Journal of Nematology 39(3):258–262. 2007.

Control of *Paratrichodorus allius* and Corky Ringspot Disease in Potato with Shank-injected Metam Sodium

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Abstract: Corky ringspot disease (CRS) of potato produces necrotic areas in tubers that are considered quality defects that can lead to crop rejection. CRS is caused by tobacco rattle virus that is vectored by stubby-root nematodes (*Paratrichodorus* spp., *Trichodorus* spp.) at very low population densities, making disease management difficult and expensive. Fumigation with metam sodium (MS) is a common practice to control soil-borne fungi and increase potato yield. MS is generally applied in water via chemigation (water-run, WR) but is ineffective at controlling CRS when WR-applied, even at high rates. Therefore, WR MS is often used in combination with 1,3-dichloropropene (1,3-D), aldicarb or oxamyl to attain adequate CRS control. Between 1996 and 2000, fields with a history of CRS were treated with WR MS, shank-injected MS, and/or 1,3-D, and tubers were evaluated for symptoms of CRS. Shank injection of MS (SH MS) at depths of 41 cm, 15 and 30 cm, or 15, 30 and 45 cm controlled CRS over 3 years of testing. All rates of 280 liters/ha or greater were effective. Shank injection of metam potassium (MP) at rates of 448 liters/ha was also effective. 1,3-D controlled CRS alone or in combination with WR or SH MS. Proper shank application of MS or MP may adequately control CRS without the additional cost of other nematicides at low (<10 *P. allius*/250 g soil) to moderate (10 to 30 *P. allius*/250 g soil) populations of the nematode vector. Although SH MS was superior to WR MS, additional research is necessary to determine if this practice would be sufficient at higher CRS disease pressure or if addition of other nematicides would be necessary.

Key words: 1,3-dichloropropene, corky ringspot, CRS, fumigants, metam potassium, metam sodium, nematicides, *Paratrichodorus allius*, potato, stubby-root nematode, tobacco rattle virus, TRV.

Corky ringspot disease (CRS), also referred to as spraing, produces dark-brown "corky" necrotic areas in the form of arcs or diffuse brown spots within potato tubers (Atanasoff, 1926). The causal agent of the disease is tobacco rattle virus (TRV) that is vectored by stubby-root nematodes (*Paratrichodorus* spp. and *Trichodorus* spp.) (Sol et al., 1960; Walkinshaw et al., 1961; Taylor and Brown, 1997; Weingartner, 2001). Damage to tubers from CRS is considered a quality defect by the potato industry, and tubers with more than one 3-mm-diam. internal arc or spot per 28 g tuber tissue are culled (USDA, 1991). Crops in which more than 6% of the tubers are graded as culls due to CRS damage are often rejected or substantially downgraded in value. CRS is a problem of concern in several potato-growing areas in the western US where *P. allius* (Jensen, 1963) Siddiqi, 1974, the vector, and TRV have been found (Jensen and Allen, 1964; Jensen et al., 1974; Mojtahedi and Santo, 1999).

CRS is controlled by managing the nematode vector with nematicides or by growing TRV-resistant cultivars. However, not all production regions have TRV-resistant cultivars that are suitable for that growing area. Ingham et al. (2000b) evaluated several nematicides for control of *P. allius* and CRS in the Columbia Basin of Oregon and Washington and reviewed similar work previously reported. Aldicarb alone significantly reduced CRS but not always to acceptable levels. Metam sodium (sodium-N-methyldithiocarbamate, MS) applied through irrigation or ethoprop alone did not control CRS, but MS plus ethoprop provided adequate control under light disease pressure (<20% culls in untreated plots). Two or three post-emergence applications of oxamyl, either with or without MS, appeared to control CRS at low disease pressure. 1,3-dichloropropene (1,3-D) controlled CRS at 94 liters/ha at low (2 *P. allius*/250 g soil) population densities and rates of 140 liters/ha or greater were adequate at higher population densities. Treatment with 1,3-D plus chloropicrin was no better than 1,3-D alone and did not always control CRS. Combinations of 1,3-D at 94 liters/ha or greater plus MS at 374 liters/ha or greater always controlled CRS. *Paratrichodorus allius* numbers were higher and severity of CRS greater after wheat than after field corn, but *P. allius* declined rapidly after potato was planted and remained at low population densities (≤ 6 *P. allius*/250 g soil) until harvest.

MS is a soil fumigant commonly used to control soil-borne pathogenic fungi, particularly *Verticillium dahliae*, and thereby reduce yield loss due to potato early dying (Hamm et al., 2003). MS is generally applied in water via chemigation (water run, WR) in 1.3 to 3.9 cm water the fall prior to potato cropping. However, whereas this practice reduces fungal propagules and increases potato yield (Hamm et al., 2003), it does not control Columbia root-knot nematode, *Meloidogyne chitwoodi* (Ingham et al., 2000a) or CRS (Ingham et al., 2000b). Therefore, additional nematicides must be applied to control nematodes (Ingham et al., 2000a), increasing the cost of production. Recently, Ingham et al. (2007) observed that shank injection of MS substantially im-

Received for publication 5 April 2007.
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The authors thank Hassan Mojtahedi and Saad Hafez for reviewing the manuscript, Nadine Wade for technical assistance and Hassan Mojtahedi for conducting TRV bioassays and consultation during the research. This research was partially supported by the Oregon Potato Commission, The Metam Sodium Task Force, Dow AgroScience and AMVAC. 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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This paper was edited by Brent Sipes.

proved control of tuber damage from *M. chitwoodi* when compared to WR MS. This paper reports the results of 3 years of research to evaluate whether shank injection of MS at different depths in the soil profile would be effective for the control of *P. allius* and CRS.

Materials and Methods

Plot design: Between 1996 and 2000, three trials were conducted to test fumigation methods for control of CRS in commercial potato fields in Umatilla County, OR. All areas had a history of severe tuber damage from CRS in which previous potato crops had been rejected by processors. Study areas in 1999 and 2000 were bioassayed to confirm the presence of viruliferous *P. allius* (Hassan Mojtahedi, personal communication). All trials were arranged in a randomized block design with four (1996) or five (1999, 2000) replications. Plots were either 4.6-m (five potato rows, 1996) or 2.6-m (three potato rows, 1999, 2000) wide. In trials where plots were three rows wide, an untreated buffer row was included between adjacent plots. All data were collected from the center row. Plots were 12.8-m (1996) or 15.4-m (1999, 2000) long. Certified seed potatoes (*Solanum tuberosum* cv. Russet Burbank [1996] or Russet Burbank cv. Newleaf Generation 2 [1999, 2000]) 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 production area.

Application methods/treatments: Descriptions of treatments and abbreviations used are listed in Tables 1 and 2. Fumigation treatments were made with commercial equipment in 1996 or with a custom-built experimental fumigator in 1999 and 2000. On the experimental fumigator, nozzles were placed on each side of ripper shanks at depths of 15, 30 and 45 cm for injection of MS. At each depth, the nozzles on each side of the shanks were 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 as shanks were pulled through the soil. Shanks were set on a 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. Material being delivered to each depth could be controlled individually so that all possible combinations of depths and rates/depth were possible. 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 products could be switched during application to facilitate delivery of several different treatments in a randomized block design during a single pass through the plots. The unit treated an area 2.6-m wide (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.

Broadcast applications of 1,3-D (Telone II, Dow Agrosciences, Indianapolis, IN) were injected 45-cm deep using shanks set 38 to 40 cm apart. Soil was sealed immediately with a disc (1996) or paddle wheel (1999, 2000) and ring roller packer that followed behind the fumigator. Metam sodium (Vapam HL, 42% a.i. formu-

Table 1. Populations (nematodes/250 g dry soil) of stubby-root nematodes (*Paratrichodorus allius*) from 0–30 cm before and after fumigation in potato fields with a history of corky ringspot disease, Umatilla Co., OR.

Treatment[a]	Before 15 Mar 1996	After 16 May 1996	Before 31 Mar 1999	After 27 May 1999	Before 10 Apr 2000	After 18 May 2000
Control	3	1	6	0	19	3
WR MS 355	1	<1	3	0	—	—
1,3-D 140	—	—	3	0	24	0
1,3-D 187	—	—	4	0	16	1
1,3-D 233	—	—	12	0	—	—
WR MS 280 + 1,3-D 140	—	—	13	0	—	—
WR MS 355 + 1,3-D 140	8	<1	—	—	—	—
WR MS 355 + 1,3-D 187	1	0	—	—	—	—
SH MS 210 at 41 cm	7	0	—	—	—	—
SH MS 355 at 41 cm	12	0	—	—	—	—
SH MS 355 at 15 & 30 cm	—	—	—	—	27	1
SH MS 280 at 15, 30 & 45 cm	—	—	5	0	—	—
SH MS 355 at 15, 30 & 45 cm	—	—	13	0	—	—
SH MS 467 at 15, 30 & 45 cm	—	—	4	0	—	—
SH MS 560 at 15, 30 & 45 cm	—	—	—	—	14	1
SH MS 700 at 15, 30 & 45 cm	—	—	—	—	17	2
SH MP 448 at 15, 30 & 45 cm	—	—	—	—	24	0
SH MS 280 + 1,3-D 140	—	—	3	0	26	1
SH MS 355 + 1,3-D 187	—	—	4	0	—	—
	ns[b]	ns	ns	ns	ns	ns

[a] WR = water-run or SH = shank-injected, MS = metam sodium at 210, 280, 355, 467, 560, or 700 liters/ha. Injections were made at single or multiple depths of 41 cm, 15 and 30 cm, or 15, 30 and 45 cm. SH MP = shank-injected metam potassium at 448 liters/ha at depths of 15 and 30 cm. 1,3-D = 1,3-dichloropropene at 140, 187 or 233 liters/ha injected at 45 cm.

[b] ns = no significant differences ($P \leq 0.05$) between any means in the column.

TABLE 2. Effects of nematicides on internal symptoms (% of potato tubers examined) of corky ringspot. Umatilla Co., OR.

Treatment[a]	1996[b]	1999[c]	2000[b]
Control	28 a[d]	72 a	24 a
WR MS 355	33 a	2 b	—
1,3-D 140	—	0 b	0 c
1,3-D 187	—	3 b	1 bc
1,3-D 233	—	2 b	—
WR MS 280 + 1,3-D 140	—	5 b	—
WR MS 355 + 1,3-D 140	5 b	—	—
WR MS 355 + 1,3-D 187	<1 b	—	—
SH MS 210 at 41 cm	29 a	—	—
SH MS 355 at 41 cm	1 b	—	—
SH MS 355 at 15 & 30 cm	—	—	3 bc
SH MS 280 at 15, 30 & 45 cm	—	0 b	—
SH MS 355 at 15, 30 & 45 cm	—	8 b	—
SH MS 467 at 15, 30 & 45 cm	—	3 b	—
SH MS 560 at 15, 30 & 45 cm	—	—	0 c
SH MS 700 at 15, 30 & 45 cm	—	—	5 b
SH MP 448 at 15, 30 & 45 cm	—	—	1 bc
SH MS 280 + 1,3-D 140	—	1 b	1 bc
SH MS 355 + 1,3-D 187	—	4 b	—

[a] WR = water-run or SH = shank-injected, MS = metam sodium at 210, 280, 355, 467, 560, or 700 liters/ha. Injections were made at single or multiple depths of 41 cm, 15 and 30 cm, or 15, 30 and 45 cm. SH MP = shank-injected metam potassium at 448 liters/ha at depths of 15 and 30 cm. 1,3-D = 1,3-dichloropropene at 140, 187 or 233 liters/ha injected at 45 cm.

[b] Tubers with necrotic arc symptoms of corky ringspot.

[c] Tubers with necrotic arc or diffuse spot symptoms of corky ringspot.

[d] Means within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

lation (0.5 kg a.i./liter), AMVAC Chemical Corp., Los Angeles, CA) was WR-applied in 1996 through the center pivot irrigation system in 1.3 cm water, and plots not receiving this treatment were covered with tarps. In 1999, WR MS was applied in 1.3 cm water to specific plots with a portable chemigation simulator system that consisted of multiple sprinkler heads that provided water coverage just over the plot area. Shank-injected (SH) MS or metam potassium (MP, potassium N-methyldithiocarbamate, K-PAM HL, 54% a.i. formulation (0.7 kg a.i./liter), AMVAC Chemical Corp., Los Angeles, CA.) treatments were delivered at various depths (see tables), and soil was sealed as described above. Combinations of SH MS delivered at 15 and 30 cm and 1,3-D delivered at 45 cm were applied simultaneously.

1996 trial: 1,3-D was applied to appropriate plots on 15 March. WR MS was applied through the center pivot on 3 April, and SH MS treatments were applied on 10 April. Seed was planted 1 May.

1999 trial: MS and 1,3-D were shank-injected with the experimental fumigator on 1 and 2 April. WR MS treatments were applied through a chemigaton simulator on 12 to 14 April. Plots were planted on 8 May.

2000 trial: Treatments were applied using the experimental fumigator on 19 and 20 April, and the field was planted on 11 May.

Nematode sampling: Soil samples for nematode evaluations (10 2.5-cm-diam. cores/plot) were taken at depths of 0 to 30 cm from the center row of each plot. No samples were taken within 1.5 m of either end of the plot. Samples were taken before fumigation (15 March 1996, 31 March 1999 and 10 April 2000), after planting (16 May 1996, 27 May 1999 and 18 May 2000), mid-season (7 August 1996, 18 August 1999 and 30 August 2000) and at harvest (10 October 1996, 19 October 1999 and 25 September 2000). Soil samples were sieved and mixed. Nematodes were extracted from 250 g subsamples by density centrifugation (Jenkins, 1964) as modified by Ingham (1994). Nematode densities were adjusted for soil moisture to convert to density per 250 g dry soil and transformed to $\log_{10}(x+1)$ before analysis (ANOVA).

Evaluation of tuber symptoms: Potatoes were harvested by digging the center row of each plot with a single-row level-bed digger. A random sample of 25 110 to 340 g tubers from each plot was inspected for symptoms of CRS by peeling and slicing each tuber into 1.3-cm-thick transverse sections and examining the exposed internal surface. In 1996 and 2000, only tubers with necrotic arc symptoms of CRS were evaluated. However, in 1999, symptom expression was predominantly in the form of diffuse necrotic spots. Damage was expressed as percentage of tubers examined. All percent damage data were transformed to arcsin square root (×) and evaluated by analysis of variance (ANOVA).

Statistical analysis: Means of transformed values were back-transformed before reporting. Duncan's Multiple Range Test was used to separate means only when ANOVA was significant at $P \leq 0.05$. All differences reported are at $P \leq 0.05$.

Results and Discussion

Nematode densities: Prefumigation populations from 0 to 30 cm averaged 5, 6 and 20 *P. allius*/250 g soil across all plots for the trial areas in 1996, 1999 and 2000, respectively (Table 1). After fumigation, *P. allius* was rarely detected (i.e., average density = 0–2 *P. allius*/250 g soil), even in untreated plots, on any sample date in any trial. No significant differences were observed between any treatments on any sample date in any trial, so only data from before and after fumigation are presented.

Tuber symptoms of CRS: The frequency of CRS symptom expression in 1996 was not reduced by WR MS or by SH MS at a rate of 210 liters/ha (Table 2). Combining 1,3-D with WR MS or increasing the rate of SH MS to 355 liters/ha significantly reduced CRS. WR MS alone was effective in 1999. All 1,3-D, SH MS or SH MP treatments in 1999 and 2000 reduced incidence of CRS to low levels.

Although moderate populations of *P. allius* were present before fumigation in some plots, average populations were low across each study site even though each field had a history of severe CRS. These results are similar to those described by Ingham et al. (2000b), who reported average site densities of 2 to 4 *P. allius*/250 g soil before fumigation in 1993 and 1994 in areas which developed extensive CRS (19–81% culls) by harvest. Similar observations were reported by Mojtahedi and Santo (1999). Apparently, potato is a poor host for *P. allius*, because in all 3 years of the current study, *P. allius* population densities remained low from planting until harvest. Ingham et al. (2000b) and Mojtahedi and Santo (1999) have also reported that potato is a poor host for *P. allius* and that populations decline and remain low during the potato crop.

Nevertheless, even these low (0–3 *P. allius*/250 g soil) population densities produced high incidences of CRS-damaged tubers in untreated plots, emphasizing the need to treat any potato crop grown in a field with a history of CRS. Because CRS is a viral disease caused by TRV, which can be vectored each time a viruliferous stubby-root nematode feeds, the damage threshold is a function of feeding events as well as population density. Thus, even low nematode populations are capable of transmitting the virus and may cause severe disease. At these low densities, treatment effects on nematode populations are difficult to observe even when treatments reduce CRS.

Ingham et al. (2000b) reported that WR MS was ineffective for management of CRS and observed no perceptible reduction in disease with WR MS in two of three trials and reduced but still unacceptable levels of CRS in the third. These results were confirmed in the 1996 trial discussed in this paper. Although WR MS was effective in 1999, consistent control of CRS with WR MS requires additional nonfumigant nematicides such as aldicarb, ethoprop or oxamyl (Ingham et al. 2000b, http://oregonstate.edu/potatoes/reports/1997/page062.pdf). New to the current study is the discovery that MS alone can be effective against CRS if shank-applied. Physically injecting MS into the soil distributes the compound deeper into the soil profile than when MS is applied via chemigation. Depth of placement is important for managing *P. allius* since these nematodes are almost evenly distributed to a depth of 60 cm and potentially deeper (Mojtahedi and Santo, 1999; Ingham et al., 2000b). Since the SH MS rate of 210 liters/ha was ineffective, as was in-row injection of MS at 187 liters/ha (Weingartner and Shumaker, 1988), there appears to be a critical dose concentration necessary for control. Rates of 280 liters/ha or greater were effective in the current study. MS was injected at various single or multiple points in the soil including 41 cm, 15 and 30 cm, and 15, 30 and 45 cm. All methods were effective. This is also the first report that SH MP is effective for controlling CRS. MP may be more attractive than MS, because adding potassium to soil is more desirable than adding sodium. Results from the current study also support previous studies (Ingham et al., 2000b) that reported excellent control of CRS with 1,3-D.

Since many potato fields contain yield-reducing pathogenic soil-borne fungi such as *Verticillium dahliae*, MS is frequently used to reduce these populations and thereby increase potato yield (Hamm et al., 2003). However, because traditional WR MS is relatively ineffective at controlling tuber damage from root-knot nematodes (Ingham et al., 2000a) and CRS (Ingham et al., 2000b), other products such as 1,3-D or nonfumigant nematicides have been needed in addition to MS, increasing the cost to the grower. Results from this study suggest that methods could be developed to control CRS with SH MS (or SH MP) alone.

Shank application of MS has been increasing in popularity. Growing environmental and health concerns regarding application of MS through sprinkler irrigation systems may provide incentive for wider use of this application practice. However, further research is necessary to determine if this procedure can control CRS in fields with higher disease pressure from CRS. In severe cases, nearly 100% of tubers may have symptoms of CRS, while incidence of symptomatic tubers in the current study averaged 24 to 72%. Similarly, Ingham et al. (2007) demonstrated that SH MS provided good suppression of tuber damage from *M. chitwoodi* in sites with moderate pressure ($\leq$53% culls in untreated plots), but not at higher levels of pressure. Nevertheless, these studies demonstrated that SH MS is far superior to WR MS for control of *M. chitwoodi* (Ingham et al., 2007), *P. allius* and CRS (current study). However, SH MS may need to be used in combination with other nematicides when disease pressure from stubby-root nematodes and CRS is high. In addition, work is needed to confirm that SH MS can provide the same control of soil-borne fungi as WR MS and maintain high yields. Alternatively, for potato cultivars resistant to *V. dahliae* which may not require MS, this research confirms that 1,3-D alone can reliably control CRS.

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