# 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

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## ABSTRACT

**The effect of plowing and deep-rip tillage, in combination with chemigation or shank injection of metam sodium, on *Verticillium dahliae* populations and disease development was assessed in two fields with differing soil types and potato rotations. Soil samples were collected on a geo-referenced basis at depths of 0 to 10 cm and 10 to 20 cm before tillage, after tillage, after chemical application, and before planting and assayed for the presence of the pathogen. Propagules of *V. dahliae* were detected at 140 of 141 sites sampled prior to tillage. Most (74.4% in heavy, sandy loam; 63.1% in light, loamy sand) were concentrated in upper 10 cm of the soil profile. Plowing redistributed inoculum vertically while deep-rip tillage did not. In the non-chemical treated areas of both fields, the *Verticillium* population reached a maximum between 25 July and 8 August before declining to near pre-tillage levels. Overall, the population generally was lower in the field with heavy soil, higher organic matter content, and a 3-year crop rotation. Metam sodium appeared to be most effective when shank injected, as the levels of inoculum in both fields declined by 60% to 80% following this application method. Chemigation was ineffective in the lighter soil, but the inoculum density in the deep-rip tillage area of the field with the heavier soil declined by nearly 20% in the upper and 60% in the lower strata following this treatment. The number of *V. dahliae* propagules at the 10- to 20-cm depth in the plowed area of the same field was reduced by 25% following chemigation, but remained unchanged in the upper strata. Wilt was reduced in both fields by as much as 50% with shank injection of metam sodium with concomitant increases in total yield, marketable yield and gross income. Increases in total yield were significant ($P < 0.05$) for the main effect of chemical, in the plowed area of the field with the heavier soil type following shank injection. These data suggest that growers might benefit from altering their tillage and chemical application practices as part of an integrated approach to managing Verticillium wilt.**

## RESUMEN

**Se probó en dos campos con diferentes tipos de suelo y rotaciones de papa, el efecto de labranza y de aradura profunda, en combinación con la aplicación de productos químicos por el agua de riego e inyección (shank injection) de metasodio en el suelo, sobre poblaciones de *Verticillium dahliae* y desarrollo de la enfermedad. Las muestras de suelo se colectaron por zonas geográficas, a profundidades de 0 a 10cm y 10 a 20 cm antes del barbecho, después del barbecho, después de la aplicación de productos químicos y antes de la siembra y se hizo la prueba de presencia del patógeno. Los propágulos de *V. dahliae* se detectaron en 140 de los 141 lugares de muestreo antes del barbecho. La mayoría (74.4% en suelos areno-arcillosos pesados; 63.1% en suelos areno-arcillosos ligeros) estaban concentrados en los 10cm superiores del suelo. La labranza redis-**

Accepted for publication 25 April 2005.

ADDITIONAL KEY WORDS: Chemigation fumigation, shank injection fumigation, plow, deep-rip

ABBREVIATIONS: AUDPC, area under disease progress curve; GPS, global positioning system; MITC, methylisothiocyanate; PED, potato early dying; RAUDPC, relative area under disease progress curve; vppg, *Verticillium* propagules per gram of soil

**tribuyó el inóculo verticalmente, mientras que la aradura profunda no lo hizo. En las áreas de ambos campos que no fueron tratadas químicamente, la población de *Verticillium* alcanzó el máximo entre el 25 de julio y el 8 de agosto antes de disminuir a niveles de pre-barbecho. Sobre todo, la población fue generalmente más baja en campos con suelo pesado, alto contenido de materia orgánica y una rotación de tres años. El metasodio se mostró más efectivo cuando se inyectó, ya que los niveles de inóculo en ambos campos disminuyeron en un 60-80% con este método de aplicación. La aplicación de productos químicos por medio del riego no fue efectiva en suelo más ligero pero la densidad de inóculo en áreas de suelo con aradura profunda y suelo más pesado disminuyó cerca de 20% en la parte superior y 60% en el estrato inferior después de este tratamiento. El número de propágulos de *V. dahliae* a 10 a 20 cm de profundidad en el área arada del mismo campo se redujo después de la aplicación de productos químicos por riego en un 25% pero permaneció igual en el estrato superior. La marchitez se redujo en ambos campos en un 50% con el metasodio inyectado al suelo con el concomitante incremento del rendimiento total, rendimiento comerciable e ingresos totales. Los incrementos en el rendimiento total fueron significativos ($P$ < 0.05), principalmente por el efecto del producto químico, en áreas del campo con suelo pesado después de inyección de producto químico. Estos datos sugieren que los productores pueden obtener beneficios alterando la labranza y las prácticas de aplicación de productos químicos como parte de un manejo integrado para marchitez por Verticillium.**

## INTRODUCTION

Early maturity and premature decline of the crop has become a significant threat to potato production in the United States in recent years and is now seen as the most serious problem affecting commercial and seed potato production by growers and research scientists alike (Powelson and Rowe 1994; Rowe et al. 1987; Rowe and Powelson 2002). The early dying complex, also referred to as potato early dying, early maturity wilt, or Verticillium wilt, is particularly problematic in areas where potatoes have been continually cropped and where they are produced in light sandy soils under irrigation. Although some controversy exists regarding the nature and management of early maturity wilt (Davis and Huisman 2004; Rowe and Powelson 2004), most authors agree that *Verticillium dahliae* Kleb. is the primary cause of potato early dying in most potato-growing areas and that lesion nematodes (*Pratylenchus penetrans* Cobb) can potentially exacerbate the problem. Other soil-borne pathogens such as *Colletotrichum coccodes* Wallr. (Davis et al. 2001; Tsror [Lahkim] and Hazanovsky 2001), *Erwinia carotovora* subsp. *carotovora* (Jones) Dye, and *Erwinia carotovora* subsp. *atroseptica* (Van Hall) Dye (Powelson 1985) may contribute to premature death of the potato crop as well.

Symptoms of Verticillium wilt range from a general progression of leaf wilting and chlorosis up from the base of the plant to early maturity wilt to early dying of all or a portion of the crop. As a result, yield, tuber size, and tuber quality may be adversely affected (Davis and Huisman 2001). Traditional approaches to disease management have relied upon the integration of an array of control measures including soil fumigation and certain cultural practices such as crop rotation, soil solarization, green manures, timing of planting and harvest, destruction of crop residue, and the management of irrigation water and soil fertility (Davis 1985; Powelson et al. 1993; Rich 1983; Rowe et al. 1987). Although genetic resistance to *V. dahliae* exists (Davis and Huisman 2001), few potato cultivars that resist this disease are widely grown (Rowe and Powelson 2002; Rowe et al. 1987).

Agricultural production methods have changed considerably over the past 100 years. Synthetic fertilizers have replaced organic fertilizers, modern pesticides have become highly efficient and both cultural practices and production equipment have been improved. Such advancements have contributed to increased yields and crop quality, but these benefits have come at some expense. Hoitink and Boehm (1999) postulated that soil organic matter has become overly mineralized and soil structure has declined with these changes. As a result, populations of soil-borne pathogens continue to increase, and epidemics can often be attributed to these changes. Plant pathosystems can be affected by a variety of soil physical properties, including water content, aeration, compaction, pore size, and temperature (Rothrock 1992). Tillage is probably the one practice, above all others, that has the potential of exerting the greatest influence upon these specific factors and upon the soil microenvironment as a whole. Any tillage operation will alter the physical properties of the soil and this in turn ultimately will influence disease development by affecting the pathogen, the crop, and/or other soil microorganisms.

The major impact that Verticillium wilt has had on the potato industry over the past 20 years could be due in part to the evolution and shift of modern tillage practices away from traditional plowing methods and toward minimum tillage or deep subsoil, "deep-rip" tillage commonly used today. Deep-rip tillage does little to mix the soil profile, leaving crop residue at the soil surface. Moldboard plowing, or other forms of tillage that bury crop residue, can reduce the pathogen populations in the upper soil layer and as a result limit the development of some foliar and soil-borne diseases (Rothrock 1992). However, although cultural practices are always considered to be an essential component in an integrated approach to managing the disease, the relationship between tillage and Verticillium wilt has not been examined. Since Verticillium wilt is a soil-borne disease, tillage should have an impact on the distribution of the pathogen population. Much of what we know today about infection of *V. dahliae* in potato is derived from research performed 20 to 25 years ago (Davis 1985; Rowe et al. 1987). Soil fumigation practices are based on this research and may be inadequate today under tillage practices currently employed. This study was undertaken to examine the effect of tillage and chemical application methods on soil populations of *V. dahliae* and to determine their influences upon the development of Verticillium wilt and subsequently, the quality of the potato crop.

## MATERIALS AND METHODS

### *Trial Locations and Field Layout*

Trials were conducted under large-scale conditions in two irrigated commercial potato production circles in 2002 and 2003. These fields were selected because of history of Verticillium wilt and contrasting soil types (heavy, sandy loam, vs light, loamy sand). In 2002, soil organic matter content was 2.8% in the heavy soil and 1.5% in the lighter soil. The following year, organic matter content of these soils was 2.9% and 1.2%, respectively. The fields also differed in cropping history. The field with the heavier soil is on a 3-year potato rotation (1997—potato; 1998—corn; 1999—soybeans; 2000—potato; 2001—soybeans; 2002—sudangrass; 2003—potato), and the location with the lighter soil has a 2-year potato rotation (1997—potato; 1998—corn; 1999—potato; 2000—corn; 2001—potato; 2002—sudangrass; 2003—potato). Both fields are located in west central Minnesota.

The effects of tillage and chemical interactions on Verticillium wilt were investigated using a strip-plot design (Gomez and Gomez 1984). In the spring of 2002, plow and deep-rip subsoil tillage operations (vertical factors) were applied across half of each circle (26 ha). Following tillage, selected portions of these areas perpendicular to the tillage treatments were treated with metam sodium (sodium methyldithiocarbamate) via chemigation or shank injection at a rate of 380 L per ha (horizontal factors). Two injection treatments were used with the fumigant being applied at two depths of 10 cm and 25 cm or at 15 cm and 30 cm using standard, commercial shank injection equipment. Metam sodium was applied between 7:30 AM and 12:30 PM with soil temperatures at a depth of 15 cm ranging from 19 to 23 C. The chemical was applied with 1.50 cm of water during chemigation applications. Soil moisture in the upper 30 cm ranged from 80% to 85% field capacity. Immediately following all metam sodium applications, a water "seal" was applied to the field by running the pivot irrigator at 100% and applying 45 to 50 mm of water. A section of each tillage area was not treated with metam sodium representing an untreated control for each vertical factor.

### *Soil Sampling*

Soil sampling sites were selected along sampling transects and marked as waypoints with a Garmin eTrex Legend 12-channel GPS receiver. Because this trial was performed in a commercial field with commercial application equipment, the exact layout and location of each treatment area could not be determined before the first sampling date. Therefore each field was "oversampled" prior to tillage and fumigation operations to assure an ample number of samples was recovered from each experimental unit. A total of 209 sites were initially sampled in both fields to establish the baseline *V. dahliae* populations. After the tillage and fumigation operations had taken place, the sample sites were consolidated to 73 sites in the field with the heavy soil and 68 sites in the location with the lighter soil. Ten samples were collected with a 2-cm-diameter soil core probe at random locations within a 3-m radius of each waypoint coordinate (replication). The samples were partitioned into upper (0-10 cm) and lower (10-20 cm) strata and bulked as such. Soil sampling was done prior to tillage (3 or 16 May 2002), after tillage (21 May 2002), and twice after chemical application (7 or 8 August 2002 and 21 May 2003). Samples also were taken from the untreated area of each field on 25 July and 20 September 2002. Soil samples were air-dried at 25 C for 3 to 4 days and stored at 15 C until analysis. Samples were assayed for the presence of *V. dahliae* by Pest Pros, Inc. (Plainfield, WI, USA) using a technique based upon that of Nicot and Rouse (1987).

### Metam Sodium Efficacy

The effect of metam sodium was determined by assessing changes in the *V. dahliae* populations within each treatment area following chemical application. Soil population data obtained from each site-specific sampling area were transformed to percentage reduction in the population where: Reduction (%) = [(pre-metam sodium *V. dahliae* population vppg – post-metam sodium *V. dahliae* population vppg) / pre-metam sodium *V. dahliae* population vppg] X 100.

### Disease Assessments

Both fields were planted to potatoes (cv Russet Burbank) in 2003. The crop was managed using standard agronomic practices recommended for the region. Disease expression (wilt) was monitored at intervals during the latter portion of the growing season. Sampling rectangles (replications) approximately 12 $m^2$, and composed of four parallel rows 3 m in length, were established at each previously GPS-marked waypoint. Sampling rectangles were added to treatment areas with fewer than six soil-monitoring replications to assure that there were 12 replications of each treatment for disease evaluations. Disease was assessed at the 12 replicated sites within each of the eight treatments for a total 96 sites in each field. Flags were positioned at the corners of each rectangle to assure that the same plants were evaluated on subsequent visits. Disease incidence was determined weekly by counting the number of wilted and dead stems within each sampling rectangle beginning 20 August 2003. The percentage of the canopy within each replication showing chlorosis and/or necrosis was estimated as a measure of disease severity. Wilt incidence was converted to area under the disease progress curve (AUDPC) according to the method outlined by Shaner and Finney (1977) as follows:

$$\text{AUDPC} = \sum_{i=1}^{n} [(W_{i+1} + W_i)/2]\,[t_{i+1} - t_i]$$

where $W_i$ = number of wilted stems at the *ith* observation, $t_i$ = time in days at the *ith* observation, and n = total number of observations. Dividing AUDPC values by the total area of the graph normalized the values. The resulting relative area under the disease progress curve (RAUDPC) was used to compare treatments (Fry 1978).

### Post-harvest Evaluations

Six of the 12 replications were randomly selected, and the center two rows were harvested for a total of 72 m of row per treatment. Tuber yield on a fresh-weight basis was determined for each harvested sample. Tubers from each replication were combined and USDA grade was determined on a single bulked sample for each treatment. Yield and grade results were entered into a standard processing contract for the region, and a market analysis was also carried out for each treatment. Data for marketable yield and processing contract estimations was not statistically analyzed since tuber yields for each replicate were bulked by treatment prior to USDA grading, resulting in a single data point for each treatment.

### Experimental Design and Statistical Analysis

To take advantage of the perpendicular design of this field experiment a strip-plot design was utilized (Gomez and Gomez 1984). The two tillage methods, each replicated three times, were the vertical factors, and the four chemical application methods, each replicated four times, were the horizontal factors. Depth of shank injection, 10 and 25 cm vs 15 and 30 cm, were replicated twice and nested within that horizontal factor. *Verticillium dahliae* populations in soil samples taken during the growing season within the untreated areas at each depth of each vertical factor were compared and tested for variance homogeneity using Levene's test (Millikin and Johnson, 1992) (SAS Institute, Inc., Cary, NC, USA). Soil populations of *V. dahliae* (vppg), foliar disease ratings, and yield were all statistically analyzed using the general linear models procedure (Proc GLM) at $\alpha = 0.05$. A one-way analysis of variance (ANOVA) was performed and *t* tests were used to detect differences in *V. dahliae* populations between sampling dates in 2002 and 2003. Differences in pre- and post-tillage *V. dahliae* populations at both sampling depths were detected using *t* tests in a one-way ANOVA performed separately for each field. *T* tests were also used to detect differences in the percentage reduction of *V. dahliae* populations at pre-and post-chemical application. Preliminary analysis of the data on *V. dahliae* populations indicated there was no interaction between the main effects of tillage method and chemical application method for either field; therefore, only main effects were further analyzed. Two-way ANOVA's were performed on the interaction of the main effects of tillage method and chemical application method for the foliar severity and incidence of disease, as well as the total yield for each field. The effect of the Verticillium wilt on total yield was determined by means of Pearson's correlation analyses, also performed for each field.

## RESULTS AND DISCUSSION

### *Soil Sampling*

Prior to tillage, the average baseline population of *V. dahliae* in the field under the 2-year rotation was 23.8 vppg and 15.4 vppg in the field with a 3-year rotation. Because of the difference between vppg levels in the two fields, the data from each field were analyzed separately. Inoculum density varied markedly between sampling sites within each field, but the effects of the variability were minimized because repeated sampling was conducted at geo-referenced sites. Many factors can influence *V. dahliae* soil populations and wilt development in potato. These include such management practices as crop sequencing, duration between potato crops, potato cultivars grown, and the soil and environmental parameters of temperature, moisture content, structure, fertility, and organic matter content. Of these, crop rotation and host crop susceptibility can directly influence the size of the resident soil population of *V. dahliae* (Ben-Yephet and Szmulewich 1985; Davis and Huisman 2001; Mol et al. 1996; Powelson and Rowe 2003; Rowe and Powelson 2002). Most other factors influence the ability of the pathogen to colonize the roots of host plants and cause wilt (inoculum efficacy).

The results of an early study (Wilhelm 1950) demonstrated that the vertical distribution of *Verticillium albo-atrum* in soil from California also varied considerably, with the greatest proportion of inoculum residing in the 30 cm nearest the surface. More recently, Hamm et al. (2003) determined that most of the *V. dahliae* propagules reside in the upper 30 cm of soil in the Columbia Basin of Oregon. Others (Ben-Yephet and Szmulewich 1985) found *V. dahliae* concentrated primarily in the upper 20 cm strata. Results obtained from this study support previous research and actually narrow the area of the surface soil layer containing the greatest quantity of inoculum. Propagules of *V. dahliae* were detected at all but one of the sites sampled in both fields prior to tillage and a large proportion of the inoculum (74.4% in heavy soil and 63.1% in the light soil) was found to be concentrated in the upper 10 cm of the soil strata.

In addition to spatial differences in inoculum density described above, we observed temporal variations in soil populations of *V. dahliae* in both fields (Figure 1). Levene's test for homogeneity of variance indicated that soil populations at each sampling depth and across tillage methods were not significantly different at each sampling date; therefore data were combined for further analysis. The total populations within untreated areas of both fields peaked in late July and early August before declining to near early season levels. The *V. dahliae* population reached a maximum of 7.8 vppg in the field on the 3-year potato rotation (Figure 1A), while the maximum population recorded in the field on the 2-year potato rotation was 46.0 vppg (Figure 1B). Inoculum levels in this field were significantly ($P < 0.05$) greater at midseason (end of July, beginning of August) than early or late in the season. Temporal changes in *Verticillium* spp. populations have been described previously (Benson and Ashworth 1976; Evans et al. 1967; Joaquim et al. 1988). Joaquim et al. (1988) documented a similar

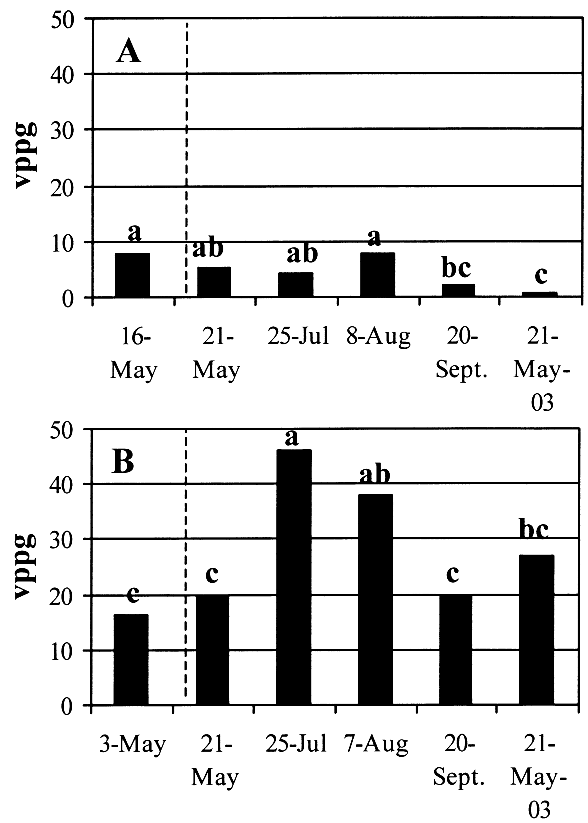


**FIGURE 1.**
**Effect of tillage upon the seasonal population dynamics of *Verticillium dahliae* in the untreated portion of a field with sandy-loam soil under a 3-year potato rotation (A) and a field with loamy-sand under a 2-year potato rotation (B). Means with the same letter are not significantly different ($P$ < 0.05) within each field. Broken vertical line indicates approximate date of tillage operations.**

pattern in Ohio potato field soils and speculated that the microsclerotia released from the protective environment of plant residue during the spring and early summer may rapidly lose their viability as the result of predation or antagonism by other soil microorganisms. Studies have shown that root colonization, root infection, and survival/germination of microsclerotia can be affected by soil-inhabiting microorganisms (Tjamos 2000). The release of microsclerotia from decaying plant residue has the maximum effect upon soil inoculum density within 2 years of a potato crop (Joaquim 1988; Mol et al. 1996), and in fields with high initial infestations, the level of *V. dahliae* in the soil remains unchanged after that (Mol et al. 1996). In fields planted to a non-susceptible crop, the *V. dahliae* population declined by 50% within 2 years and by 90% within three years after a potato crop (Ben-Yephet and Szmulewich 1985).

Our results support these observations (Figures 1 and 2). The *V. dahliae* population in the field with heavy soil was substantially lower than in the field with lighter soil. High organic matter content should provide an environment more suitable for biological breakdown of debris and microsclerotia, but in this case, differences could also be due to the 3-year rotation. The population prior to planting in May of 2003 was 10% of that measured in May of 2002 at this location, although this difference was not significant (Table 1, Figure 1A). On the other hand, the initial *V. dahliae* population in the field with a 2-year potato rotation and having soil with lower organic content, remained high (23.3 vppg) at the start of the 2003 field season, essentially remaining unchanged between years of the study (Table 1, Figure 1B).

Because a greater quantity of *V. dahliae* inoculum was concentrated in the areas of both fields to be deep-rip tilled (Figure 2), mean separations were nested within the main effects of tillage. In both fields, moldboard plowing distributed the inoculum vertically (Figure 2A,C) while deep-rip tillage did not

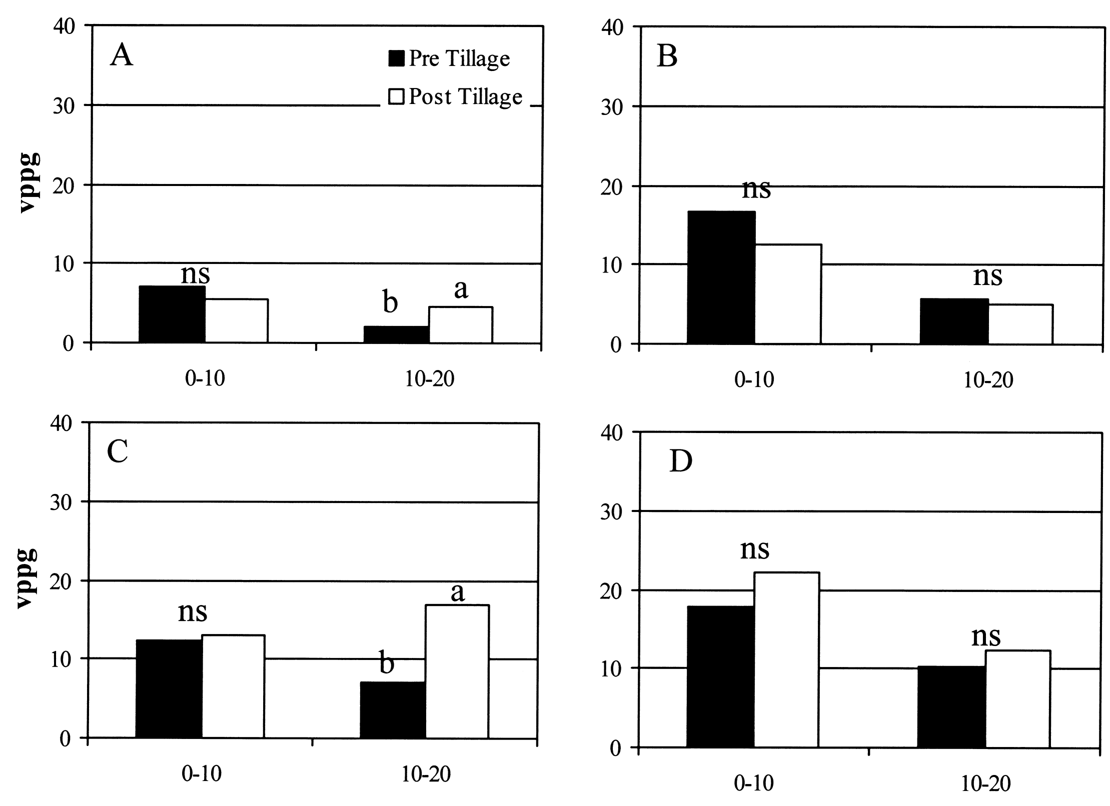


**FIGURE 2.**
**Effect of tillage method on the soil population of *Verticillium dahliae* at depths of 0 to 10 cm and 10 to 20 cm in a field with sandy-loam soil under a 3-year potato rotation with plow (A), and deep-rip (B) tillage operations and a field with loamy-sand under a 2-year potato rotation with plow (C), and deep-rip (D) tillage operations. Means with the same letter are not significantly different ($P < 0.05$) at each sampling depth within each field (ns = no significant differences between treatments).**

(Figure 2B,D). Significantly more *V. dahliae* inoculum ($P < 0.05$) was found at the 10- to 20-cm depth after plowing (Table 2, Figure 2A,C). In contrast, the number of propagules in the upper and lower soil layers did not differ significantly after deep-rip tillage in either field (Table 2, Figure 2B,D). The ratio (0-10 cm):(10-20 cm) of *V. dahliae* propagules decreased from (3.3 : 1 to 1.2 : 1) in the field with the 3-year rotation after plowing, but remained virtually unchanged (2.9 : 1 vs 2.5 : 1) following deep-rip tillage. Results were similar at the location under a 2-year potato rotation. Plowing reduced the ratio from 1.7 : 1 to 0.8 : 1 while pre- and post-deep-rip tillage ratios remained unchanged at 1.8 : 1 and 1.8 : 1, respectively. Ben-Yephet and Szmulewich (1985) observed similar changes in propagules distribution in a tillage study comparing disc incorporation to deep plowing.

TABLE 1—*Analysis of variance (ANOVA) for the effect of sampling date on the reduction of* Verticillium *propagules per gram (vppg) of soil in untreated areas across sampling depths and tillage methods.*

| Source of Variation | df | *F* value | $P > F$ |
|---|---|---|---|
| 3-Year Rotation | | | |
| Sampling Date | 5 | 2.48 | 0.0385 |
| 2-Year Rotation | | | |
| Sampling Date | 5 | 8.13 | <0.0001 |

### *Metam Sodium Efficacy*

Whether applied by shank injection or via chemigation, metam sodium affected the level of inoculum in both fields although the extent of the effect was related to the method of application, tillage conditions, and soil type (Figure 3). These changes were significant ($P < 0.05$) in the lower strata of the field under a 3-year rotation following deep-rip tillage where the *V. dahliae* population decreased following both chemiga-

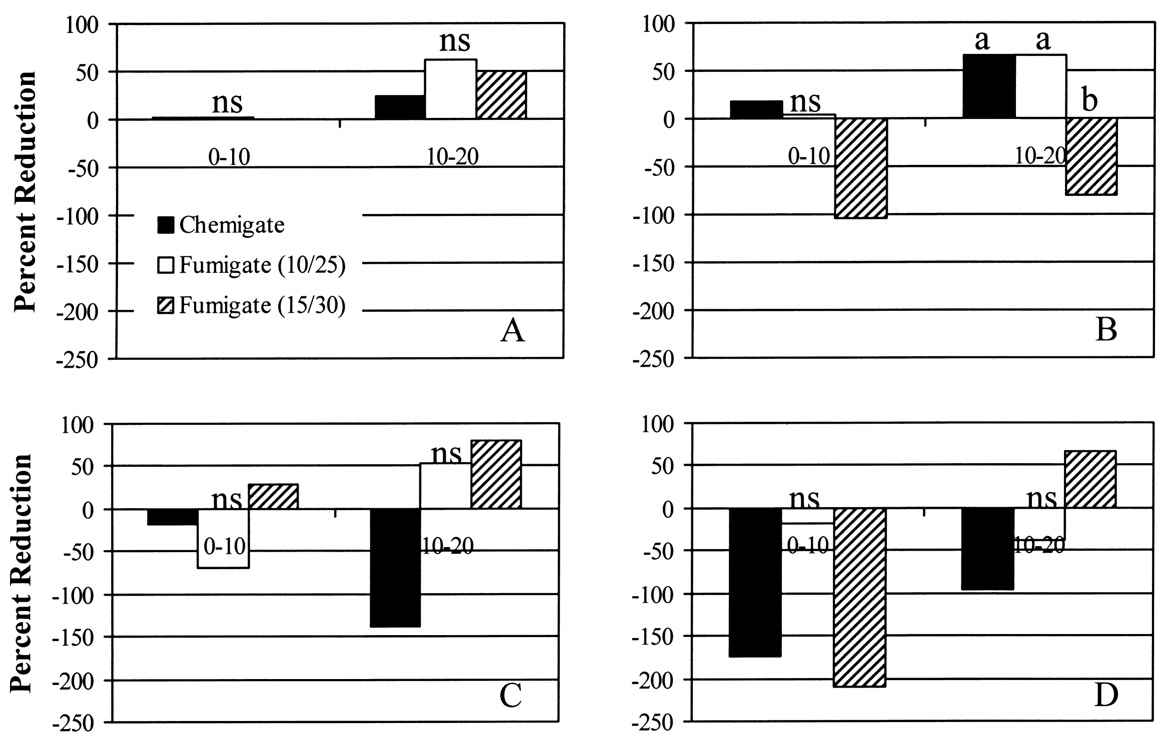


**FIGURE 3.**
**Effect of tillage and method of metam sodium application on the soil population of *Verticillium dahliae* at sampling depths of 0-10 cm and 10-20 cm in a field with sandy-loam soil under a 3-year potato rotation with plow (A), and deep-rip (B) tillage operations and a field with loamy-sand under a 2-year potato rotation with plow (C), and deep-rip (D) tillage operations. Percent reduction is based the differences between pre-metam sodium (21 May 2002) and post-metam (7 or 8 August 2002) populations of *V. dahliae* at each treated soil monitoring site. Means with the same letter are not significantly different ($P < 0.05$) at each sampling depth (ns = no significant differences between treatments).**

TABLE 2—*Analysis of variance (ANOVA) for the effect of tillage method on the reduction of* Verticillium *propagules per gram (vppg) of soil at two sampling depths.*

| Source of Variation | 0-10 cm Sampling Depth df | *F* value | *P* > *F* | 10-20 cm Sampling Depth df | *F* value | *P* > *F* |
|---|---|---|---|---|---|---|
| 3-year Rotation—Plow Tillage Timing | 1 | 1.41 | 0.2395 | 1 | 6.46 | 0.0134 |
| 3-year Rotation—Deep-Rip Tillage Timing | 1 | 2.87 | 0.0941 | 1 | 0.36 | 0.5508 |
| 2-year Rotation—Plow Tillage Timing | 1 | 0.09 | 0.7606 | 1 | 7.03 | 0.0103 |
| 2-year Rotation—Deep-Rip Tillage Timing | 1 | 1.53 | 0.2199 | 1 | 1.24 | 0.2687 |

TABLE 3—*Analysis of variance (ANOVA) for the effect of chemical application method on the reduction of* Verticillium *propagules per gram (vppg) of soil within tillage methods at two sampling depths.*

| Source of Variation | 0-10 cm Sampling Depth df | *F* value | *P* > *F* | 10-20 cm Sampling Depth df | *F* value | *P* > *F* |
|---|---|---|---|---|---|---|
| 3-year Rotation—Plow Tillage Chemical | 2 | 0.00 | 0.9987 | 2 | 0.71 | 0.4993 |
| 3-year Rotation—Deep-Rip Tillage Chemical | 2 | 3.13 | 0.0577 | 2 | 5.62 | 0.0100 |
| 2-year Rotation—Plow Tillage Chemical | 2 | 0.86 | 0.4251 | 2 | 2.7 | 0.0857 |
| 2-year Rotation—Deep-Rip Tillage Chemical | 2 | 1.79 | 0.1891 | 2 | 1.50 | 0.2447 |

Data were transformed from vppg to percentage reduction in population before analysis.

tion and shank fumigation of metam sodium at 10/25 cm (Table 3, Figure 3B). In contrast to these treatments, inoculum density increased significantly following fumigation at 15/30 cm. Although other changes in the pathogen population were not significant, certain trends were associated with the tillage and metam sodium treatments. The inoculum level in the upper soil layer of the plowed portion of the field on the 3-year rotation essentially remained unchanged following all metam sodium treatments while the *V. dahliae* population in the lower soil layer apparently declined following all chemical treatments (Figure 3A). Shank injection of metam sodium appeared to be generally more effective than chemigation in reducing inoculum levels overall, and it had the greatest impact in the lower soil layer after plow tillage (Figure 3A,C). These results clearly illustrate the difficulty in effectively killing microsclerotia in the upper soil profile (0-10 cm) where MITC is more likely to be lost due to volatility of the compound.

In the field on the 2-year rotation, the greatest reduction in the *V. dahliae* population was observed with plow tillage followed by shank fumigation of metam sodium (Figure 3C). This combination also had the most pronounced effect in the lower soil layer. These results are similar to those obtained in the field on the 3-year rotation (Figure 3A). Shank injection was not as effective following deep-rip tillage in the field on the 2-year rotation. Chemigation did not reduce the level of inoculum in this field when combined with either tillage method (Figure 3C,D). The apparent increase in the *V. dahliae* population in this field following chemigation may not necessarily relate to that treatment's efficacy and is likely related to a large midseason flush-release of propagules observed at that location (Figure 1B). Although a similar release was observed in the field with the 3-year rotation, *V. dahliae* populations did not increase significantly suggesting that the majority of the *V. dahliae* propagules were released from plant residue over the 2 years prior to sampling. These results further demonstrate the importance of longer rotations in reducing Verticillium populations and the difficulty in reducing populations of this pathogen with metam sodium on a 2-year rotation between potato crops.

Plowing, followed by shank application of metam sodium at 15/30 cm depths, and shank application of metam sodium at 10/25 cm following deep-rip tillage were associated with the greatest reductions in the *V. dahliae* populations in both fields. Shank injection at 15/30 cm depths following deep-rip tillage was generally the least effective treatment. The *V. dahliae* population increased following this treatment except at the 10- to 20-cm depth in the field on the 2-year rotation (Figure 3D). This observation possibly can be attributed to the proportionally larger amount of *V. dahliae* inoculum in the upper 10-cm soil strata where loss of fumigant in a vapor state would be greater (Figure 2). It is clear from these data that the current industry standard in the midwestern USA is a combination of deep-rip tillage and shank injection of metam sodium at two depths (10/25) is an effective means of reducing *V. dahliae* inoculum.

## *Disease Assessments*

We observed changes in soil inoculum levels with the treatments applied in this study; however, other work has shown that population density is not necessarily predictive of disease severity (Davis 1985; Davis et al. 2001). Therefore, inoculum potential, wilt development in the subsequent potato crop, and yield effects offer the best assessment of the efficacy of the tillage and chemical treatments employed in the current study. The method of chemical application had an effect upon disease development in the ensuing growing season; however, differences between tillage and metam sodium treatments were not significant (data not shown). Generally, metam sodium fumigation via shank injection appeared to be more effective than chemigation in reducing the number of wilted or dead stems. Disease severity based upon the percentage of canopy affected paralleled disease incidence in both fields (data not shown). The amount of wilt observed in the plowed areas of both fields was reduced by nearly 50% with the shank-injection methods. Similar trends were observed in the areas under deep-rip tillage, but wilt was apparently reduced only with shank injection at 10/25 cm in the field on the 3-year rotation. Shank fumigation at either 10/25 cm or 15/30 cm combined with moldboard plowing were the treatments most effective in reducing wilt. While the amount of wilt in the plowed area under the 3-year rotation was reduced with chemigation, approaching levels attained with shank injection, this treatment was ineffective in reducing disease in the field with the 2-year rotation under this tillage treatment. Wilt was not reduced in the deep-rip tilled and chemigated areas of either field.

## *Post-harvest Evaluations*

Although differences between disease incidence and disease severity and between tillage methods and chemical application methods were not significant, there was a relationship between Verticillium wilt and total yield (Figure 4). A strong and highly significant correlation ($P < 0.05$) existed between wilt (RAUDPC) and total yield (mT/ha) in the field with the 3-year rotation (Figure 4A). Marketable yield data obtained from USDA grading paralleled total yield in each field, as did processor analysis (data not shown). According to standard contract criteria used to estimate the value of the harvested crop, the shank-fumigated plowed areas in the field with the 3-year potato rotation grossed from $500 to $1200 more per ha when compared to the untreated areas (data not shown). Similar results were obtained in the field on the 2-year potato rotation but the magnitude of the estimated gain was smaller at $185 to $370 per ha.

Soil composition and structure can have an effect on chemical efficacy. Metam sodium is converted to its biologically active form, MITC, in the soil (Munnecke et al. 1962), but MITC is readily adsorbed to clay and organic matter such as peat, potentially reducing the efficacy of the metam sodium initially applied (Munnecke et al. 1962, 1964). Although organic matter and clay content were higher in the field with the heavier soil, soil structure may be the more important factor contributing to the results obtained at that location. Ben-Yephet et al. (1983) demonstrated that metam sodium can be effective in soil with clay content as high as 54% when the soil has good natural structure. In that study, microsclerotia of *V. dahliae* were killed to a greater depth when this soil was clodded as opposed to being finely sieved. These observations may partially explain why chemigation was effective in the field on a 3-year rotation having heavier soil and better overall structure

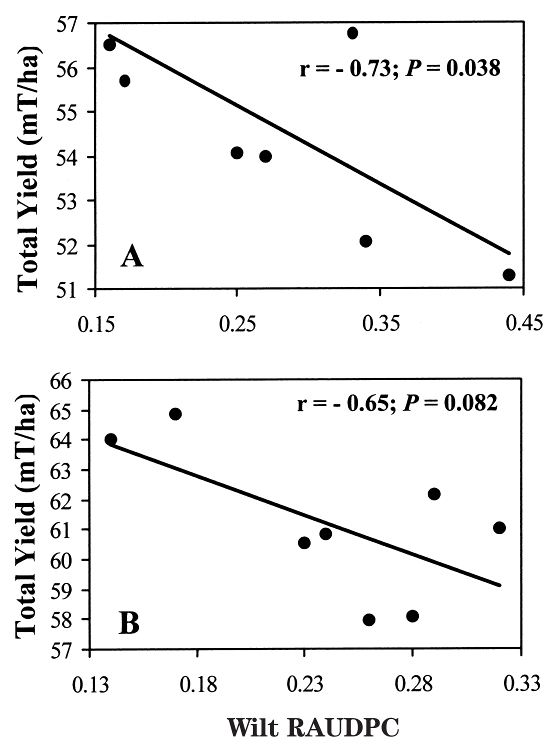


**FIGURE 4.**
**Correlation of relative area under the disease progress curve (RAUDPC) and total yield (mT/ha) in a field with sandy-loam soil under a 3-year potato rotation (A) and a field with loamy-sand under a 2-year potato rotation (B).**

(Figure 3A,B). Chemigation failed to reduce the soil populations of *V. dahliae* (Figure 3C,D) or limit the ensuing level of disease in the field with the lighter soil and on a 2-year rotation. The soil is loosely aggregated and composed of larger, coarser-grained particles. Loss of fumigant due to volatilization is more likely to occur in soil of this type where moisture is more difficult to retain. The ineffectiveness of chemigation was particularly evident in the portion of field under the commonly used method of deep subsoil rip tillage where structure was reduced the most. Another mitigating factor is related to changes in the soil population over time. Fumigant efficacy in the field with the 2-year rotation also was most likely compromised because a much larger proportion of inoculum was released into the soil from the previous potato crop after the metam sodium treatments were applied (Figure 1), which would be consistent with previous studies (Joaquim 1989; Mol et al. 1996)

Our results suggest that under the conditions of this study, shank injection of metam sodium is superior to chemigation, especially when combined with plow tillage. In this situation, we believe plowing inverts a significant proportion of the *V. dahliae* inoculum from the upper to lower soil strata and shank injection places metam sodium where it is needed, potentially limiting any reduction in efficacy due to volatilization and adsorption. Shank-injected metam sodium reduced populations in both fields, and this translated into better disease control and higher yields, even in the heavier soil with a higher organic matter content (Figures 3, 4).

Verticillium wilt is presently managed through an integrated approach that includes soil fumigation, host resistance, and a variety of additional cultural practices. Although research involving traditional methods for managing Verticillium wilt continues to add to our knowledge of this complex disease, future restrictions on the use of soil fumigants will undoubtedly necessitate the development of novel management strategies. A simple approach might involve additional adjustments in cultural practices, such as tillage and the use of green manures (Davis et al. 1996), both of which are relatively easy and economical to implement. Moldboard plowing can reduce the severity of black dot tuber infections by as much as 34% (Denner et al. 2000), but prior to the current study, the relationship between tillage and the severity of Verticillium-induced wilt and early maturity death of potato had not been investigated. Our results provide insights into the effect of tillage practices on distribution and survival of the pathogen in soil and how this correlates with development and wilt severity, particularly when chemical control measures are applied.

In research reported here, we demonstrate that a large proportion of the *V. dahliae* inoculum is limited to the upper 10 cm of the soil profile. This study also confirms that plowing redistributes much of the inoculum in the lower soil layer where biological activity may contribute to its breakdown and fumigation is most effective. Burying plant residue should also reduce windblown dispersal of inoculum as well as reduce the quantity of inoculum placed in proximity to the root zone during hilling operations. Furthermore, these results demonstrate that the combination of plowing and shank injection of metam sodium can substantially reduce the amount of Verticillium inoculum in the soil. This is consistent with the results obtained in an earlier study detailing the effects of chloropicrin fumigation as applied either in conjunction with plowing or via shank injection after plow tillage (Easton et al. 1977). As a result, the level of disease will be lower and yield and gross income can be increased with such treatments. In light of the data presented here, growers might consider altering tillage and chemical application practices as part of an integrated approach to manage Verticillium wilt. Moldboard plowing is no longer routinely practiced so in areas where conservation tillage is an issue, the grower might need to assess the advantages and disadvantages of plowing before adapting this method. While this strategy in not conducive to highly erodible soils, growers wishing to implement this management technique could plow their potato soils immediately following harvest and then plant a cover crop such as rye. Our results suggest that such an approach might prove beneficial in areas where the soil populations are very high and Verticillium wilt is a perennial problem, even in the first year following plowing and particularly when combined with fumigation.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Minnesota Area II Potato Growers Association, USDA-ARS (grant number: 59-0790-3-067) and AMVAC Chemical Co. The authors thank Dean Peterson, Darrel Serfling, Dick Nilles, Colin Auwarter, and Graham Gudmestad for technical assistance in conducting these experiments and Harikrishnan Ramasubramaniam, Department of Plant Pathology, and Curt Doetkott, Statistician, Information Technology Services, North Dakota State University, for advice and assistance with data analysis.

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