida pusley, and jimsonweed.

Table 7
Influence of fumigation time and aeration time of metam sodium alone, and with 1,3-D + C-17, on stand counts, and vigor, 1999–2000

Treatments, fumigation, and aeration time			Stand counts[d] (plants l m^{-1})			Vigor rating[e] (1–10 scale)	
Treatments[a]	Polyethylene covered[b] (days)	Aeration[c] (days)	First[f]		Second	Tobacco	
			Tobacco	Tomato	Tobacco	First	Second
1,3-D + C-17 + MS	7	1	0 f	0 g	0 g	1.0 e	3.0 d
1,3-D + C-17 + MS	7	7	19 b–e	10 c–e	22 a–d	7.4 bcd	8.6 a–c
1,3-D + C-17 + MS	7	14	23 a–d	14 a–c	23 a–c	7.4 bcd	8.6 a–c
1,3-D + C-17 + MS	14	1	25 a–d	5 ef	29 a	8.8 ab	9.8 a
1,3-D + C-17 + MS	14	7	24 a–d	19 a	24 ab	7.8 a–d	9.0 a–c
1,3-D + C-17 + MS	14	16	16 c–e	13 b–d	16 b–e	6.0 d	7.4 bc
Metam sodium	7	1	0 f	0 g	3 fg	1.8 e	1.0 e
Metam sodium	7	7	25 a–d	9 de	23 a–c	8.2 abc	9.0 a–c
Metam sodium	7	14	28 ab	16 ab	24 a–c	7.2 bcd	8.6 a–c
Metam sodium	14	1	33 a	14 a–d	33 a	9.4 a	9.8 a
Metam sodium	14	7	27 a–c	15 ab	25 ab	8.0 abc	9.4 ab
Metam sodium	14	16	17 b–e	11 b–d	14 b–e	6.4 cd	8.4 a–c
Methyl bromide	7	1	11 ef	3 gh	14 c–e	7.6 bcd	8.9 a–c
Non-treated	—	—	21 b–d	14 a–d	11 ef	7.4 bcd	3.3 d

[a] Plots treated on 9 November 1999. 1,3-D + C-17 (Telone C-17, 93 l ha^{-1}) and metam sodium (42% MS) (349 l ha^{-1}) applied and covered with polyethylene film. Telone C-17 applied with six chisels and metam sodium sprayed and rototilled into soil. Methyl bromide 98% was applied at 650 kg h^{-1}

[b] Time in days the plots remained covered with polyethylene film.

[c] Aeration time after fumigation is from when the polyethylene film was removed to when crops were seeded.

[d] Tomato variety H8704 seeded at 5.66 seed ft^{-1} and tobacco (Coker 371 Gold) was seeded at 18.16 ft^{-1}. Stand counts is plants l m^{-1} of row.

[e] Vigor ratings on scale of 1–10 for tobacco and tomato made on 18 February and 14 March 2000.

[f] Stand counts were made 4 weeks after seeding on 20 December 1999. The second count was made on 23 February 2000.

tape (Webster et al. 2001). Over 79,000 ha of vegetables are currently grown in Georgia alone (Doherty and Mizelle, 2001), with a large percentage being grown in methyl-bromide-fumigated soil. The safety of metam sodium alone and in combination with 1,3-D + C-17 as an alternative to methyl bromide needs to be evaluated on transplanted vegetable crops prior to its adoption by the vegetable industry.

Table 8
Influence of fumigation time and aeration time of metam sodium alone, and with 1,3-D + C-17, on weed population control,[a] 1999–2000

Treatments, fumigation, and aeration time			17 February				20 March			
Treatments[b]	Polyethylene coverage[c] (days)	Aeration (days)[d]	GNAPU[e]	SPRAR	OEOLA	EUPCP	GNAPU	SPRAR	OEOLA	EUPCP
1,3-D + C-17 + MS	7	1	100[f]	100	100	100	100	100	98	100 a
1,3-D + C-17 + MS	7	7	89	95	84	84	86	94	84	82 a
1,3-D + C-17 + MS	7	14	90	91	88	73	73	85	84	62 ab
1,3-D + C-17 + MS	14	1	100	100	98	99	99	100	98	98 a
1,3-D + C-17 + MS	14	7	95	100	96	74	90	100	96	69 ab
1,3-D + C-17 + MS	14	16	97	91	94	76	97	91	94	61 ab
Metam sodium	7	1	100	100	100	97	100	100	100	96 a
Metam sodium	7	7	92	97	86	83	85	97	80	82 a
Metam sodium	7	14	88	93	85	70	73	88	82	61 ab
Metam sodium	14	1	91	95	98	97	93	95	98	96 a
Metam sodium	14	7	95	98	92	67	86	98	86	63 ab
Metam sodium	14	16	89	92	91	74	86	91	91	51 b
Methyl bromide	7	1	100	100	100	100	100	100	100	100 a

[a] Weed control was estimated visually using a scale of 0 (no control) to 100 (complete weed control) based on non-treated control plots in mid-February and late March. Chlorosis, stunting, and weed density were used in making the visual estimates.

[b] Plots treated on 9 November 1999. 1,3-D + C-17 (Telone C-17, 93 l ha^{-1}) and metam sodium (42% MS) (349 l ha^{-1}) applied under polyethylene film. 1,3-D + C-17 applied with six chisels and metam sodium sprayed and rototilled into soil. Time of fumigation as noted, plastic removed and plots seeded on days after aeration. Methyl bromide 98% was applied at 650 kg h^{-1}.

[c] Time in days the plots remained covered with polyethylene film.

[d] Aeration time after fumigation is from when the polyethylene film was removed to when crops were seeded.

[e] GNAPU = purple cudweed (*G. purpureum* L.), SPRAR = corn spurry (*Spergula arvensis* L.), OEOLA = cutleaf evening primrose (*O. laciniata* Hill), and EUPCP = dog fennel (*E. capillifolium* (Lam.) Small).

[f] Data are means of five replications. Means followed by the same letter are not different ($P = 0.05$) according to Duncan's multiple range test, no letters indicate no significance.

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