Supplement to the Journal of Nematology 32(4S):556–565. 2000.

Control of *Meloidogyne chitwoodi* in Potato with Fumigant and Nonfumigant Nematicides[1]

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Abstract: During 1993–94, several fumigant and nonfumigant nematicides were tested alone and in combination at various rates for control of Columbia root-knot nematode (*Meloidogyne chitwoodi*) in potato. Ethoprop, oxamyl, or metam sodium alone did not adequately reduce tuber infection. Metam sodium plus ethoprop reduced culled tubers to 3%, and metam sodium plus 2 or 3 foliar applications of oxamyl reduced culls to ≤10% in all but one instance. Fosthiazate provided excellent control of tuber infection with or without metam sodium. Rates of 1,3-dichloropropene (1,3-D) below 234 liters/ha did not always adequately 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 chloropicrin did not provide better control than 1,3-D alone. Combinations of 1,3-D at 94 liters/ha or greater plus metam sodium at 374 liters/ha or greater consistently provided excellent control of tuber damage by *M. chitwoodi* and would be the treatment of choice where soilborne fungal pathogens are also present.

Key words: 1,3-dichloropropene, aldicarb, chloropicrin, ethoprop, fosthiazate, fumigants, *Meloidogyne,* metam sodium, nematicides, oxamyl, potato, root-knot nematode.

The Pacific Northwest is the largest area of potato production in the United States. In 1997, Idaho, Oregon, and Washington produced 54% by weight and 47% by value ($1 billion) of all potatoes in the United States (National Potato Council, 1998) making potatoes among the most important cash crops in the area. However, the Columbia root-knot nematode (*Meloidogyne chitwoodi* Golden et al.) is a significant threat to potato quality in much of the region. These nematodes infect and develop in tubers, causing galling on the surface and minute brown spots surrounding females, which may penetrate 5 to 6 mm into the tuber. Quality standards required by potato processors and the U.S. Food and Drug Administration require that tubers with even a low level of infection be rejected as culls. If as few as 6% of the tubers in a field are culled due to nematode infection, the entire crop may be substantially devalued or rejected. This represents an economic loss to the grower that can reach $7,660/ha, based on average yield and market price for the Columbia Basin in 1997 (Korn, 1998).

Meloidogyne chitwoodi becomes active at 6 °C and multiplies rapidly at warm temperatures, completing three or more generations in long, warm growing seasons (Pinkerton et al., 1991). Assuming a conservative 10-fold increase/generation, a population at the detection limit of 1/250 g soil at planting could increase to several thousand/250 g soil by harvest. Tuber infection and crop rejection are a certainty under these conditions. Furthermore, since *M. chitwoodi* can continue to develop at storage temperatures, infected tubers put into storage without symptoms may express enough symptoms after storage to warrant rejection. Therefore, growers must try to keep populations as low as possible throughout the season.

The primary products used for nematode control in the Columbia Basin of the U.S. Pacific Northwest prior to 1990 were metam sodium (sodium-N-methyldithiocarbamate) and ethoprop, with 1,3 dichloropropene

Received for publication 10 April 2000.

[1] Oregon State University Agricultural Experiment Station Technical Report 11706. Mention of a trade name or proprietary product does not constitute an endorsement of a product and does not imply its approval to the exclusion of other products that may also be suitable.

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The authors thank Steve Thomas for reviewing the manuscript and Kathy Merrifield and Nadine Wade for technical assistance. This research was partially supported by the Oregon Potato Commission, Dow AgroScience, DuPont, ISK Biotech, Rhone-Poulenc, and Zeneca.

This paper was edited by Terry L. Kirkpatrick.

(1,3-D) used in some areas. Aldicarb, used to control Colorado potato beetle (*Leptinotarsa decemlineata*), provided some additional nematode suppression. In 1987, for example, metam sodium, ethoprop, aldicarb, and 1,3-D were applied to 68%, 66%, 29%, and 2%, respectively, of the potato acreage within the Columbia Basin area of Oregon (Rinehold and Witt, 1989; Williamson and Kriesel, 1989). However, even with these management procedures, infection often reached unacceptable levels on long-season crops during warm summers. This paper describes 2 years of research to improve control of *M. chitwoodi* damage to potato.

Materials and Methods

Plot design: Trials were conducted in commercial potato fields near Umatilla, Oregon, that had a history of *M. chitwoodi* damage. Study areas in 1993 and 1994 were in different fields on the same farm and were preceded by field corn. The 1993 trial was located on a Quincy loamy fine sand with 0 to 5% slope; the soil type for the 1994 trial was a Quincy loamy fine sand with a gravelly substratum and 0 to 5% slope. In both trials, 16.7-m × 4.9-m (approximately 5 rows wide) plots were established in a randomized-block design with 4 (1993) or 5 (1994) replications. Seed spacing was 22.5 cm, and row spacing was 85 cm. All cultural practices were conducted by the cooperating grower and were consistent with typical procedures for that growing area. Potatoes (*Solanum tuberosum* cv. Russet Burbank) were harvested from the middle row of each plot with a single-row level bed digger. All tubers from the center 7.6 m of that row were collected and sorted by weight, and a random sample of 25 tubers (114–341 g) was evaluated for root-knot nematode infection.

Application methods: The descriptions of the nematicide treatments and abbreviations used in data tables are listed in Table 1. Broadcast applications of 1,3-D and 1,3-D plus chloropicrin were injected 45 cm deep using shanks set 38 cm apart. Soil was sealed immediately with a disc and packer that followed behind the fumigator. Metam sodium (32% a.i. formulation) at the desired rates

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

Abbreviation	Treatment description
Control	Untreated control
1,3-D 94	1,3-dichloropropene[a] at 94 liters/ha
1,3-D 140	1,3-dichloropropene at 140 liters/ha
1,3-D 187	1,3-dichloropropene at 187 liters/ha
1,3-D 234	1,3-dichloropropene at 234 liters/ha
1,3-D + chloropicrin	1,3-dichloropropene with 17% chloropicrin[b] at 257 liters/ha
MS 514	Metam sodium[c] at 514 liters/ha
Ethoprop 13	Ethoprop 10 G[d] at 13.2 kg a.i./ha
Oxamyl 3X	Three foliar applications of oxamyl[e] at 1.1 kg a.i./ha
Fosthiazate 6	Fosthiazate[f] at 6.6 kg a.i./ha
1,3-D 94 + MS 514	1,3-dichloropropene at 94 liters/ha + metam sodium at 514 liters/ha
1,3-D 140 + MS 514	1,3-dichloropropene at 140 liters/ha + metam sodium at 514 liters/ha
1,3-D 187 + MS 514	1,3-dichloropropene at 187 liters/ha + metam sodium at 514 liters/ha
1,3-D 94 + MS 274	1,3-dichloropropene at 94 liters/ha + metam sodium at 374 liters/ha
1,3-D 140 + MS 374	1,3-dichloropropene at 140 liters/ha + metam sodium at 374 liters/ha
1,3-D 140 + ethoprop 13	1,3-dichloropropene at 140 liters/ha + ethoprop 10 G at 13.2 kg a.i./ha
MS 514 + oxamyl 1X	Metam sodium at 514 liters/ha + one foliar application of oxamyl at 1.1 kg a.i./ha
MS 514 + oxamyl 2X	Metam sodium at 514 liters/ha + two foliar applications of oxamyl at 1.1 kg a.i./ha
MS 514 + oxamyl 3X	Metam sodium at 514 liters/ha + three foliar applications of oxamyl at 1.1 kg a.i./ha
MS 514 + ethoprop 13	Metam sodium at 514 liters/ha + ethoprop 10 G at 13.3 kg a.i./ha
MS 514 + fosthiazate 6	Metam sodium at 514 liters/ha + fosthiazate at 6.6 kg a.i./ha

[a] Telone II, Dow Elanco, Indianapolis, IN.
[b] Telone C-17, Dow Elanco, Indianapolis, IN.
[c] Vapam, 32% a.i. formulation, AMVAC Chemical Corp., Los Angeles, CA.
[d] Mocap 10G, Aventis CropScience, Research Triangle Park, NC.
[e] Vydate L, DuPont Agricultural Products, Wilmington, DE.
[f] Fosthiazate 900 EC, ISK Biosciences, Mentor, OH.

was delivered in 1.9 cm water through a portable sprinkler applicator, except for the 514-liters/ha treatment in 1994. In this case, plots that were not to receive this treatment were covered with plastic tarps and metam sodium was applied to the remaining plots through center pivot chemigation. Tarps were then removed and other rates applied through the portable sprinkler applicator. Ethoprop 10 G was broadcast by measuring the appropriate amount of material for each plot into an ACME gravity-flow Spread-Rite granule spreader (pbi/Gordon Corp., Kansas City, KS) and shaking out the material during at least two passes over the treated area. Fosthiazate was applied with a CO_2 backpack sprayer in a 365-liters/ha spray solution. Ethoprop and fosthiazate were incorporated to 15 cm with a tractor-mounted rototiller immediately after application. Foliar applications of oxamyl were made with a CO_2 backpack sprayer in a 150–187-liters/ha spray solution and followed by overhead irrigation within 24 hours.

Nematode sampling: Soil samples for nematode assay (ten 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. No samples were taken within 1.5 m of either end of the plot. Soil samples were sieved and mixed, and nematodes were extracted from 250-g subsamples by density centrifugation (Jenkins, 1964) as modified in Ingham (1994).

Evaluation of tuber infection: Tubers were peeled, and the number of nematode infection sites was counted under a magnifying lamp. Data were summarized as percent infection (tubers with at least one or more infection sites), percent culls (tubers with six or more infection sites), and 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) as a measure of infection intensity (Pinkerton et al., 1986).

Statistical analysis: All percent damage data were transformed to arcsin square root (x) and evaluated by analysis of variance (ANOVA). Nematode densities were adjusted for soil moisture to convert to density/250 g dry soil and transformed to $\log_{10}(x + 1)$ before analysis (ANOVA). Least significant difference (LSD) was used to separate means only when the ANOVA was significant at $P \leq 0.05$.

1993 trial: 1,3-dichloropropene and 1,3-D plus chloropicrin were applied on 26 March 1993, and metam sodium was applied on 3 to 5 April. Soil temperature was 12 °C and 7 °C at depths of 10 and 45 cm, respectively. Ethoprop and fosthiazate were applied and incorporated on 15 April when soil temperature at 20 cm was 11 °C. The study area was planted to potato cv. Russet Burbank on 22 April. Foliar applications of oxamyl were made on 31 May, 10 June, and 20 June.

All plots had been sampled for nematodes on 25 November 1992, when soil temperature was 6 °C at 20 cm and 4 °C at 45 cm. However, cold weather prevented effective fumigation at this time, so plots were resampled on 15 March 1993 before applications were made in the spring. This provided an opportunity to examine change in nematode densities over the winter. All plots were resampled after fumigation (14 April), at early (7 July) and late (24 August) midseason, and at harvest (14 October; 0 to 30 cm only).

1994 trial: 1,3-dicloropropene was applied on 10 March 1994. Soil temperature at the time of application was 9 °C at a depth of 15 cm and 5 °C at a depth of 45 cm. Metam sodium was applied through the center pivot irrigation system on 25 March, and sprinkler applications were completed on 1 and 2 April when soil temperature was 12 °C at a depth of 15 cm. The study area was planted to potato cv. Russet Burbank on 14 April. Foliar applications of oxamyl were made on 3 June, 3 July, and 2 August. Potatoes were harvested on 29 September. All plots were sampled for nematodes before fumigation (7 March), after fumigation and planting (26 April), at midseason (11 August), and at harvest (29 September).

Results

1993 nematode densities: Excluding plots without *M. chitwoodi* in November or March, population densities in fall 1992 averaged 129 and 71 J2/250 g dry soil in the first and second 30 cm of soil, respectively (data not shown), and in spring 1993 averaged 141 and 48/250 g dry soil in the 0 to 30-cm (Table 2) and 30 to 60-cm depths (Table 3), respectively. This represented no change over the winter in the top 30 cm but a 33% decline ($P \leq 0.05$) in the second 30 cm.

There was no difference in *M. chitwoodi* densities between individual treatments in either soil depth after fumigation. By the 7 July sample, all treatments had fewer ($P \leq 0.05$) nematodes in the top 30 cm than in the control (61/250 g soil). Nematode densities averaged 1 J2/250 g soil in plots fumigated with 1,3-D, 12/250 g soil in plots fumigated with metam sodium, 6/250 g soil in plots treated with a nonfumigant nematicide (average of ethoprop, oxamyl, and fosthiazate), and 7/250 g soil in plots treated with metam sodium and a nonfumigant nematicide. In the 30 to 60-cm depth, all treatments with a fumigant had lower ($P \leq 0.05$) populations than in the control, but none of the nonfumigant treatments were different from the control or from each other.

In August, densities of *M. chitwoodi* J2 remained low in all plots fumigated with 1,3-D and plots treated with metam sodium plus ethoprop at both depths, while the number of J2 in other plots increased, especially in nonfumigated plots. Densities in harvest samples (0 to 30 cm only) were equal to those in the control in plots treated with metam sodium or nonfumigant nematicides alone. Population densities in all other treatments were lower ($P \leq 0.05$) than the control and equal to each other.

1993 tuber infection: The percentage of culled tubers in plots treated with 1,3-D at 187 liters/ha, metam sodium alone, or oxamyl alone was not different ($P \leq 0.05$) than in the control (Table 4). Infection was reduced with ethoprop alone but not a level acceptable to the industry. Metam sodium plus oxamyl, 1,3-D at 140 liters/ha, and 1,3-D plus chloropicrin lowered the percentage of culls to ≤10%, which may be acceptable in some contracts. All other treatments reduced *M. chitwoodi* infection to levels that meet industry standards.

1994 nematode densities: Before fumigation, populations of *M. chitwoodi* across the plot area averaged 412 and 105 J2/250 g dry soil in the first (Table 5) and second (Table 6) 30-cm depths, respectively. Populations declined in all plots by planting, but there was little indication that the fumigants, alone or in combination, reduced the number of *M. chitwoodi* found at either depth. At midseason, all treatments (except metam sodium alone at the deeper level) had lower densi-

TABLE 2. Effects of nematicides on populations of Columbia root-knot nematodes (*Meloidogyne chitwoodi*) from 0 to 30 cm deep in a potato field at Umatilla, Oregon, in 1993.[a]

Treatment	15 March[b]	14 April[c]	7 July	24 August	14 October[d]
Control	18	120	61 b[e]	758 d	1,074 e
Ethoprop 13	59	271	14 a	324 abcd	449 cde
Oxamyl 3X	306	61	3 a	887 bcd	872 de
Fosthiazate 6	187	332	1 a	561 cd	222 bcde
MS 514	282	250	12 a	80 abc	1,802 e
1,3-D 140	17	4	0 a	3 ab	32 abcd
1,3-D 187	40	24	<1 a	4 ab	18 abcd
1,3-D 234	7	<1	5 a	2 ab	1 abc
1,3-D + chloropicrin	315	136	1 a	0 a	13 abcd
MS 514 + ethoprop 13	73	8	3 a	3 ab	25 abcd
MS 514 + oxamyl 3X	63	36	<1 a	66 abc	75 abcde
MS 514 + fosthiazate 6	14	2	25 a	135 abc	<1 ab
1,3-D 187 + MS 514	24	38	0 a	6 ab	<1 ab
1,3-D 140 + ethoprop 13	34	3	<1 a	4 ab	0 a

[a] Juveniles per 250 g dry soil. See text for full description of treatments.
[b] Before fumigation.
[c] After fumigation.
[d] At harvest.
[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 of Columbia root-knot nematodes (*Meloidogyne chitwoodi*) from 30 to 60 cm deep in a potato field at Umatilla, Oregon, in 1993.[a]

Treatment	15 March[b]	14 April[c]	7 July	24 August
Control	43	25	42 d[d]	294 cd
Ethoprop 13	211	35	78 bcd	4 ab
Oxamyl 3X	13	2	50 cd	236 bcd
Fosthiazate 6	76	86	102 cd	453 d
MS 514	9	47	9 abc	488 abc
1,3-D 140	21	0	0 a	0 a
1,3-D 187	25	6	0 a	<1 ab
1,3-D 234	<1	0	0 a	0 a
1,3-D + chloropicrin	45	14	<1 ab	1 ab
MS 514 + ethoprop 13	4	2	0 a	5 ab
MS 514 + oxamyl 3X	20	1	0 a	15 ab
MS 514 + fosthiazate 6	9	1	0 a	16 ab
1,3-D 187 + MS 514	2	4	<1 ab	2 ab
1,3-D 140 + ethoprop 13	12	1	0 a	0 a

[a] Juveniles per 250 g dry soil. See text for full description of treatments.
[b] Before fumigation.
[c] After fumigation.
[d] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

ties at both depths than in the control plots. In addition, most treatments also had lower population densities than for metam sodium. Metam sodium reduced populations in the top 30 cm (87%) but not in the second 30 cm, while the average reduction by 1,3-D was the same at both depths (97%). Plots treated with metam sodium and either 2 or 3 applications of oxamyl had fewer *M. chitwoodi* in the top 30 cm than with metam sodium alone, but not in the second 30-cm depth.

Similar relationships between treatments were present at harvest, except that population densities increased more in the three treatments with 1,3-D at 94 liters/ha than with higher rates of 1,3-D. Suppression in metam-sodium-alone plots was also less than at midseason. Population densities were 77% and 40% lower than in the control in

TABLE 4. Effects of nematicides on infection of potato tubers by Columbia root-knot nematode (*Meloidogyne chitwoodi*) at Umatilla, Oregon, in 1993.

Treatment[a]	Percent infection[b]	Percent culls[c]	Infection index[d]
Control	77 d[e]	57 e	2.78 f
Ethoprop 13	29 abc	24 abcd	1.12 bcde
Oxamyl 3X	41 abcd	30 bcde	1.44 bcde
Fosthiazate 6	4 a	1 ab	0.06 ab
MS 514	68 cd	59 de	3.11 ef
1,3-D 140	21 a	8 abc	0.47 ab
1,3-D 187	68 bcd	23 cde	1.40 cdef
1,3-D 234	33 abcd	2 abc	0.40 bc
1,3-D + chloropicrin	24 abc	8 abc	0.53 bcde
MS 514 + ethoprop 13	16 a	3 abc	0.26 ab
MS 514 + oxamyl 3X	21 ab	10 abc	0.52 bcd
MS 514 + fosthiazate 6	9 a	1 ab	0.12 ab
1,3-D 187 + MS 514	4 a	0 ab	0.04 ab
1,3-D 140 + ethoprop 13	1 a	0 a	0.01 a

[a] See text for full description of treatments.
[b] Percent of tubers with 1 or more *M. chitwoodi*.
[c] Percent of tubers with 6 or more *M. chitwoodi*.
[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 of Columbia root-knot nematodes (*Meloidogyne chitwoodi*) from 0 to 30 cm deep in a potato field at Umatilla, Oregon, in 1994.[a]

Treatment	Before fumigation[b]	After fumigation[c]	Midseason[d]	Harvest[e]
Control	205	64 bc[f]	383 d	544 g
MS 514	270	17 abc	48 c	126 f
MS 514 + oxamyl 1X	645	120 c	14 abc	81 ef
MS 514 + oxamyl 2X	598	23 ab	8 ab	65 ef
MS 514 + oxamyl 3X	365	89 bc	8 ab	31 ef
1,3-D 94	597	8 a	14 b	27 def
1,3-D 140	218	32 abc	11 bc	2 ab
1,3-D 187	308	30 abc	2 ab	0 a
1,3-D 234	418	93 abcd	2 ab	3 abc
1,3-D 94 + MS 514	537	96 c	1 a	53 cde
1,3-D 140 + MS 514	319	13 a	6 ab	8 abcd
1,3-D 187 + MS 514	390	13 ab	<1 a	3 abc
1,3-D 94 + MS 374	493	138 cd	1 a	26 bcd

[a] Juveniles per 250 g dry soil. See text for full description of treatments.
[b] 7 March 1994.
[c] 26 April 1994.
[d] 11 August 1994.
[e] 29 September 1994.
[f] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

the upper and second 30-cm depths, respectively. Harvest populations of *M. chitwoodi* J2 in metam sodium or metam sodium plus oxamyl plots were lower than in untreated plots in the first 30 cm but not in the second 30 cm. There was a trend toward fewer nematodes in the top 30 cm with more applications of oxamyl, but none of the oxamyl treatments lowered J2 populations compared with metam sodium alone.

1994 tuber infection: Metam sodium alone reduced ($P \leq 0.05$) the percentage of tubers culled due to *M. chitwoodi* infection relative to the control (Table 7), but the level (30%) remained above acceptable industry standards. Metam sodium plus two applications

TABLE 6. Effects of nematicides on populations of Columbia root-knot nematodes (*Meloidogyne chitwoodi*) from 30 to 60 cm in a potato field at Umatilla, Oregon, in 1994.[a]

Treatment	Before fumigation[b]	After fumigation[c]	Midseason[d]	Harvest[e]
Control	84	26	169 f[f]	180 d
MS 514	73	15	68 ef	108 cd
MS 514 + oxamyl 1X	46	62	22 de	20 abc
MS 514 + oxamyl 2X	531	26	38 de	41 bcd
MS 514 + oxamyl 3X	71	20	16 cde	15 abcd
1,3-D 94	47	10	2 ab	9 ab
1,3-D 140	52	17	4 abc	2 a
1,3-D 187	34	23	15 cde	4 ab
1,3-D 234	65	45	7 abc	2 a
1,3-D 94 + MS 514	99	18	8 abcd	7 ab
1,3-D 140 + MS 514	59	18	11 abcd	2 a
1,3-D 187 + MS 514	89	20	9 bcd	4 a
1,3-D 94 + MS 374	73	31	2 a	30 abc
1,3-D 140 + MS 374	43	17	16 cde	6 a

[a] Juveniles per 250 g dry soil. See text for full description of treatments.
[b] 7 March 1994.
[c] 26 April 1994.
[d] 11 August 1994.
[e] 29 September 1994.
[f] Means within the same column followed by the same letter are not different ($P \leq 0.05$).

TABLE 7. Effects of nematicides on infection of potato tubers by Columbia root-knot nematode (*Meloidogyne chitwoodi*) at Umatilla, Oregon, in 1994.

Treatment[a]	Percent infection[b]	Percent culls[c]	Infection index[d]
Control	97 g[e]	88 f	4.23 g
MS 514	77 ef	30 e	1.71 fg
MS 514 + oxamyl 1X	51 de	34 e	1.54 ef
MS 514 + oxamyl 2X	29 cd	7 cd	0.57 de
MS 514 + oxamyl 3X	39 de	20 de	0.98 ef
1,3-D 94	34 d	14 cd	0.74 de
1,3-D 140	31 d	2 bcd	0.41 cd
1,3-D 187	25 bcd	2 abc	0.32 bc
1,3-D 234	3 ab	1 ab	0.06 ab
1,3-D 94 + MS 514	4 abc	1 ab	0.08 ab
1,3-D 140 + MS 514	3 ab	0 a	0.04 ab
1,3-D 187 + MS 514	4 ab	1 ab	0.06 ab
1,3-D 94 + MS 374	12 abc	5 ab	0.28 ab
1,3-D 140 + MS 374	1 a	0 a	0.01 a

[a] See text for full description of treatments.
[b] Percent of tubers with 1 or more *M. chitwoodi*.
[c] Percent of tubers with 6 or more *M. chitwoodi*.
[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 ($P \leq 0.05$).

of oxamyl reduced percent culls compared to metam sodium alone and achieved a level (7%) that would be acceptable in some instances, but three applications of oxamyl in combination with metam sodium did not reduce the number of culls as well as two applications. All treatments with 1,3-D alone substantially reduced the percentage of culls, and all but the lowest rate met industry standards for quality. In addition, all 1,3-D plus metam sodium combinations, including the lowest rate of each fumigant, lowered infection to acceptable levels.

DISCUSSION

Performance of nonfumigant nematicides: Ethoprop did not control *M. chitwoodi* populations or tuber infection when used alone. However, in combination with metam sodium, ethoprop reduced numbers of *M. chitwoodi* more than metam sodium alone and provided adequate tuber protection. Pinkerton et al. (1986) found that ethoprop had no effect on soil population densities of *M. chitwoodi* but reduced culls from 100% in nontreated plots to 28% when used alone, and from 85% in 1,3-D plots to <3% when used in combination with 1,3-D. Santo and Wilson (1990) found no effect of ethoprop on either soil population densities of *M. chitwoodi* or tuber infection. Performance of ethoprop in different studies may be affected by historical use because soils treated with this nematicide can experience enhanced biodegradation and reduced effectiveness (Mojtahedi et al., 1991b).

Similar to ethoprop, oxamyl had no effect on *M. chitwoodi* when used alone. However, population densities in plots treated with metam sodium plus oxamyl were lower than with metam sodium alone in 1993, but not in 1994. Populations in all oxamyl treatments were lower than those in the control in the top 30 cm of soil but not at the 30 to 60-cm depth, suggesting that oxamyl did not penetrate far enough to impact nematodes deeper than 30 cm. Tuber infection was only marginally acceptable in treatments of metam sodium plus 2 (1994) or 3 (1993) oxamyl applications. The increase in *M. chitwoodi* infection with three oxamyl applications over that with two applications in 1994 may be attributed to the insecticidal properties of oxamyl, which reduced late-season insect damage compared to other treatments. Plants in these plots lived longer and permitted further nematode development than in other plots. While oxamyl showed promise for reducing tuber infection, the percentage of culls was still unacceptable in most treatments. Relying on the systemic absorption of oxamyl through leaves when applied as a foliar spray in a low volume of water may be an ineffective strategy to prevent tuber infection by *M. chitwoodi*. Furthermore, the 1-month interval between applications may be too long for suitable protection.

Fosthiazate provided excellent control of tuber infection even though populations of J2 in the soil remained high. This suggests that fosthiazate may interfere with tuber invasion, or development of nematodes in tubers after penetration, rather than by reducing nematode populations in the soil alone.

Fumigant nematicides: Spring fumigation with 1,3-D or metam sodium, alone or in combination, did not reduce the number of J2 recovered in post-fumigation samples. This was because density centrifugation extracts both live and dead nematodes and the interval between fumigation and sampling was too short for dead nematodes to be degraded. No evaluation of viability was made during enumeration.

In 1993, metam sodium lowered population densities of *M. chitwoodi* J2 early in the season but there was no difference from nontreated plots at harvest. Similar results were observed in 1992 when rates as high as 935 liters/ha had no effect on populations at harvest (Ingham, unpubl. data). In 1994, metam sodium suppressed *M. chitwoodi* populations at midseason and harvest in the top 30 cm but had no effect on populations below 30 cm. Consequently, metam sodium never controlled tuber infection. In Washington, fall- or spring-applied metam sodium at 153 or 184 liters a.i./ha lowered midseason *M. chitwoodi* densities from 39/250 cm^3 soil in nontreated plots to 3/250 cm^3 soil in treated plots (Pinkerton et al., 1986). Harvest densities averaged 1,118 and 153 J2/250 cm^3 soil in control and treated plots, respectively. All metam sodium treatments reduced the number of culled tubers (16% vs. 100% in control plots) but not to acceptable levels (Pinkerton et al., 1986). Santo and Qualls (1984) found that metam sodium reduced post-treatment populations of *M. chitwoodi* to undetectable levels and reduced the number of infected tubers to 2%, compared to 82% in untreated plots. However, their harvest date (8 September) was relatively early. If the harvest date had been comparable to those in this study, nematode infection would likely have been much higher. Rejectable levels of tuber infection after metam sodium application also have been observed with *M. hapla* (Ingham et al., 1991). Thus, the inability of metam sodium applied through chemigation to control root-knot nematodes may explain why high levels of tuber infection can occur in fields where metam sodium is the only nematicide applied. This can be compounded when unusually warm growing seasons permit additional nematode population increase.

By contrast, 1,3-D at rates of 140 liters/ha or greater reduced *M. chitwoodi* population levels and reduced the percentage of culled tubers in all but one instance. It is unclear why 1,3-D at 187 liters/ha did not lower tuber infection in two plots in 1993 even though soil populations of *M. chitwoodi* were suppressed. Data from other treatments in 1993 and 1994 suggest that 1,3-D at 187 liters/ha would ordinarily control *M. chitwoodi.* In 1992, rates of 140, 187, and 234 liters/ha of 1,3-D reduced J2 populations at harvest to undetectable levels at both soil depths compared to 100 and 214 J2/250 g soil from untreated plots in the first and second 30 cm, respectively (Ingham, unpubl. data). Griffin (1989) also observed good control of *M. chitwoodi* with 1,3-D in Utah, but Pinkerton et al. (1986) and Santo and Wilson (1990) reported that 1,3-D failed to control *M. chitwoodi* infection in Washington (85% and 49% culls in the two studies, respectively). The fumigant was injected 20 to 30 cm deep in the Washington trials compared to 45 cm in our studies, so it may have failed to control nematodes deeper in the profile. *Meloidogyne chitwoodi* can migrate upward from depths of 120 cm and still cause tuber damage (Mojtahedi et al., 1991a). Failure of ethoprop, oxamyl, or metam sodium to reduce populations below 30 cm may also influence why these treatments did not control tuber infection. Therefore, an effective strategy can be the use of a fumigant to suppress initial populations followed by a nonfumigant nematicide that may intercept J2 migrating upward (Pinkerton et al., 1986; this study).

1,3-dichloropropene plus chloropicrin did not provide better control of *M. chitwoodi* than 1,3-D alone, and the additional expense of this formulation limits its use in potato (Rinehold and Jenkins, 1996). In contrast, 1,3-D plus metam sodium combination treatments provided excellent nematode control, averaging 1% culls in the six treatments tested. Furthermore, control of early dying by metam sodium generally compensates for the additional cost.

Implications: Results from these studies demonstrate that chemigation with metam sodium alone is insufficient to control *M. chitwoodi* in long-season potatoes grown in the Columbia Basin. Unfortunately, with the suspension of aldicarb registration in 1989 (Thomas et al., 1993) and the reduction in use of ethoprop after 1987 (Rinehold and Jenkins, 1996), many potato fields in Oregon had been treated with only metam sodium, a practice that likely contributed to the increase in nematode infection experienced during the early 1990s. In contrast, 1,3-D was very effective at reducing root-knot infection at most rates in our studies. Consequently, the use of 1,3-D was increased during the years when these studies were being conducted and reported to growers. By the end of 1993, 32% of the potato acreage in the Columbia Basin of Oregon was being treated with 1,3-D (Rinehold and Jenkins, 1996). 1,3-dichloropropene provides little control of soilborne fungal pathogens, however. For maximum yields and high quality, growers need both metam sodium to suppress soilborne fungal pathogens (Kunkel and Weller, 1965) and a nematicide to control root-knot nematodes. Metam sodium plus either fosthiazate or ethoprop provided good control under the conditions of our study, and metam sodium plus oxamyl provided adequate control for contracts that would permit up to 10% culls. However, protection with metam sodium plus nonfumigant nematicides could be less effective under greater nematode pressure such as that which occurs when potato follows excellent host crops, like field corn. This may be further aggravated when there is little decline in densities over the winter, as in 1992–93.

The most effective control was attained with any combination of metam sodium and 1,3-D, but only the combination of 1,3-D at 187 liters/ha plus metam sodium at 514 liters/ha was labeled before this study was conducted. Our results indicate that several 1,3-D plus metam sodium combinations at lower rates of each provide adequate nematode control at lower cost. Companion studies have established that these reduced rates are also sufficient to reduce soil-borne fungi and maintain yields (Ingham and Hamm, unpubl. data). This information, and comparable results from Washington (Santo et al. 1991, 1993), have led to new labels that permit reduced rates of each fumigant when the two materials were used together, saving growers nearly $250/ha over the original labeled rates.

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