American Journal of Potato Research (2018) 95:413–422
https://doi.org/10.1007/s12230-018-9641-5

Effect of Soil Temperature, Injection Depth, and Rate of Metam Sodium Efficacy in Fine-Textured Soils with High Organic Matter on the Management of Verticillium Wilt of Potato

S. K. R. Yellareddygari[1] · Neil C. Gudmestad[1]

Published online: 22 February 2018

Abstract

Metam sodium is a widely used soil fumigant for Verticillium wilt management in most potato production regions of the United States. Environmental concerns regarding volatilization losses have led to restrictions on the use of metam sodium. The potato industry adapted to these restrictions by replacing metam sodium applications through sprinkler irrigation with shank injection applications of the fumigant. Previous research established parameters for effective shank application of metam sodium based on soil temperature, injection depth and rate of fumigation. However, these recommendations were based on research conducted under coarse-textured soil conditions with a low organic matter (OM) content (<1.3%). However, many potato production soils in North Dakota and Minnesota have a finer silt loam texture and OM contents of >2.5%. Therefore, it is important to know whether metam sodium fumigation recommendations for coarse-textured soils can be adapted to fine-textured soils. Two field trials were conducted using a split strip-block design for studying metam sodium efficacy in managing wilt. In both years, metam sodium injection depth and soil temperature at the time of injection did not result in significant differences in any study variable evaluated. All metam sodium fumigation rates significantly ($P < 0.05$), lowered Verticillium microsclerotia, reduced wilt severity, and improved tuber yield compared to non-treated plots. However, significant differences among fumigation rates were not observed across any variable evaluated. A relatively low rate of 373 l/ha is as effective as higher metam sodium rates for effective control of Verticillium wilt. Results presented here suggest that current metam sodium recommendations for shank injection applications in coarse-textured soils can be implemented in field soils with a fine texture and higher OM content.

Resumen

Metam sodio es un fumigante del suelo ampliamente utilizado para el manejo del marchitamiento por *Verticillium* en la mayoría de las regiones productoras de papa de los Estados Unidos. Las preocupaciones ambientales en relación a las pérdidas por volatilización han conducido a restricciones en el uso de Metam sodio. La industria de la papa se ha adaptado a estas restricciones mediante el reemplazo de las aplicaciones de este fumigante por la vía de riego por aspersión con aplicación por inyección de mango del producto. Investigaciones previas establecieron parámetros para aplicación efectiva de mango de metam sodio basada en la temperatura del suelo, profundidad de la inyección y el nivel de la fumigación. No obstante, estas recomendaciones se basaron en investigación llevada a cabo bajo condiciones de un suelo de textura gruesa, con un bajo contenido de materia orgánica (OM) (<1.3). No obstante, muchos suelos de producción de papa en Dakota del Norte y Minnesota tienen textura limosa más fina y contenidos de OM de >2.5%. De aquí que es importante saber si las recomendaciones de la fumigación con metam sodio para suelos de textura gruesa se pueden adaptar a los de textura fina. Se condujeron dos ensayos de campo utilizando un diseño de bloques divididos para estudiar la eficacia del metam sodio en el manejo de la marchites. En ambos años, la profundidad de la inyección del fumigante y la temperatura del suelo al momento de la inyección no resultó en diferencias significativas en ninguna de las variables evaluadas del estudio. Todas las dosis de fumigación del metam sodio bajaron significativamente ($P < 0.05$) los microesclerocios de *Verticillium,* redujeron la severidad de la marchites y mejoraron el rendimiento de tubérculo en comparación con los lotes no tratados. No obstante, no se observaron diferencias significativas

✉ Neil C. Gudmestad
neil.gudmestad@ndsu.edu

[1] Department of Plant Pathology, North Dakota State University, Fargo 58105, USA

por los niveles de fumigación entre las variables evaluadas. Una dosis relativamente baja de 373 l/ha es tan efectiva como dosis más altas de metam sodio para un control efectivo de la marchites por *Fusarium*. Los resultados que aquí se presentan sugieren que las recomendaciones actuales de metam sodio para la aplicación por la inyección de mango en suelos de textura gruesa pueden implementarse en suelos del campo con textura fina y contenido de OM mas alto.

Keywords Organic matter · Metam sodium · Fumigation · Wilt

Introduction

Potato is an important vegetable crop produced in many regions of the world. Verticillium wilt of potato, primarily caused by *Verticillium dahliae,* is a destructive pathogen due to prolonged persistence of microsclerotia in the soil (Wilhelm 1955; Powelson and Rowe 1993; Pasche et al. 2013a). Wilt in potato production areas can adversely affect yield, tuber size and tuber quality (Davis and Huisman 2001; Taylor et al. 2005). Cultural management practices are not adequate because infected plants produce numerous microsclerotia and extended crop rotations have failed to lower wilt incidence (Busch 1973; Easton et al. 1972; Leon-M and Devaux 1977; Johnson and Cummings 2015). Metam sodium (sodium N-methyl dithiocarbamate) is a stand-alone fumigant for wilt management in a number of potato production regions in the world, and particularly in the United States of America (Ben-Yephet et al. 1983; Saeed et al. 1997, Rowe and Powelson, 2002; Taylor et al. 2005; Tsror et al. 2005; Pasche et al. 2014).

Metam sodium is most commonly applied either through a sprinkler irrigation system or by direct injection into the soil (Ben-Yephet et al. 1983; Taylor et al. 2005; Pasche et al. 2014). Metam sodium in soil rapidly transitions from a liquid to a gas phase under moist conditions to release volatile methyl isothiocyanate (MITC), which can be toxic to some soil-borne fungi, soil arthropods, and ectoparasitic nematodes (Gerstl et al. 1977; Saeed et al. 1997; Triky-Dotan et al. 2009). Mortality of *V. dahliae* microsclerotia due to toxicity is a function of MITC concentration and the exposure period. (Kaufman et al. 1985; Triky-Dotan et al. 2009). The dissipation of MITC is influenced by soil factors such as water content, organic matter (OM) level, and texture (Ben-Yephet and Frank 1985; Saeed et al. 1997; Pasche et al. 2014). Additionally, soil porosity and continuity of the pore space affects the movement of the fumigant (Goring 1962; Kolbezen et al. 1974; Lembright 1990; Yates et al. 2002).

A significant challenge in applying metam sodium efficaciously was determining the distribution of *V. dahliae* in the soil profile. Previous research established that nearly all of the *V. dahliae* inoculum was in the upper 20 cm soil profile, with 60 to 78% of the inoculum in the top 10 cm (Taylor et al. 2005). Given this type of *V. dahliae* distribution in the soil it became evident why applications of metam sodium through sprinkler irrigation systems were the most efficacious for the management of Verticillium wilt of potato (Taylor et al. 2005). However, in a number of states or areas within a state, the application of metam sodium via sprinkler irrigation was either illegal or impossible given the close proximity of fields to urbanized areas making shank injection of the soil fumigant the only option. As a result of the aforementioned study, the potato industry responded by modifying shank injection of soil fumigants by splitting the injection of the fumigant into two depths, typically at 15 and 25 cm, in an effort to improve the reduction of *V. dahliae* inoculum in the top 10 cm of soil.

Environmental protection agency (EPA) restrictions on the application of metam sodium via sprinkler irrigation led to shank injection gaining popularity (Saeed et al. 2000; Zheng et al. 2006; Pasche et al. 2014). Targeted application by shank injection at predefined soil depths reduces environmental loss and improves efficacy of the fumigant. Previous research established parameters of effective shank application of metam sodium to reduce *V. dahliae* soil population based on soil temperature, injection depth and rate of fumigation (Pasche et al. 2014). This research determined that there was no rate response with metam sodium in the management of Verticillium wilt of potato (Pasche et al. 2014). Application rates of metam sodium (42% active, Amvac Chemical Corporation) at 373 l/ha were as efficacious as any higher use rate up to 655 l/ha. Furthermore, metam sodium applications at colder soil temperatures of 4 °C were significantly more efficacious at reducing *V. dahliae* inoculum compared to applications at higher soil temperatures of 13-15 °C (Pasche et al. 2014). Another noteworthy adoption for potato industry was abandoning dual injections (at 15 and 25 cm depth), because a single injection at 25 cm was determined to be as efficacious as injection at two depths (Pasche et al. 2014). Applying metam sodium at a single application depth of 25 cm is economically important considering the high cost of fumigation control (Ochiai et al. 2007; Rowe and Powelson 2008). All of these modifications have been widely adopted by the potato industry in the Midwestern USA. The reduction in the rate of metam sodium fumigant applied, at a colder soil temperature and at a single injection depth has dramatically improved Verticillium wilt disease control, increased sustainability of the potato industry, reduced off-gassing of MITC and non-target exposure of humans and animals.

The recommendation of metam sodium applied at a single depth was based on field studies conducted in loamy sand, medium to coarse-textured soil with a relatively low OM content (<1.3%) (Pasche et al. 2014). This type of soil is typically favored by that portion of the potato industry producing potatoes under irrigation for the French fry and tablestock markets. However, not all irrigated potatoes are produced under these type of low OM and medium-textured soil conditions. Questions arose from the potato industry asking whether similar application parameters were appropriate in fine-textured soils, such as a silt loam, with higher OM content (>2.5%).

High organic matter content in the soil increases the MITC degradation, but also impedes the MITC (gaseous-phase) movement through the soil profile thus reducing fumigation efficacy (Gan et al. 1999; Dungan et al. 2003; Simpson et al. 2011). In addition, accelerated degradation of MITC in soil can result in a loss of efficacy against pests (Triky-Dotan et al. 2009). Therefore, higher organic matter content in the soil may influence the currently practiced fumigation recommendations. Furthermore, in fine-textured soils the air pockets surrounding soil particles are much smaller which could impede the vertical movement of the MITC gas as it volatilizes and moves upward from its injection point. Since many potato production soils in North Dakota and Minnesota have a sandy loam to silt loam texture and OM contents of >2.5%, the proposed research is aimed at improving soil fumigation in these types of soil.

Our hypothesis was that a higher soil temperature at the time of metam sodium injection may be needed to improve vertical movement and dispersal of the fumigant. As a result of the finer texture of a silt loam soil with some clay content, a dual injection depth, rather than a single injection depth, may be necessary to insure that the *V. dahliae* inoculum in the upper soil profile was treated effectively. We also hypothesized that a rate of metam sodium higher than 373 l/ha may be necessary to compensate for the increased degradation of the fumigant caused by higher OM levels.

The primary objective of this study was to determine the efficacy of metam sodium based on rate, soil temperature, and inoculum level of *V. dahlia*e in a fine-textured, higher OM soil. Another objective was to develop guidelines for subsurface metam sodium applications at different soil temperatures that effectively control *V. dahliae* while complying with the more restrictive EPA regulations.

Materials and Methods

Two field trials were established near Ponsford, MN, during 2014–2015 and 2015–2016 and will be referred as 2015 and 2016 trials. The soil texture class was silt loam in the 2015 (58% sand, 34% silt, 8% clay, and 3.9% OM) and in the 2016 field sites (62% sand, 26% silt, 12% clay, and 2.9% OM). Russet Burbank, moderately susceptible to *V. dahliae* (Rowe and Powelson, 2002; Pasche et al. 2013a, b), was planted with a seed spacing of 0.36 × 0.91 m.

Experimental units were strips fumigated (via shank injection) using standard commercial fumigation equipment as previously described (Pasche et al. 2014). The experimental design was split strip-block having two replications, with fumigation timing/temperature (2 levels) and injection depth (2 levels) as main strips (sized as 716.2 × 8.2 m) and rates (five) randomized within each strip. The soil treatments consisted of a 2 × 2 × 5 factorial arrangement with either the rows or columns being the blocks. In total there were 40 plots (20*2 replications), each sized as 143.2 × 8.2 m. In 2015, early (mid-October) and late application (mid-November) of metam sodium was performed at 12^{o} C and 3^{o} C, respectively. Soil temperature during early (13^{o} C) and late fumigation (5^{o} C) were slightly higher for the 2016 trial. Strips were fumigated with metam sodium injected either at a single depth of 25 cm or split at two depths of 15 cm and 25 cm (metam sodium split 50:50). Metam sodium (Vapam HL ™ = metam sodium-42% active, Amvac Chemical Corporation) fumigation rates injected into the soil profile were 0 (control), 373, 467, 561, 655 l/ha. To prevent MITC volatilization into the atmosphere, a water seal of 1.5 cm was applied to the fields using a pivot irrigator (Pasche et al. 2014). Water seal was not applied at late fumigation due to decommissioning the irrigation equipment for the season to prevent freeze damage (Pasche et al. 2014).

Levels of *V. dahliae* were determined before and after fumigation to determine metam sodium fumigation efficacy. Soil sampling was performed twice (pre- and post-fumigation) at five pre-designated points (flagged) within each treatment. Pre-fumigation soil samples were collected in the fall (mid-September) when the experimental units were arranged, and post-fumigation samples were collected prior to planting the following spring (mid-April). A total of 200 (5 predesignated sites × 20 treatments × 2 replications) soil samples per year were obtained. At each sampling (flagged area) site (within 1 m radius), ten soil cores were excised at 0–10 cm and 10–20 cm soil depths. Ten soil samples collected at each site were aggregated/bulked and stored at 15^{o} C prior to analysis (Pasche et al. 2014). Collected soil samples were sent to Pest Pros, Inc. (Plainfield, WI) for determining (dilution plating technique) *V. dahliae* propagules per gram of soil (Vppg) (Nicot and Rouse 1987a). The economic threshold for *V. dahliae* inoculum is 8–10 Vppg (Nicot and Rouse 1987b), indicating soil fumigation is necessary at levels of inoculum above this threshold.

Beginning at mid-potato vegetative growth and flowering stage, wilt was visually assessed at seven day intervals until harvest. Wilt intensity over time was quantified using area under the wilt progress curve (AUWPC) (Shaner and Finney 1977). Further, AUWPC values were normalized by dividing them by the total area and the resulting relative area under the wilt progress curve (RAUWPC) was used to compare the treatments (Fry 1978; Pasche et al. 2014). Tubers were harvested from a single 7.6 m row (extending through pre-designated sampling site) and total yield was calculated (fresh weight basis). Tubers were combined by replication and French fry processing (FFP) grade was determined (Pasche et al. 2014).

Data Analysis

V. dahliae propagule per gram (Vppg) soil population data consisted of many zero values (zero inflated) and causing the data to not be normally distributed. Analysis of variance (ANOVA) assumption (normal distribution of errors) was not satisfied and transforming Vppg (count) data are not always justifiable (O'Hara and Kotze 2010). Also, Vppg data obtained from a multifactorial treatment structure and having interaction terms is not supported by non-parametric analysis (Wheeler and Johnson 2016). Due to the above concerns, permuatational multivariate analysis of variance (PERMANOVA) was used to test the composition or Vppg levels at pre- and post-fumigation (Anderson 2001; Wheeler and Johnson 2016). PERMANOVA is invariant to characteristics of the data described above and permissive to hypothesis testing in multifactorial design (Wheeler and Johnson 2016). Similar to ANOVA, PERMANOVA compares within and among groups variation by constructing *pseudo*-F statistics. PERMANOVA was used to test the null hypothesis that the role of metam sodium (rate, soil temperature, injection depth) had no effect on the differentiation between pre- and post-fumigation fungal populations. PERMANOVA was performed using Adonis function in Vegan R package (Oksanen et al. 2013). As a follow up, pairwise comparisons to determine the differences among rates were performed. Percentage reduction of Vppg were calculated as (pre-fumigation-post-fumigation)/pre-fumigation). Pearson correlations were performed to study the relationship between Vppg in soil and yield components. RAUWPC, Total yield, marketable yield, and FFP tuber grade data were analyzed using PROC Mixed of SAS at $\alpha = 0.05$.

Results

Metam Sodium Effect on Levels of Vppg of Soil

There was substantial variation of Vppg populations between pre- and post-fumigated plots (Figs. 1 and 2). Contrasting levels of Vppg were found between the 2015 and 2016 studies. In non-fumigated treatments, very high levels of *V. dahliae* inoculum were detected in 2015, 105 Vppg, and in 2016 relatively low inoculum levels, 25 Vppg. The amount of Vppg generally decreased after metam sodium fumigation across both trials. In 2015, percentage reduction of Verticillium propagules ranged from 12 to 77% in the 0–10 cm soil depth and from 39 to 93% in the 10–20 cm depth across all rates of metam sodium. Overall reductions of Verticillium propagules across metam sodium rates in the 2016 trial ranged from 25 to 90% in the 0–10 cm soil depth and from 37 to 98% in the 10–20 cm depth. For both trials, PERMANOVA results demonstrate that pre- and post-fumigation Vppg levels (sampled at both soil depths) significantly differed by fumigation rate and rate interaction with soil temperature and metam sodium injection depth (Table 1). However, metam sodium injection depth (except for soil sampled at 0–10 cm for 2015 trial; $P = 0.01$) and soil temperature at the time of injection had no significant effect on Vppg soil levels between pre- and post-fumigation (Table 1). In the 2015 trial, metam sodium rate did not significantly affect Vppg levels in soil at the 0–10 cm ($P = 0.001$) and 10–20 cm ($P = 0.001$) depths. Also, Vppg sampled at 0–10 cm ($P = 0.001$) and 10–20 cm ($P = 0.001$) depths were significantly different among fumigation rates in the 2016 field trial (Tables 2 and 3). All metam sodium rates (373, 467, 561, and 655 l/ha) in the 2015 trial, significantly ($P < 0.05$) lowered Vppg populations when compared to non-fumigated control (0 l/ha) (Table 2). In 2016 (at 0–10 cm soil depth), metam sodium rate of 473 l/ha significantly ($P = 0.02$) lowered Vppg levels when compared to non-fumigated control (Table 3). There were also significant differences between pre- and post- fumigation Vppg levels (sampled at 10–20 cm depth) for 373 l/ha vs. non-treated ($P = 0.009$) control, 561 l/ha vs. non-treated ($P = 0.02$), and 561 vs. 655 l/ha ($P = 0.03$) metam sodium rates (Table 3). For both trials, metam sodium rate interaction with soil temperature (at 0–10 cm ($P = 0.001$) and 10–20 cm ($P = 0.001$) were significant. In both years, there was a significant interaction between metam sodium rate and injection depth at 0–10 cm ($P = 0.001$) and 10–20 cm ($P = 0.001$) soil sampling depths. These two-way interactions were not significant ($P > 0.05$), however, when the non-treated control was removed from the analysis (data not shown). This indicates that the interaction is likely due to the high Vppg levels in the non-treated plots. The three-way interaction (in both trials) of metam sodium rate x injection depth x soil temperature at the time of injection for Vppg differentiation in 0–10 cm ($P = 0.001$) and 10–20 cm ($P = 0.001$) sampling depths was significant. When the non-treated control was removed from the analysis, the three way interactions were also not significant ($P > 0.05$; data not shown), except for Vppg sampled in 2015 trial at 0–10 cm soil depth ($P = 0.03$). This indicates that Vppg levels in control plots may have led to the mutual dependence among all three variables.

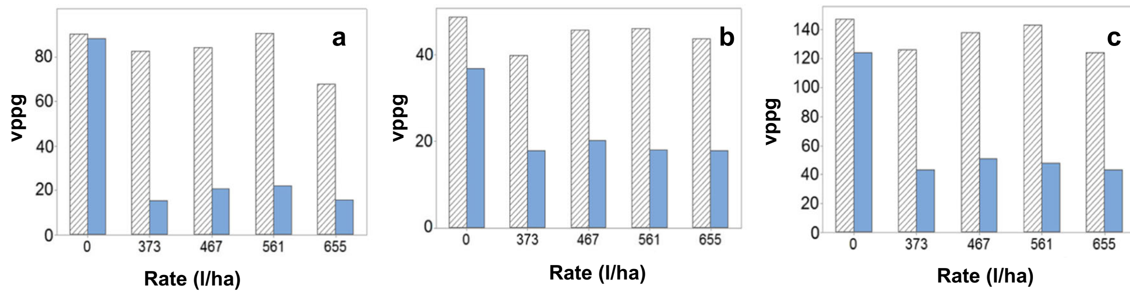

Fig. 1 Average *V. dahliae* propagules per gram of soil (Vppg) of pre-fumigation (bars with grey lines) and post fumigation (shaded bars) samples for metam sodium rate (2015 trial). **a**, represent soil sampling at 0–10 cm depth and **b**, represent sampling at 10–25 cm depth. **c**, represent combined sample at 0–25 cm depth

Effect of Metam Sodium on Verticillium Wilt Management

Despite the high levels of Vppg in the soil prior to soil fumigation in 2015, shank injection of metam sodium significantly $(P < 0.05)$ reduced Verticillium wilt (RAUWPC) at all rates compared to the non-fumigated control (Table 4). RAUWPC for metam sodium rates were also significantly different from non-treated plots in the 2016 trial $(P = 0.02)$. For both trials, the depth of metam sodium injection and the temperature at the time of injection did not significantly affect the development of Verticillium wilt during the growing season (Table 5). There was also no significant correlation between Vppg in the 0–10 cm depth and wilt severity expressed as RAUWPC (2015 trial, $r = 0.32$, $P = 0.17$ and 2016 trial, $r = 0.26$, $P = 0.27$); or Vppg in the 10–20 cm depth (2015 trial, $r = 0.16$, $P = 0.5$ and 2016 trial, $r = 0.21$, $P = 0.36$). This indicates that besides Vppg levels in the field, soil, environment, and plant factors and their interactions with Vppg may influence potato wilt symptom expression.

Metam Sodium Influence on Potato Yield

A negative correlation existed between Vppg levels in soil at the 0–10 cm and total yield (2015 trial, $r = -0.68$, $P = 0.0001$ and 2016 trial, $r = -0.66$, $P = 0.002$); and at the 10–20 cm depth (2015 trial, $r = -0.85$, $P < 0.0001$ and 2016 trial, $r = -0.65$, $P = 0.002$). There was a negative correlation association between Vppg at the 0–10 cm depth and marketable yield observed (2015 trial, $r = -0.63$, $P = 0.002$ and 2016 trial, $r = -0.74$, $P = 0.000$); and at the 0–20 cm depth (2015 trial, $r = -0.82$, $P < 0.0001$ and 2016 trial, $r = -0.63$, $P = 0.003$)]. However, wilt severity (RAUWPC) and yield components were poorly correlated and non-significant (except in 2016). In 2015, there was no significant correlation between RAUWPC and yield components (total and marketable yield). There was a significant negative correlation between RAUWPC and total yield during 2016 trial ($r = -0.47$, $P = 0.01$). A poor correlation of RAUWPC with yield components is consistent with non-significant correlation between RAUWPC and Vppg.

In 2015, soil fumigation with metam sodium significantly increased both total $(P = 0.01)$ and marketable $(P < 0.01)$ yields when compared to non-fumigated control (Table 4). However, significant differences among fumigation rates were not observed for total and marketable yields. A relatively low rate of 373 l/ha was as effective as higher metam sodium rates for influencing potato yield. Fumigation significantly increased the percentage of tubers greater than 283 g $(P = 0.03)$ and 170 g $(P = 0.03)$ when compared to non-treated plots regardless of the rate of metam sodium. Furthermore, a significant difference between high (655 l/ha)

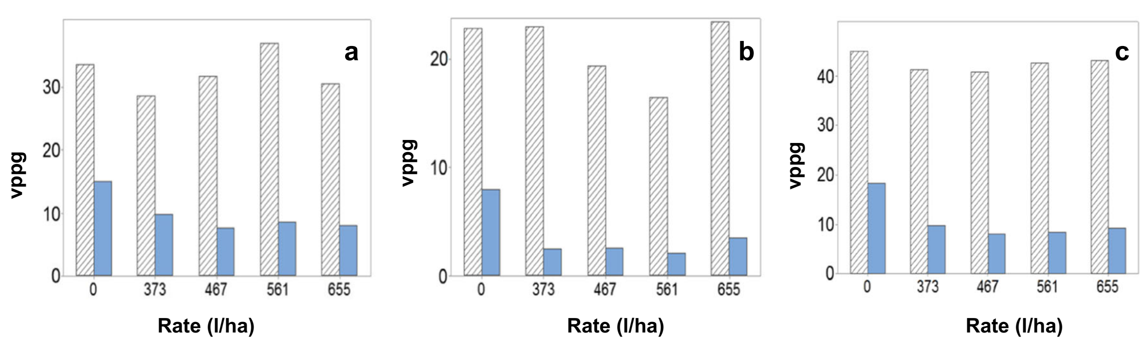

Fig. 2 Average *V. dahliae* propagules per gram of soil (Vppg) of pre-fumigation (bars with grey lines) and post fumigation (shaded bars) samples for metam sodium rate (2016 trial). **a**, represent soil sampling at 0–10 cm depth and **b**, represent sampling at 10–25 cm depth. **c**, represent combined sample at 0–25 cm depth

Table 1 Permuational multivariate analysis of variance (PERMANOVA) tables for Verticillium propagules per gram of soil (Vppg) differentiation between pre-fumigation and post-fumigation samples obtained at 0–10 and 10–20 cm soil depths

Year	Source of variation	DF	sum of squares	Pseudo-*F*	*P* value
2015	0–10 cm (Soil depth)				
	Rate	4	0.83	14.7	0.001*
	Injection Depth (ID)	1	0.06	4.26	0.01*
	Soil Temperature (ST)	1	0.02	1.89	0.15
	Block	1	0.02	1.65	0.17
	Rate x ID	4	2.63	46.47	0.001*
	Rate x ST	4	0.89	15.74	0.001*
	ID x ST	1	0.01	0.97	0.34
	Rate x ID x ST	4	4.54	80.08	0.001*
2016	0–10 cm (Soil depth)				
	Rate	4	0.81	11.2	0.001*
	Injection Depth (ID)	1	0.03	2.02	0.16
	Soil Temperature (ST)	1	0.04	2.68	0.08
	Block	1	0.01	0.57	0.53
	Rate x ID	4	2.81	39.11	0.001*
	Rate x ST	4	0.97	13.52	0.001*
	ID x ST	1	−0.001	−0.1	1
	Rate x ID x ST	4	1	13.91	0.001*
2015	10–20 cm (Soil depth)				
	Rate	4	1.03	14.23	0.001*
	Injection Depth (ID)	1	0.02	0.97	0.35
	Soil Temperature (ST)	1	0.05	3.03	0.06
	Block	1	−0.02	−1.09	1
	Rate x ID	4	2.82	38.8	0.001*
	Rate x ST	4	0.96	13.27	0.001*
	ID x ST	1	0.004	0.26	0.78
	Rate x ID x ST	4	4.69	64.61	0.001*
2016	10–20 cm (Soil depth)				
	Rate	4	0.83	11.56	0.001*
	Injection Depth (ID)	1	0.001	0.08	0.94
	Soil Temperature (ST)	1	0.01	0.64	0.48
	Block	1	0	0.001	0.9
	Rate x ID	4	2.89	39.98	0.001*
	Rate x ST	4	0.98	13.62	0.001*
	ID x ST	1	−0.005	−0.28	1
	Rate x ID x ST	4	4.95	68.41	0.001*

[x] Injection depths for metam sodium were either a single depth of 25 cm or split two depths of 15 cm and 25 cm; Soil temperature at the time of early metam sodium injection was 12° C for 2015 trial and 13° C for 2016 trial. Soil temperatures for late fumigation were 3° C for 2015 trial and 5° C for 2016 trial

[y] *P* values were computed by permutation; *indicates *P values* that are significant ($\alpha < 0.05$)

Table 2 Pairwise comparison of the fumigation rate for the soil Verticillium propagules per gram of soil (VPPG) sampled in 2015 trial

Rate vs. Rate (l/ha)	Adjusted *P* value
0–10 cm (Soil depth)	
nontreated vs. 373	0.03*
nontreated vs. 467	0.02*
nontreated vs. 561	0.01*
nontreated vs. 655	0.01*
373 vs. 467	0.51
373 vs. 561	0.49
373 vs. 655	0.99
467 vs. 561	0.53
467 vs. 655	0.54
561 vs. 655	0.70
10–20 cm (Soil depth)	
nontreated vs. 373	0.01*
nontreated vs. 467	0.01*
nontreated vs. 561	0.01*
nontreated vs.655	0.01*
373 vs. 467	0.92
373 vs. 561	0.41
373 vs. 655	0.21
467 vs. 561	0.62
467 vs. 655	0.20
561 vs. 655	0.27

*indicates *P values* that are significant ($\alpha < 0.05$)

and low (373 l/ha and 467 l/ha) metam sodium rates was observed for percentage of tubers greater than 283 g ($P = 0.03$) and 170 g ($P = 0.03$). In 2016, fumigation significantly increased total ($P = 0.02$) and marketable ($P = 0.006$) yields when compared to that of the non-fumigated control (Table 4). However, significant differences among fumigation rates were not observed across any yield variable evaluated. Soil temperature and metam sodium injection depth were non-significant in improving total and marketable yields for two growing seasons (Table 5). In 2015 and 2016, there were no significant interactions between the main effects of total yield, marketable yield, or other tuber quality parameters.

Discussion

Metam sodium is currently undergoing re-registration with EPA and increasing scrutiny by environmental groups may impose additional restrictions on its use for controlling soil-borne pathogens. EPA restrictions on metam sodium application are ever increasing and could result in further usage limitations by growers (MacRae and Noling 2010; Pasche et al. 2013a). The results from this study further fine-tunes recommendations for sub-surface shank applications of metam sodium, potentially reduce off-gassing of MITC and assist in re-establishing best management practices for its use.

Table 3 Pairwise comparison of the fumigation rate for the soil Verticillium propagules per gram of soil (VPPG) sampled in 2016

Rate vs. rate (l/ha)	Adjusted *P* value
0–10 cm (Soil depth)	
nontreated vs. 373	0.19
nontreated vs. 467	0.02*
nontreated vs. 561	0.15
nontreated vs.655	0.16
373 vs. 467	0.73
373 vs. 561	0.10
373 vs. 655	0.87
467 vs. 561	0.18
467 vs. 655	0.96
561 vs. 655	0.21
10–20 cm (Soil depth)	
nontreated vs. 373	0.009*
nontreated vs. 467	0.11
nontreated vs. 561	0.02*
nontreated vs.655	0.23
373 vs. 467	0.42
373 vs. 561	0.08
373 vs. 655	0.84
467 vs. 561	0.14
467 vs. 655	0.12
561 vs. 655	0.03*

*indicates *P values* that are significant ($\alpha < 0.05$)

Higher populations of fungal propagules were consistently present in the 0–10 cm soil depth when compared to 10–20 cm depth. In 2015, about 61% and 39% of Vppg were found in the upper and lower soil profiles, respectively. In 2016 trial, 60% and 40% Vppg levels were found in the upper and lower soil profiles, respectively. These results are similar to previous studies reporting that higher Vppg distribution in the top soil profile (Hamm et al. 2003; Taylor et al. 2005; Pasche et al. 2014). The higher concentrations of Vppg in the upper soil profile is likely due to potato vines being left on the soil surface following the potato harvest operations. The incorporation of dead potato tissue in only the soil surface layers initially led us to believe that metam sodium applications should be more concentrated in the upper soil profile. However, previous research demonstrated that inoculum in the upper soil profile may be higher but inoculum in the lower soil profile may be more efficient and important in the *V. dahliae* infection process (Pasche et al. 2014). Studying spatial analysis may assist in describing the patterns (random or aggregate) of Vppg distribution in the soil and developing more effective wilt management tactics.

Pre-fumigation Vppg populations were generally higher than post-fumigation Vppg levels. In both trials, the percentage Vppg reduction was higher at lower soil stratum (10–25 cm) when compared to upper soil stratum (0–10 cm). This could be due to the 1.5 cm water seal restricting the gas diffusion and causing the MITC movement deeper into the soil profile closer to the depth of 10–25 cm. A previous study reported that a water seal of 1.3 cm acted as barrier and restricted MITC off-gassing near the 15 cm and increased the gas accumulation near 25 cm depth (Simpson et al. 2010). However, the grower experience contradicts these results. The upper profile is very difficult to keep moist and sealed due to environmental conditions which allows MITC gas to escape readily which concomitantly decreases efficacy. A more likely explanation is due to the presence of lower Vppg levels in the 10–25 cm soil stratum and a higher concentration of metam sodium which leads to a higher reduction. In this study, a higher soil population of *V. dahliae* caused a

Table 4 Effect of metam sodium rate on relative area under the wilt progress curve (RAUWPC), yield, and French fry processing grade

Metam sodium rate (l/ha)	RAUWPC	Total yield (mt/ha)	Market yield (mt/ha)	Tubers greater than 283 g (%)	Tubers greater than 170 g (%)	Unusable tubers (%)
2015						
Nontreated	0.23b	41.09b	36.91b	10b	45.43b	10.65a
373	0.16a	55.21a	51.81a	21.64a	63.10a	6.38a
467	0.16a	57.26a	53.14a	22.5a	63.25a	7.14a
561	0.13a	56.40a	52.21a	19.14a	60.71ab	7.52a
655	0.14a	57.88a	53.68a	18.37ab	60.79ab	7.39a
2016						
Nontreated	0.15b	57.74b	41.77b	6.35a	35.61a	27.70a
373	0.13a	64.39a	48.47a	8.32a	40.50a	24.73a
467	0.12a	64.32a	48.66a	7.67a	39.77a	24.30a
561	0.13a	64.74a	50.01a	8.70a	40.91a	22.77a
655	0.12a	64.99a	50.11a	8.38a	40.62a	23.00a

Means separated by the same letter are not significantly different according to Fisher's protected least significant difference ($\alpha < 0.05$)

Table 5 Effect of metam sodium injection and soil temperature at the time of injection on relative area under the wilt progress curve (RAUWPC), yield, and French fry processing grade

Metam sodium	RAUWPC	Total yield (mt/ha)	Market yield (mt/ha)	Tubers greater than 283 g (%)	Tubers greater than 170 g (%)	Unusable tuber (%)
2015						
Injection depth						
25 cm	0.17	54.95	50.91	19.76	61.02	7.46
15 + 25 cm	0.12	58.42	54.51	21.07	62.91	6.76
P value	0.30	0.13	0.12	0.64	0.58	0.49
Soil temperature						
12° C	0.17	51.28	47.53	16.87	57.92	7.80
3° C	0.17	55.86	51.57	19.80	59.40	7.84
P value	0.91	0.22	0.17	0.13	0.17	0.97
2016						
Injection depth						
25 cm	0.13	65.42	49.70	8.53	40.46	24.03
15 + 25 cm	0.13	63.80	48.93	8.01	40.44	23.38
P value	0.75	0.73	0.79	0.87	0.75	0.67
Soil temperature						
13° C	0.13	63.75	48.87	9.08	42.46	23.53
5° C	0.14	62.72	46.74	6.70	36.51	25.48
P value	0.32	0.67	0.51	0.55	0.31	0.35

[x] Metam sodium injection depth unit is Centimeter (cm); Soil temperature unit is Celsius (° C)

greater decrease in yield. Soil populations of Vppg were very high in 2015 compared to 2016 and consequently lower yields were observed in 2015 compared to the yield in the 2016 trial. This pattern is similar to previous research, where Vppg populations at both soil depths were negatively correlated with yield (Davis and Everson 1986; Davis et al. 2001; Pasche et al. 2014). However, Vppg was found to be not significantly correlated with wilt severity, an indication that severity assessment may not be ideal for estimating crop yield loss relationship. The lack of association could be due to other environmental and plant factors influencing potato wilt symptom expression. Furthermore, unbiased estimation of visual wilt severity rating is needed for accurate estimation of wilt association with other disease and crop related variables (Yellareddygari and Gudmestad 2017).

In both trials, metam sodium injection depth and soil temperature at the time of application showed no significant effect on either the Vppg level, wilt severity, or tuber yield. All metam sodium rates significantly lowered Vppg levels, reduced wilt severity and improved yield when compared to non-treated plots. However, fumigation rates were consistently different from control (0 l/ha) and but few differences were found among metam sodium rates. For example, a relatively low rate of 373 l/ha was generally as efficacious as higher rates of the soil fumigant. Previous fumigation study also demonstrated lack of higher rate response of metam sodium towards reducing Vppg, controlling wilt severity, and increasing yield (Pasche et al. 2014). The lack of higher rate response of metam sodium is good for the sustainability (such as reduced input cost) of the potato industry and in reducing environmental impact due to lower MITC emissions into the atmosphere (Pasche et al. 2014). Studying soil respiration and soil microbial content associated with MITC dissipation can provide more insight into the relationship between dosage and activity.

The levels of *V. dahliae* in the field (non-treated plot) of 2015 and 2016 trials were >15- and >3-fold higher than the economic threshold for Russet Burbank. Previous research by our group has demonstrated that high populations of *V. dahliae* cannot be completely ameliorated by soil fumigation (Pasche et al. 2014; Taylor et al. 2005). Metam sodium fumigation kills only a certain percentage of total Vppg and the residual Vppg would infect the growing susceptible plants (Johnson and Dung 2010; Johnson and Cummings 2015). The residual level of inoculum in 2015 after fumigation was high and still well above established economic thresholds for the cultivar used in this study (Nicot and Rouse 1987b) which likely negated much of the treatment effect expected from soil fumigation. Another reason could be due to fumigant movement influenced by soil texture. For example, MITC infiltration in sandy soils is higher when compared to that of fine-textured silt loam soil because of the larger pore space (Simpson et al. 2011). This poor lateral dispersion in finer textured soils can lead to inconsistent pathogen control due to inadequate availability of MITC in some areas of the soil profile. Therefore, understanding the soil type is important as it pertains to level of organic matter and texture. Further studies should perhaps examine delivery systems for shank-injected metam sodium that would improve lateral dispersion of the fumigant specifically for fine-textured soils.

Our hypothesis of increased OM content in the soil may alter the metam sodium fumigation recommendations was rejected. The findings of this study are consistent with previous study, where increased OM content did not significantly alter disease control efficacy of MITC (Simpson et al. 2010). Our results contradict with previous findings observed with other soil fumigants where organic matter is known to affect the soil fumigant dispersion (Thomason and McKenry 1974). Overall, the results from this study indicate that growers can continue with current metam sodium application recommendations regardless of organic matter content or soil texture. In conclusion, metam sodium applications at single injection depth (25 cm), lower soil temperature at the time of injection (~5 °C), and a lower dosage (373 l/ha) are appropriate for any soil type regardless of OM or texture. Since there was little difference between the lower and higher rates of metam sodium efficacy it would be interesting to determine if lower rates of metam sodium would be effective in managing Verticillium wilt in moderately susceptible cultivars. Future research should aim at studying rates of metam sodium rates lower than those used in the current study for the control of Verticillium wilt of potato.

Acknowledgements The authors gratefully acknowledge the financial support of this research by RD Offutt, Co., Minnesota Area II Potato Growers Association, and AmVac, Inc. The authors also gratefully acknowledge the technical assistance of Dean Peterson and Russell Benz.

References

Anderson, M.J. 2001. A new method for non-parametric multivariate analysis of variance. *Austral Ecology* 26: 32–46.

Ben-Yephet, Y., and Frank. Z.R. 1985. Effect of soil structure on penetration by metham-sodium and of temperature on concentrations required to kill soilborne pathogens. *Phytopathology* 75: 403–406.

Ben-Yephet, Y., E. Siti, and Z. Frank. 1983. Control by metam-sodium in loessial soil and effect on potato tuber yields. *Plant Disease* 67: 1223–1225.

Busch, L.V. 1973. Effect of some cropping practices on survival of Verticillium. *American Potato Journal* 50: 381–382.

Davis, J.R., and D.O. Everson. 1986. Relation of *Verticillium dahliae* in soil and potato tissue, irrigation method, and N-fertility to Verticillium wilt of potato. *Phytopathology* 76: 730–736.

Davis, J.R., and Hulsman. O.C. 2001. Verticillium wilt. In: Compendium of Potato Diseases. APS Press, Minneapolis, pp: 45–46.

Davis, J.R., O.C. Huisman, D.O. Everson, and A.T. Schneider. 2001. Verticillium wilt of potato: a model of key factors related to disease severity and tuber yield in southeastern Idaho. *American Journal of Potato Research* 78: 291–300.

Dungan, R.S., J. Gan, and S.R. Yates. 2003. Accelerated degradation of methyl isothiocyanate in soil. *Water, Air, and Soil Pollution* 142: 299–310.

Easton, G.D., M.E. Nagle, and D.L. Bailey. 1972. Effect of annual soil fumigation and pre-harvest vine burning on Verticillium wilt of potato. *Phytopathology* 62: 520–524.

Fry, W.E. 1978. Quantification of general resistance of potato cultivars and fungicide effects for integrated control of potato late blight. *Phytopathology* 68: 1650–1655.

Gan, J., S.K. Papiernik, S.R. Yates, and W.A. Jury. 1999. Temperature and moisture effects of fumigant degradation in soil. *Journal of Environmental Quality* 28: 1436–1441.

Gerstl, Z., U. Mingelgrin, and B. Yaron. 1977. Behavior of Vapam and methyl isothiocyanate in soils. *Soil Science Society of America Journal* 41: 545–548.

Goring, C.A.I. 1962. Theory and principles of soil fumigation. *Advance Pest Control Research* 5: 47–84.

Hamm, P.B., R.E. Ingham, J.R. Jaeger, W.H. Swanson, and K.C. Volker. 2003. Soil fumigant effects on three genera of potential soilborne pathogenic fungi and their effect on potato yield in the Columbia Basin of Oregon. *Plant Disease* 87: 1449–1456.

Johnson, D.A., and T.F. Cummings. 2015. Effect of extended crop rotations on incidence of black dot, silver scurf, and Verticillium wilt of potato. *Plant Disease* 99: 257–262.

Johnson, D.A., and J.K.S. Dung. 2010. Verticillium wilt of potato – the pathogen, disease and management. *Canadian Journal of Plant Pathology* 32: 58–67.

Kaufman, D.D., J. Katan, D.F. Edwards, and E.D. Jordan. 1985. Microbial adaptation and metabolism of pesticides. In: Agricultural Chemicals of the Future. J.L. Hilton. [Ed.] Rowman & Allanheld Press, NJ pp: 437–451.

Kolbezen, M.J., D.E. Munnecke, W.D. Wilbur, L.H. Stolzy, F.J. Abu-El-Haj, and T.E. Szuszkiewicz. 1974. Factors that affect deep penetration of field soils by MeBr. *Hilgardia* 42: 465–492.

Lembright, H.W. 1990. Soil fumigation: Principles and application technology. *Supplemental*. *Journal of Nematology* 22: 632–644.

MacRae, A., and J. Noling. 2010. Overview of new EPA regulations affecting use of metam sodium and metam potassium. *University of Florida Extension* HS1167.

Nicot, P.C., and D.I. Rouse. 1987a. Precision and bias of three quantitative soil assays for *Verticillium dahliae*. *Phytopathology* 77: 875–881.

Nicot, P.C., and D.I. Rouse. 1987b. Relationship between soil inoculum density of *Verticillium dahliae* and systemic colonization of potato stems in commercial fields over time. *Phytopathology* 77: 1346–1355.

O'Hara, R.B., and D.J. Kotze. 2010. Do not log transform count data. *Methods in Ecology and Evolution* 1: 118–122.

Ochiai, N., M.L. Powelson, R.P. Dick, and F.J. Crowe. 2007. Effects of green manure type and amendment rate on Verticillium wilt severity and yield of Russet Burbank potato. *Plant Disease* 91: 400–406.

Oksanen, J., F.G. Blanchet, R. Kindt, P. Legendre, P.R. Minchin, G.L. Simpson, P. Solymos, M.H.H. Stevens, and H. Wagner. 2013. Vegan: Community ecology package. R package verison 2.0-7. http://vegan.r-forge.r-project.org/.

Pasche, J.S., I. Mallik, N.R. Anderson, and N.C. Gudmestad. 2013a. Development and validation of a real-time PCR assay for the quantification of *Verticillium dahliae* in potato. *Plant Disease* 97: 608–618.

Pasche, J.S., A.L. Thompson, and N.C. Gudmestad. 2013b. Quantification of field resistance to *Verticillium dahliae* in eight russet-skinned potato cultivars using real-time PCR. *American Journal of Potato Research* 90: 158–170.

Pasche, J.S., R.J. Taylor, N.L. David, and N.C. Gudmestad. 2014. Effect of soil temperature, injection depth, and metam sodium rate on the management of Verticillium wilt of potato. *American Journal of Potato Research* 91: 277–290.

Powelson, M.L., and R.C. Rowe. 1993. Biology and management of early dying of potatoes. *Annual Review of Phytopathology* 31: 111–126.

Rowe, R.C., and M.L. Powelson. 2002. Potato early dying: Management challenges in a changing production environment. *Plant Disease* 86: 1184–1193.

Rowe, R.C., and M.L. Powelson. 2008. Potato health management: a holistic approach. In: Potato health management (2nd ed.) D.A. Johnson [Ed.] St. Paul: American Phytopathological Society Press pp: 1–5.

Saeed, I.A.M., D.I. Rouse, J.M. Harkin, and K.P. Smith. 1997. Effects of soil water content and soil temperature on efficacy of metam sodium against *Verticillium dahliae*. *Plant Disease* 81: 773–776.

Saeed, I.A.M., D.I. Rouse, and J.M. Harkin. 2000. Methyl isothiocyanate volatilization from fields treated with metam-sodium. *Pest Management Science* 56: 813–817.

Shaner, G., and R.E. Finney. 1977. The effect of nitrogen fertilization on the expression of slow-mildewing resistance in Knox wheat. *Phytopathology* 67: 1051–1056.

Simpson, C.R., S.D. Nelson, J.E. Stratmann, and H.A. Ajwa. 2010. Surface water seal application to minimize volatilization loss of methyl isothiocyanate from soil columns. *Pest Management Science* 66: 686–692.

Simpson, C.R., S.D. Nelson, and H.A. Ajwa. 2011. Impact of soil texture and organic matter on methyl isothiocyanate volatilization from soil columns. *Journal of Agricultural Science and Technology* 1: 194–198.

Tartier, Leon-M., and A. Devaux. 1977. Survey on Verticillium wilt of potatoes in the regions north of Montreal. *Phytoprotection* 58: 115–120.

Taylor, R.J., J.S. Pasche, and N.C. Gudmestad. 2005. Influence of tillage and method of metam sodium application on distribution and survival of *Verticillium dahliae* in the soil and the development of Verticillium wilt of potato. *American Journal of Potato Research* 82: 451–461.

Thomason, I.J., and M.V. McKenry. 1974. Part I, movement and fate as affected by various conditions in several soils. *Hilgardia* 42: 393–420.

Triky-Dotan, S., M. Austerweil, B. Steiner, Y. Peretz-Alon, J. Katan, and A. Gamliel. 2009. Accelerated degradation of metam-sodium in soil and consequences for root-disease management. *Phytopathology* 99: 362–368.

Tsror, L., E. Shlevin, and I. Peretz-Alon. 2005. Efficacy of metam sodium for controlling *Verticillium dahliae* prior to potato production in sandy soils. *American Journal of Potato Research* 82: 419–423.

Wheeler, D.L., and D.A. Johnson. 2016. *Verticillium dahliae* infects, alters plant biomass, and produces inoculum on rotation crops. *Phytopathology* 106: 602–613.

Wilhelm, S. 1955. Longevity of Verticillium wilt fungus in the laboratory and field. *Phytopathology* 45: 180–181.

Yates, S.R., J. Gan, S.K. Papiernik, R. Dungan, and D. Wang. 2002. Reducing fumigant emissions after soil application. *Phytopathology* 92: 1344–1348.

Yellareddygari, S.K.R., and N.C. Gudmestad. 2017. Bland-Altman comparison of two methods for assessing severity of Verticillium wilt of potato. *Crop Protection* 101: 68–75.

Zheng, W., S.R. Yates, S.K. Papiernik, and J. Nunez. 2006. Conversion of metam sodium and emission of fumigant from soil columns. *Atmospheric Environment* 40: 7046–7056.