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Control of *Meloidogyne chitwoodi* in Potato with Shank-injected Metam Sodium and other Nematicides

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Abstract: Metam sodium (MS) is often applied to potato fields via sprinkler irrigation systems (water-run, WR) to reduce propagules of soil-borne pathogenic fungi, particularly *Verticillium dahliae*, to prevent yield loss from potato early dying disease. However, this procedure has not been effective for controlling quality defects in tubers caused by Columbia root-knot nematode (*Meloidogyne chitwoodi*). In five trials from 1996 to 2001, application of MS by soil shank injection (SH) provided better control and tuber quality than that generally obtained by WR MS, in three of five trials. Results were similar when SH MS was injected at one (41–45 cm), two (15 and 30 cm) or three (15, 30 and 45 cm) depths. In the two trials where SH metam potassium was tested, culls were reduced to 3% and 0% and were equivalent to those resulting from a similar rate in kg a.i./ha of SH MS. A shank-injected tank mix of MS plus ethoprop EC and SH MS plus in-season chemigation applications of oxamyl provided acceptable control in trials where SH MS alone was inadequate. In-furrow application of aldicarb at planting following SH MS did not appear to increase performance. Most consistent control (0–2% culled tubers in five trials) occurred when SH MS at 280 liters/ha was used together with 1,3-dichloropropene (140 liters/ha), applied simultaneously or sequentially. This was similar to combinations of 1,3-D and WR MS, but SH MS may be preferred under certain conditions.

Key words: 1,3-dichloropropene, aldicarb, ethoprop, fumigation, *Meloidogyne*, management, metam sodium, nematicides, oxamyl, potato, Columbia root-knot nematode, shank injection, *Solanum tuberosum*

Based on National Potato Council statistics for 2003 (www.nationalpotatocouncil.org), western states produce 64% by weight and 61% by value ($1.5 billion) of all potatoes (*Solanum tuberosum* L.) grown in the United States. However, Columbia root-knot nematode (*Meloidogyne chitwoodi* Golden et al.) is a significant threat to potato quality in much of the western region. *Meloidogyne chitwoodi* infect and develop in tubers. Although not causing yield reductions, they do cause quality defects such as galling on the surface and minute brown spots surrounding adult females that are visible when the tuber is peeled. These external and internal defects are unacceptable for the fresh market, and internal defects are unacceptable for processing. If 5 to 15% of the tubers in a field display excessive symptoms, the entire crop from that field may be substantially devalued or rejected. At an estimated value of $9,900/ha (based on average yield and market price for Umatilla and Morrow Co. in the southern Columbia Basin of Oregon for 2005, see Bosecker and Coba, 2006), the rejection of a potato crop grown on an average 52.6 ha irrigated circle represents a loss of over $500,000 to the grower. Losses are not as high in areas of the west with lower yields, but still represent a major loss to the grower. Furthermore, developing export opportunities in Southeast Asia, Mexico and other world markets have a zero tolerance for *M. chitwoodi*. The presence of any *M. chitwoodi* in tubers will result in rejection and return of the entire shipment. Similarly, there is no tolerance for *M. chitwoodi* in seed potato production.

Because *M. chitwoodi* reproduces rapidly during warm seasons (Pinkerton et al., 1991), crop rejection may occur even with low population levels, and generally fields with any *M. chitwoodi* must be treated with a preplant fumigant, nonfumigant nematicides, or both. Several products have been used alone and in combination in attempts to reduce tuber infection to acceptable levels (Ingham et al., 2000). Metam sodium (sodium *N*-methyldithiocarbamate, MS) applied through the irrigation system (water-run, WR), ethoprop, oxamyl, or aldicarb (Griffin, 1989) alone did not adequately reduce tuber infection. WR MS plus ethoprop reduced culled tubers to 3%, and WR MS plus two or three foliar applications of oxamyl reduced culls to ≤10% in all but one instance. Application rates of 1,3-dichloropropene (1,3-D) below 234 liters/ha did not always control tuber damage, but 140 liters/ha of 1,3-D plus ethoprop reduced the percentage of culled tubers to zero. 1,3-dichloropropene plus 17% chloropicrin did not provide better control than 1,3-D alone. Combinations of 1,3-D at 94 liters/ha or greater plus WR MS at 280 liters/ha (42% a.i.) or greater consistently provided excellent control of tuber damage by *M. chitwoodi*. WR MS at this rate also provided control of soil-borne fungal diseases (Hamm et al., 2003). Consequently, treatment with WR MS at 280 liters/ha plus 1,3-D at 140 liters/ha has become the industry standard in the Columbia Basin of Oregon and Washington.

WR MS is generally applied in irrigation water via chemigation to reduce propagules of soil-borne patho-

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genic fungi that may reduce potato yield. Applications generally target soil-borne propagules whose numbers are greater in the upper 30 cm (Hamm et al., 2003). However, *M. chitwoodi* can be distributed much deeper in the soil profile (Mojtahedi et al., 1991a), and adding enough water to reach these depths would dilute MS to less than efficacious concentrations. In addition, *M. chitwoodi* can migrate into surface soils from below the treated area (Mojtahedi et al., 1991a), so targeting both nematodes and soil-borne fungi with WR MS is difficult. Therefore, 1,3-D is generally applied in addition to WR MS. Furthermore, environmental and human health concerns in the future may place restrictions on application of MS through sprinkler irrigation systems. This paper reports on several studies that examined procedures for shank-injection of MS to control tuber damage from *M. chitwoodi* while maintaining yield when used alone or in combination with other nematicides.

Materials and Methods

Plot design: Between 1996 and 2001, five trials were conducted in commercial potato fields in Umatilla (1996, 1997, 2000) and Morrow (2001) Co., OR, and at the Hermiston Agriculture Research and Extension Center, Hermiston, Umatilla Co., OR (1998). Each area had a history of *M. chitwoodi* damage associated with previous potato crops. All trials were arranged in a randomized block design with five replications. Plots were either 4.6-m (five potato rows, 1996–1997) or 2.6-m (three potato rows, 1998–2001) wide. In trials where plots were three rows wide, an untreated buffer row was included between adjacent plots. Plots were 12.8-m (1996), 15.4-m (1997, 2000), 9.2-m (1998), or 31-m (2001) long. Certified seed potatoes (*Solanum tuberosum* cv. Russet Burbank or Russet Burbank, Newleaf) were planted at a seed spacing of 22.5 cm and a row spacing of 85 cm. All cultural practices were consistent with typical procedures for that growing area.

Fumigation equipment: Fumigation treatments were applied with commercial equipment (1996–97) or with a custom built experimental fumigator (1998–2001). In the initial design of the experimental fumigator, nozzles were placed on each side of ripper shanks at depths of 15, 30 and 45 cm on each shank. At each depth, the nozzles on each side were set 10 cm from the center of the shank so that they were positioned 20 cm apart. A wing was welded to each side of the shank to protect the nozzles. Shanks were set on 40 cm spacing so that a nozzle on the right hand side of one shank was 20 cm from the nozzle on the left side of the adjacent shank. This permitted a broadcast application of MS at each depth. Material being delivered to each depth could be controlled individually so that all possible combinations of depths and rates/depth could be evaluated. 1,3-D was delivered at the tip of the shank at 45 cm below the soil surface independent of MS so that 1,3-D could be applied alone or simultaneously with any depth delivery of MS. Rates and combinations of MS and 1,3-D could be switched between plots during application to facilitate delivery of several different treatments in a randomized block design. The fumigator unit treated a 2.6-m wide area (three potato rows) and had a paddle wheel that collapsed the soil over the furrows made by the shanks. A ring roller packer was pulled behind the fumigator to compress and seal the soil surface. In 2001, the experimental fumigator was modified so that MS was delivered on separate shanks for each depth to facilitate movement of the fumigator through the soil and the flow of soil around shanks. Injection at 45 cm was made from nozzles behind wings on the ripper shanks, which were followed by noble blades with nozzles at each 30 cm, which were followed by nozzles behind spray blades set at 15 cm. Spacing and choice of nozzles allowed for broadcast delivery of MS at each depth during application. Delivery of 1,3-D was off the back of the ripper shanks as before.

Application methods/treatments: The descriptions of the nematicide treatments and abbreviations are listed in Table 1. Broadcast applications of 1,3-D were injected 45 cm deep using shanks set 38 to 40 cm apart. Soil was sealed immediately with a disc or paddle wheel and packer that followed behind the fumigator. WR MS was delivered at the selected rates through center pivot irrigation system delivering 1.3 cm (0.5-acre-inch) of water, and plots not to receive this treatment were covered with tarps. In other treatments, MS or metam potassium (potassium N-methyldithiocarbamate, MP) was shank-injected (SH) at various depths (see text below for details). Combinations of SH MS and 1,3-D were applied simultaneously (simult.) or sequentially (sequen.). Ethoprop 6 EC was broadcast applied in 210 liters/ha spray solution delivered through a CO_2 backpack sprayer and incorporated throughout the surface 15 cm with a tractor-mounted rototiller immediately after application. Tank mixtures of MS and ethoprop were applied the same as SH MS alone. Aldicarb was applied in-furrow before planting via a modified Planet Junior continuous belt applicator. Foliar applications of oxamyl were delivered in 1.3 cm (0.5-acre-inch) of water through a portable overhead chemigation system.

1996 trial: 1,3-D was applied to appropriate plots on 15 March 1996. WR MS was applied through the center pivot on 3 April, and SH (41 cm) MS treatments were applied on 10 April. Ethoprop was applied as a broadcast spray and incorporated by rototilling on 18 April. Potato seed cv. Russet Burbank was planted, and aldicarb applied in-furrow to appropriate plots on 1 May. Oxamyl treatments were made on 15 July, 1 August and 15 August.

1997 trial: MS and 1,3-D were applied to appropriate plots with different applicators on 23 April 1997. The low rate of MS was shank-applied at 41 cm, while half of the high rate was shank-applied and half was sprayed on

TABLE 1. Descriptions of nematicide treatments and abbreviations used in text and tables.

Abbreviations	Description
Control	Untreated Control
1,3-D 140	1,3-dichloropropene[a] at 140 liters/ha
1,3-D 187	1,3-dichloropropene at 187 liters/ha
Aldicarb 3	Aldicarb[b] (A3) granules at 3.3 kg a.i./ha applied in-furrow
Ethoprop 13	Ethoprop[c] 6 EC (E13) at 13.2 kg a.i./ha broadcast, preplant incorporated
Oxamyl X	X foliar applications of oxamyl[d] (OX) at 1.1 kg a.i./ha
Oxamyl 2 X	X foliar applications of oxamyl (2OX) at 2.2 kg a.i./ha
SH MS 210	Shank-applied (SH metam sodium[e] (MS) at 210 liters/ha
SH MS 280	SH metam sodium at 280 liters/ha
SH MS 355	SH metam sodium at 355 liters/ha
SH MS 467	SH metam sodium at 467 liters/ha
SH MS 560	SH metam sodium at 560 liters/ha
SH MS 700	SH metam sodium at 700 liters/ha
SH MS (l/ha)/Ex mix	Tank mix of metam sodium (liters/ha) + ethoprop (kg a.i./ha)
WR MS 355	Water-run (WR) metam sodium at 355 liters/ha
SH MP 448	SH metam potassium[f] (MP) at 448 liters/ha
SH MP 467	SH metam potassium at 467 liters/ha

Metam sodium (MS) and 1,3-D were applied simultaneously (simult.) or sequentially (sequen.)
See individual studies for details.

[a] Telon II, Dow Agrosciences, Indianapolis, IN.
[b] Temik 15G, Bayer Cropscience, Research Triangle Park, NC.
[c] Mocap 6 EC, Bayer Cropscience, Research Triangle Park, NC.
[d] Vydate L, Du Pont Agricultural Products, Wilmington, DE.
[e] Vapam, 42% a.i. formulation (0.5 kg a.i./liter), AMVAC Chemical Corp., Los Angeles, CA.
[f] Kpam, 54% a.i. formulation (0.7 kg a.i./liter), AMVAC Chemical Corp., Los Angeles, CA.

the surface and incorporated by the following disc. SH MS and 1,3-D in the combination treatment were applied separately but within a few hours to simulate simultaneous application. Russet Burbank was planted, and aldicarb was applied in-furrow to appropriate plots on 14 May. Applications of oxamyl were made on 16 July, 30 July, 19 August, 3 September and 22 September.

1998 trial: MS (45 cm, 15 and 30 cm, or 15, 30 and 45 cm) and 1,3-D were shank-applied with the experimental fumigator on 19 May. All 1,3-D and SH MS combination treatments were delivered simultaneously, with MS delivered at 15 and 30 cm. Plots were planted with Russet Burbank, Newleaf on 9 June.

2000 trial: SH treatments were applied using the experimental fumigator on 19 and 20 April. MS alone was injected at 15 and 30 or 15, 30 and 45 cm and at 15 and 30 cm in combination treatments with 1,3-D. Surface broadcast application of ethoprop was made on 9 May. Aldicarb was applied on 10 May, and Russet Burbank, Newleaf Generation 2 was planted on 11 May.

2001 trial: 1,3-D was applied (at 45 cm) on 5 April 2001 to plots receiving 1,3-D alone or sequential applications of 1,3-D and MS (at 15 and 30 cm). Heavy rain delayed the application of MS alone (15 and 30 cm, or 15, 30 and 45 cm), MS/ethoprop tank mix and 1,3-D/MS simultaneous treatments until 18 and 19 April. Plots were planted with Russet Burbank on May 10–11.

Nematode sampling: Soil samples for nematode evaluations (10 2.5-cm-diam. cores/plot) were taken at depths of 0 to 30 cm and 30 to 60 cm from the center row of each plot. However, population densities from 30 to 60 cm were low at all sites and rarely responded to treatment, so these data are not presented. No samples were taken within 1.5 m of either end of the plot (see tables for the specific sample dates during each trial). Soil samples were sieved and mixed, and nematodes extracted from 250 g subsamples by density centrifugation (Jenkins, 1964) as modified by Ingham (1994). Since the period of time between pre- and post-fumigation sample dates in the 2001 trial was too short for all killed nematodes to decompose, live/dead *M. chitwoodi* J2 evaluations were made for each sample from the post-fumigation sample date. Nematodes that were moving or moved when prodded were considered alive, and those that did not move when prodded were considered dead. Only total J2 were recorded on all other sample dates in each study. Nematode population densities were adjusted for soil moisture to convert to numbers per 250 g dry soil and transformed to $\log_{10}(x+1)$ before analysis.

Evaluation of tuber infection: Potatoes were harvested by digging the center row of each plot with a single row level bed digger. A random sample of 25 tubers weighing 110 to 340 g each was collected from each plot and peeled by hand. Nematode infection sites were counted under a magnifying lamp. Data were summarized as percent infected (tubers with one or more infection sites) and percent culls (tubers with six or more infection sites), and an infection index (0 = 0, 1 = 1–3, 2 = 4–5, 3 = 6–9, 4 = 10–49, 5 = 50–99, 6 = 100 or more infection sites) was used to measure infection intensity (Pinkerton et al., 1986). All percent damage data were transformed to arcsin square root (x) before analysis.

Statistical analysis: All population and percent infection data were evaluated by analysis of variance (ANOVA). Means of transformed values were back transformed before reporting, and Duncan's Multiple Range Test was used to separate means only when ANOVA was significant at $P \leq 0.05$. The infection index data were evaluated with a Mann-Whitney procedure (SAS Institute, Cary, NC). All differences reported are at $P \leq 0.05$ unless otherwise stated.

RESULTS

1996 nematode population densities: Population densities of *M. chitwoodi* averaged 4 J2/250 g dry soil from 0 to 30 cm throughout the study area before fumigation and remained low in all treatments until the harvest sample date (Table 2). Significant differences between treatments were only noted in final populations and can be divided into three groups: (i) Populations in most treatments with WR MS alone or in combination with nonfumigant nematicides tended to be lower but were not statistically less than those in control plots; (ii) Treatments with WR MS and 1,3-D reduced final populations to near zero, and these populations were significantly less than in untreated plots or treatments with WR MS; and (iii) *M. chitwoodi* densities in treatments with SH MS or WR MS plus aldicarb and three applications of oxamyl had intermediate nematode levels which were not different from treatments with higher (the other WR MS treatments) or lower (WR MS plus 1,3-D) populations.

1996 tuber infection: 355 liters WR MS/ha, alone or followed by ethoprop, had no significant effect on *M. chitwoodi* infection of tubers (Table 2). However, WR MS plus aldicarb or three applications of oxamyl reduced percent culls to 1%. Furthermore, examining tuber infection (all tubers with one or more nematodes, i.e., a more sensitive indicator) suggested that aldicarb plus oxamyl (1% infected) following WR MS may be better than either product alone (12% infected). This might have been reflected in culled tubers if nematode densities had been higher. All combinations of MS and 1,3-D and all shank-applied applications of MS, even at 280 liters/ha, reduced percent culled tubers to less than 1%.

1997 nematode population densities: Initial populations of *M. chitwoodi* across the entire study area averaged 14 J2/250 g soil in the top 0 to 30 cm (Table 3). At mid-season, (post-treatment) populations had reached 194 J2/250 g soil in untreated plots and were significantly lower in all treatments except the lower rate of SH MS alone. The low rate combination of SH MS and 1,3-D and all treatments with SH MS and oxamyl had the lowest population densities at harvest. There was no difference in populations in combination treatments with aldicarb compared to like treatments without aldicarb.

1997 tuber infection: The percentage of tubers culled due to *M. chitwoodi* was not significantly reduced by SH MS alone or by SH MS plus aldicarb (Table 3). Percent culls were significantly reduced with 280 liters SH MS/ha plus five applications of 1.1 or 2.2 kg a.i. oxamyl/ha, with or without in-furrow applications of aldicarb. 280 liters SH MS/ha plus 140 liters1,3-D/ha also reduced the percentage of culls to low levels.

1998 nematode population densities: The study area was characterized by relatively low populations of *M. chitwoodi* averaging 2 J2/250 g dry soil from 0 to 30 cm across all plots before treatment (Table 4). Harvest populations of *M. chitwoodi* in plots injected with 280 and 355 liters MS/ha at 45 cm were 93 and 100% less than in control plots, respectively. There was no effect of increased rate of SH MS on *M. chitwoodi* populations when applied at 15, 30 and 45 cm. Although all multi-level injection treatments reduced populations by an average of 86% relative to the control, this reduction was not significant. Both rates of 1,3-D, alone or with SH MS, reduced populations to 0–1 J2/250 g dry soil.

1998 tuber infection: SH MS injected at 45 cm or at 15, 30 and 45 cm did not significantly reduce the percentage of infected or culled tubers (Table 4). While the

TABLE 2. Effects of nematicides on populations (J2/250 g dry soil from 0 to 30 cm) and infection of potato tubers by Columbia root-knot nematodes (*Meloidogyne chitwoodi*)—Umatilla Co., OR, 1996.

Treatment[a]	Before fumigation 15 March	Harvest 10 October	Percent tuber infection[b]	Percent culled tubers[c]	Infection Index[d]
Control	5	83 a[e]	71 a	47 a	2.18 a
WR MS 355	2	20 abc	47 ab	16 abc	1.18 ab
WR MS 355 + E13	7	32 ab	47 ab	33 ab	1.77 abc
WR MS 355 + A3	<1	11 abcd	12 bcd	1 cd	0.32 cd
WR MS 355 + A3 + E13	4	25 abc	31 bc	13 bcd	1.06 abcd
WR MS 355 + O3X	12	12 abcd	12 bcd	1 cd	0.24 bcd
WR MS 355 + A3 O3X	5	4 bcd	1 d	<1 cd	0.04 d
SH MS 210	<1	1 bcd	2 cd	0 d	0.06 cd
SH MS 355	<1	1 cd	8 cd	<1 cd	0.12 cd
SH MS 355 + A3	3	2 bcd	3 cd	<1 cd	0.06 cd
SH MS 355 + O3X	6	4 bcd	1 cd	0 d	0.03 cd
WR MS 355 + 1,3-D 140	6	<1 d	12 bcd	0 d	0.14 cd
WR MS 355 + 1,3-D 187	10	<1 d	7 cd	0 d	0.08 cd

[a] WR = water-run or SH = shank-applied, MS = metam sodium at 210 or 355 liters/ha.
The MS and 1,3-D combination treatment was made sequentially with a 26-d interval.
E13 = ethoprop 6 EC at 13.2 kg a.i./ha broadcast, preplant incorporated.
A3 = aldicarb granules at 3.3 kg a.i./ha applied in-furrow.
O3X = 3 foliar applications of oxamyl at 1.1 kg a.i./ha.
1,3-D = 1,3-dichloropropene at 140 or 187 liters/ha.
[b] Percent of tubers with 1 or more *M. chitwoodi* infection sites.
[c] Percent of tubers with 6 or more *M. chitwoodi* infection sites.
[d] Measure of intensity of infection (ranges from 0–6).
[e] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

TABLE 3. Effects of nematicides on populations (J2/250 g dry soil from 0–30 cm) and infection of potato tubers by Columbia root-knot nematodes (*Meloidogyne chitwoodi*)—Umatilla Co., OR, 1997.

Treatment[a]	Before fumigation 8 March	Midseason 7 August	Harvest 14 October	Percent tuber infection[b]	Percent culled tubers[c]	Infection Index[d]
Control	9	194 a[e]	78 a	89 a	67 a	3.08 a
SH MS 355	11	7 bc	5 bcd	72 abc	39 abc	1.99 ab
SH MS 280	9	18 ab	36 ab	87 ab	48 abc	2.35 ab
SH MS 280 + 1,3-D 140	2	2 bc	3 cd	15 cd	1 d	0.34 c
SH MS 280 + O5X	18	5 bc	4 bcd	45 abcd	8 bcd	1.07 bc
SH MS 280 + 2O5X	1	0 c	3 d	9 d	<1 d	0.18 c
SH MS 280 + A3	1	5 bc	13 abcd	62 abc	28 abcd	1.63 ab
SH MS 280 + A3 + O5x	2	1 bc	3 cd	40 bcd	7 cd	0.80 bc
SH MS 280 + A3 + 2O5x	14	4 bc	5 bcd	10 d	3 d	0.26 c

[a] SH MS = shank-applied metam sodium at 280 or 355 liters/ha.
1,3-D = 1,3-dichloropropene at 140 liters/ha.
The MS and 1,3-D combination treatment was made sequentially on the same day.
A3 = aldicarb granules at 3.3 kg a.i./ha applied in-furrow.
O5X = 5 foliar applications of oxamyl at 1.1 kg a.i./ha.
2O5X = 5 foliar applications of oxamyl at 2.2 kg a.i./ha.
[b] Percent of tubers with 1 or more *M. chitwoodi* infection sites.
[c] Percent of tubers with 6 or more *M. chitwoodi* infection sites.
[d] Measure of intensity of infection (ranges from 0–6).
[e] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

higher rate (355 liters/ha) tended to reduce infection compared to the lower rate (280 liters/ha) with both injection procedures, there was no further increase in control with 467 liters/ha. In contrast, 140 or 187 liters 1,3-D/ha with or without simultaneous injection of 280 or 355 liters SH MS/ha, respectively, reduced culls to zero in nearly all plots.

2000 nematode population densities: Very few *M. chitwoodi* were recovered from plots in two of the blocks on any sample date, so only data from the other three blocks were analyzed. In the blocks analyzed, *M. chitwoodi* from 0 to 30 cm averaged 7 J2/250 g dry soil before treatment (Table 5). After fumigation, populations were numerically lower in all treatments than in the control, but the differences were not significant (data not presented). By midseason, however, populations in untreated plots had increased four-fold while those in all treatments remained low and statistically less ($P \leq 0.05$) than in the control plots. At harvest, populations in untreated plots were 14 times greater than at planting. The trend was for lower nematode population densities with increasing rates of SH MS, but only the 700 liters/ha rate was different from control plots. SH MP, 140 liters 1,3-D/ha, SH MS plus 1,3-D, and all SH MS plus ethoprop treatments also had populations that were lower than those in the untreated control. Average population density in the 187 liters 1,3-D/ha treatment was skewed by high populations in one plot.

2000 tuber infection: All treatments had significantly fewer culls than in control plots (Table 5). However, while the percentage of culled tubers was not statistically different between most treatments, not all treatments would have been commercially acceptable.

TABLE 4. Effects of nematicides on populations (J2/250 g dry soil from 0–30 cm) and infection of potato tubers by Columbia root-knot nematodes (*Meloidogyne chitwoodi*)—Umatilla Co., OR, 1998.

Treatment[a]	Before fumigation 13 May	Harvest 27 October	Percent tuber infection[b]	Percent culled tubers[c]	Infection Index[d]
Control	6	95 a[e]	83 a	66 a	3.06 a
SH MS 280 at 45 cm	1	7 bc	66 ab	38 a	2.22 ab
SH MS 355 at 45 cm	3	0 c	41 abcd	16 abcd	1.40 abc
SH MS 280 at 15, 30 & 45 cm	1	12 abc	56 abc	37 ab	2.17 ab
SH MS 355 at 15, 30 & 45 cm	4	18 ab	45 abc	13 abcd	1.11 abc
SH MS 467 at 15, 30 & 45 cm	2	12 abc	52 abc	22 abc	1.32 ab
1,3-D 140	3	0 c	17 bcd	<1 cd	0.21 bcd
1,3-D 187	1	0 c	15 cd	0 cd	0.16 cd
SH MS 280 + 1,3-D 140 simult.	1	1 bc	4 d	0 d	0.06 d
SH MS 355 + 1,3-D 187 simult.	2	0 c	11 cd	0 cd	0.13 cd

[a] SH MS = shank-applied metam sodium at 280, 355, or 467 liters/ha.
1,3-D = 1,3-dichloropropene at 140 or 187 liters/ha.
The MS and 1,3-D combination treatment was made simultaneously.
[b] Percent of tubers with 1 or more *M. chitwoodi* infection sites.
[c] Percent of tubers with 6 or more *M. chitwoodi* infection sites.
[d] Measure of intensity of infection (ranges from 0–6).
[e] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

TABLE 5. Effects of nematicides on populations (J2/250 g dry soil from 0–30 cm) and infection of potato tubers by Columbia root-knot nematodes (*Meloidogyne chitwoodi*)—Umatilla Co., OR, 2000.

Treatment[a]	Before fumigation 10 April	Midseason 30 August	Harvest 23 September	Percent tuber infection[b]	Percent culled tubers[c]	Infection Index[d]
Control	15	67 a[e]	238 a	98	94 a	3.84 a
SH MS 355 at 15 & 30 cm	15	3 b	39 ab	76	35 b	1.81 ab
SH MS 560 at 15, 30 & 45 cm	5	1 b	19 ab	50	6 bc	0.76 bcd
SH MS 700 at 15, 30 & 45 cm	8	0 b	3 b	41	3 bc	1.27 bcd
SH MP 448 at 15, 30 & 45 cm	5	0 b	6 b	44	3 bc	0.62 bcd
1,3-D 140	7	2 b	3 b	66	11 bc	1.04 bcd
1,3-D 187	1	1 b	22 ab	68	20 bc	1.35 abc
SH MS 280/E10 mix at 15 & 30	5	1 b	9 b	63	12 bc	1.27 bcd
SH MS 355/E13 mix at 15 & 30	4	0 b	1 b	32	0 c	0.36 cd
SH MS 355/E13 mix at 15 & 30 + A3	5	0 b	2 b	27	0 c	0.29 d
SH MS 355 at 15 & 30 + E13 + A3	6	1 b	3 b	56	15 bc	1.25 bcd
SH MS 280 + 1,3-D 140 simult.	4	0 b	8 b	40	2 bc	0.51 bcd

[a] SH = shank-applied metam sodium (MS) at 280, 355, 560, or 700 liters/ha, and metam potassium (MP) at 448 liters/ha.
1,3-D = 1,3-dichloropropene at 140 or 187 liters/ha.
The MS and 1,3-D combination treatment was made simultaneously.
E13 = ethoprop 6 EC at 13.2 kg a.i./ha broadcast, preplant incorporated.
E10 and E13 mix = ethoprop 6 EC at 9.9 and 13.2 kg a.i./ha, respectively, in a tank mix with metam sodium.
A3 = aldicarb granules at 3.3 kg a.i./ha applied in-furrow.
[b] Percent of tubers with 1 or more *M. chitwoodi* infection sites.
[c] Percent of tubers with 6 or more *M. chitwoodi* infection sites.
[d] Measure of intensity of infection (ranges from 0–6).
[e] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

There was a trend that product combinations were often more effective than single products. For example, 355 liters SH MS/ha injected at 15 and 30 cm reduced culls from 94% to 35%. Following this treatment with a broadcast, preplant incorporated application of ethoprop plus aldicarb applied in-furrow at planting reduced culls to 15%. However, when ethoprop was injected as a tank mix with MS, with or without aldicarb, culls were reduced to 0%. This tank mix procedure was not as effective when the rates of both MS (280 liters/ha) and ethoprop (10 kg a.i./ha) were reduced, but it was still numerically better (12%) than SH MS alone. Similarly, while 1,3-D alone at 140 or 187 liters/ha was not acceptable, even low rate combinations of SH MS (280 liters/ha) and 1,3-D (140 liters/ha) injected simultaneously provided excellent control (2% culls). SH MS at 560 or 700 liters/ha and 467 liters SH MP/ha injected at 15, 30 and 45 cm reduced culls to 6% or less.

2001 nematode population densities: This study site was characterized by a shallow (about 45 cm) hardpan evident in the two blocks nearest the field edge which reduced the performance of the fumigants in that area and contributed to a significant block effect. The analysis was limited to the three blocks in which fumigation performance did not appear to be influenced by soil conditions. Before fumigation, root-knot nematode J2 populations from 0 to 30 cm soil depth averaged 231/250 g dry soil over all plots (Table 6). One month after fumigation, the untreated control averaged 63 live J2/250 g dry soil, while all fumigation treatments averaged only 0–2 J2/250 g dry soil. At harvest, nematode population density in the untreated plots had increased to 1,767 J2/250 g dry soil, while all fumigation treatments remained significantly less, at or below 51 J2/250 g dry soil.

2001 tuber infection: Percentage of tubers infected with root-knot nematode, percentage of tubers culled due to root-knot nematode and infection index were less ($P \leq 0.05$) in all fumigation treatments than in the control, and there were no differences between fumigation treatments among any of these parameters (Table 6). Tubers culled from nematode damage averaged 53% in the untreated plots but never exceeded 1% in any treatment.

DISCUSSION

Pinkerton et al. (1986) and Ingham et al. (2000) reported that 355 liters WR MS/ha failed to reduce the percentage of tubers culled because of *M. chitwoodi* damage. Although Santo and Qualls (1984) found that WR MS reduced infected tubers to 2% in an application that had received twice as much water as in the current study, the crop was harvested much earlier (September 8), which avoided infection from late-season population increase. Apparently other nematicides (ethoprop, aldicarb, oxamyl or 1,3-D) are generally needed in addition to WR MS for adequate nematode control. Following WR MS with ethoprop before planting has substantially reduced *M. chitwoodi* recovered at harvest and produced tubers of acceptable quality in previous studies (Ingham et al., 2000), but this treatment was not effective in the current study. Performance of ethoprop in other trials has been inconsistent, from markedly reducing infection (Pinkerton et al., 1986; Ingham et al., 1991) to having no effect (Santo and Wilson, 1990), possibly due to potential biodegradation of the active ingredient (Mojtahedi et al., 1991b). At-plant addition of aldicarb after WR MS provided acceptable control even though aldicarb alone has been reported to be

TABLE 6. Effects of nematicides on populations (J2/250 g dry soil from 0–30 cm) and infection of potato tubers by Columbia root-knot nematodes (*Meloidogyne chitwoodi*)—Morrow Co., OR, 2001.

Treatment[a]	Before fumigation 3 April	After fumigation 22 May	Harvest 4 October	Percent tuber infection[b]	Percent culled tubers[c]	Infection Index[d]
Control	369 a[e]	63 a	1,767 a	100 a	53 a	2.49 a
SH MS 280 at 15 & 30 cm	130 a	0 b	51 b	36 b	1 b	0.42 b
SH MS 355 at 15 & 30 cm	333 a	0 b	9 bc	18 b	0 b	0.18 b
SH MS 467 at 15, 30 & 45 cm	60 a	1 b	15 bc	23 b	1 b	0.36 b
SH MS 560 at 15, 30 & 45 cm	63 a	0 b	31 bc	18 b	0 b	0.23 b
SH MS 700 at 15, 30 & 45 cm	532 a	2 b	12 bc	23 b	1 b	0.35 b
SH MP 467 at 15, 30 & 45 cm	186 a	0 b	21 bc	24 b	1 b	0.36 b
1,3-D 187	34 a	0 b	1 c	3 b	0 b	0.06 b
SH MS 280 + 1,3-D 140—simult.	616 a	0 b	21 bc	23 b	0 b	0.24 b
SH MS 355 + 1,3-D 187—simult.	164 a	0 b	3 bc	28 b	0 b	0.32 b
SH MS 280 + 1,3-D 140—sequen.	159 a	0 b	31 bc	29 b	0 b	0.37 b
SH MS 355 + 1,3-D 187—sequen.	223 a	1 b	14 bc	31 b	0 b	0.40 b
SH MS 355/E10 mix at 15 & 30	241 a	0 b	26 bc	22 b	0 b	0.28 b
SH MS 280/E13 mix at 15 & 30	161 a	0 b	12 bc	35 b	0 b	0.37 b
SH MS 355/E13 mix at 15 & 30	209 a	1 b	26 bc	14 b	0 b	0.16 b

[a] SH = shank-applied metam sodium (MS) at 280, 355, 467, 560, or 700 liters/ha, and metam potassium (MP) at 467 liters/ha.
1,3-D = 1,3-dichloropropene at 140 or 187 liters/ha.
The MS and 1,3-D combination treatment was made either simultaneously or sequentially with a 14-days interval.
E10 and E13 mix = ethoprop 6 EC at 9.9 and 13.2 kg a.i./ha, respectively, in a tank mix with metam sodium.
[b] Percent of tubers with 1 or more *M. chitwoodi* infection sites.
[c] Percent of tubers with 6 or more *M. chitwoodi* infection sites.
[d] Measure of intensity of infection (ranges from 0–6).
[e] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

ineffective (Griffin, 1989). Excellent control was observed in the current study with WR MS plus three post-emergence applications of oxamyl. This was superior to the performance of MS and oxamyl observed by Ingham et al. (2000) and was likely due to improved application of oxamyl. In the earlier studies, oxamyl was delivered as a foliar spray through a boom and incorporated with water at the next irrigation, whereas in the current trials oxamyl was applied by simulating chemigation so that incorporation with water was immediate. All combinations of WR MS and 1,3-D reduced culls to near zero as observed by Ingham et al. (2000).

In contrast, over several trials, the performance of SH MS for control of *M. chitwoodi* was better than that observed for WR MS. Since *M. chitwoodi* can be found deep in the soil profile and can migrate upward to infect tubers (Mojtahedi et al., 1991a), the main benefit from a shank application is that MS is distributed deeper than normally occurs during water-run application. An additional benefit may result from longer retention of the fumigant in the soil. Sullivan et al. (2004) observed that half as much active ingredient was lost after 72 hours when MS was shank-applied as opposed to delivery through chemigation. This fact may also make shank application more environmentally acceptable.

However, shank application of MS did not always provide acceptable control when used alone, and performance may be related to infection pressure. SH MS at 355 liters/ha was effective in trials where culls in untreated plots averaged 53% or less (1996, 2001). When culled tubers exceeded 53% in control plots, SH MS alone was not sufficient unless the rate was increased to 560 or 700 liters/ha (2000). There was no clear trend that control was improved by increasing the number of injection depths within the soil profile. In 2000, control appeared better when MS was injected at 15, 30 and 45 cm as opposed to 15 and 30 cm only, but rates were higher in the deeper injection treatments. Best performance occurred in 2001, when applications followed rain, and soil contained more water than in previous studies reported here. However, this trial also utilized a different fumigator design that may have improved distribution of the fumigant through the soil since there was movement of soil around the shanks. More work is necessary to define conditions for optimum performance of shank injection of MS. However, because of the extreme industry standards for tuber quality, it is unlikely that any single nematicide can be consistently effective. Combination treatments of SH MS and ethoprop in a tank mix were superior to broadcast application and mechanical incorporation of ethoprop following either WR (Ingham et al., 2000) or SH (current trials) MS. Since ethoprop is fairly immobile in soil, shank injection at 15 and 30 cm and mixing by the paddle wheel may have established a better distribution of the product. This procedure should be investigated further. SH MS plus in-season applications of oxamyl, particularly at 2.2 kg a.i/ha, were also effective. However, the most consistent treatment in all trials was SH MS plus 1,3-D. As reported by Ingham et al. (2000), combinations with rates of 280 liters MS/ha and 140 liters 1,3-D/ha were as effective (0–2% culls in five trials) as combinations with higher rates.

Shank application of MS can be of considerable benefit to potato growers with nematode and soil-borne disease problems. High winds often occur during the spring and fall when WR MS applications are made. Wind can influence the distribution of MS delivered though sprinkler irrigation systems and delay WR applications but does not affect shank-injected products. Provided soil moisture and temperature are adequate, shank injection is not constrained by unavailability of irrigation water as can happen with WR MS in late fall or early spring. Additionally, shank application allows use of MS in growing areas without center pivot irrigation. However, for shank applications to be an effective alternative to water-run applications, impact to soilborne pathogens, particularly *Verticillium dahliae*, must be determined.

Shank applications of MS and 1,3-D can be made sequentially or simultaneously. If both products can be applied with the same equipment, application costs in labor and fuel can be reduced since only one pass through the field is needed. This would also reduce the time necessary to complete fumigation. Another benefit of simultaneous application of both products is that growers would be less likely to be prevented from completing fumigation by a sudden drop in soil temperature between 1,3-D and MS applications in the fall. The combined application would also be beneficial if used in the spring. Besides soil moisture, minimum soil temperatures are also required for an effective fumigation. By waiting in the spring to achieve minimum soil temperatures, growers cannot plant as early as required for long-season potato crops to achieve maximum yields. Simultaneous applications would shorten the interval between the start of fumigation and planting compared to the sequential treatment.

However, the active ingredients of MS and 1,3-D have been reported to be incompatible, and simultaneous applications at the same soil depth are not recommended (Guo et al., 2005). In the current work, either simultaneous or sequential applications of these two products provided excellent control and were indistinguishable when included in the same randomized design. In these treatments, SH MS was applied at 15 and 30 cm, while 1,3-D was injected at 45 cm, which may have minimized the chemical interaction between the two products because of the differences in the depth of the soil profile where each were applied. Soil conditions may also be a factor in this interaction. While both sequential and simultaneous applications provided excellent control under normal soil conditions, in an area with a hardpan (2001), the simultaneous treatments had twice as many culled tubers as the sequential treatments at both rate combinations. Thus, a potentially incompatible interaction may have been induced in shallow soils where the two fumigants remained concentrated in a smaller soil volume and came in contact more readily. This suggests that there may be certain soil conditions that are not understood in which simultaneous applications of MS and 1,3-D may not be effective.

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