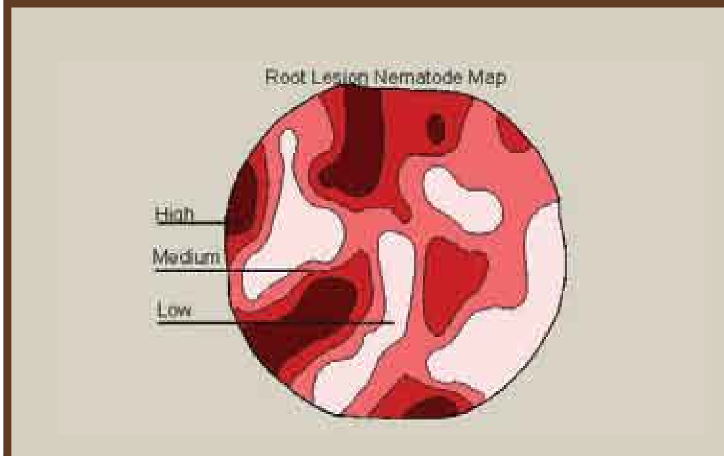
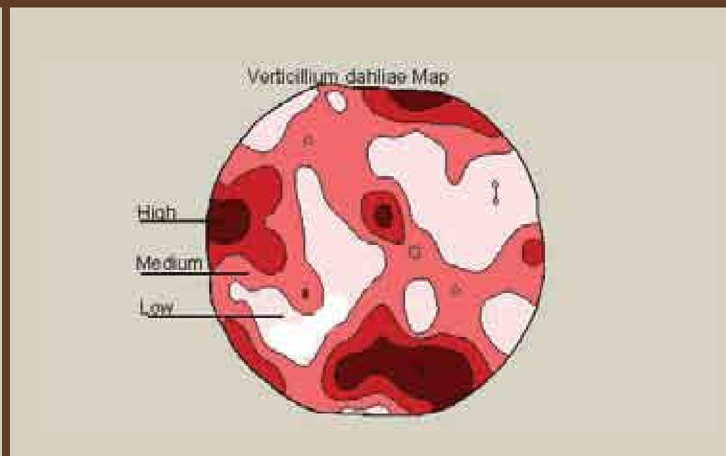
GPS-Guided and Site-Specific Application of Metam Sodium for Verticillium and Root Lesion Nematode Management





by John Taberna, Jr
Western Ag Research

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John Taberna Jr., Research Agronomist with Western Ag Research LLC, was the principle investigator on this project and author of this publication. The results and suggestions are based upon the growing conditions found in eastern Idaho at an elevation of 4,000 to 5,300 feet. Taberna received both his B.S. and M.S. degrees in Agronomy from the University of Idaho. He is a Certified Professional Agronomist (CPAg) with the American Society of Agronomy.

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End guns sometimes apply chemicals to non-target areas.

Metam Sodium Use in Potato Production

This guide describes the site-specific soil injection of metam sodium for potato production in southeastern Idaho to replace chemigation and its associated problems, as well as to reduce metam sodium use.

Metam sodium use has had a long and proven history of maintaining or increasing potato yields and tuber quality. The yield increase and improved tuber quality have been attributed primarily to the suppression of *V. dahliae*, root-lesion nematodes, various other nematodes, *Rhizoctonia solani*, other fungal pathogens, and numerous weeds and insects. Metam sodium is an indiscriminate, broad-spectrum biocide.

The popularity and heavy use of metam sodium is not without risks.

The popularity and heavy use of metam sodium is not without risks. A key concern is drift to non-target areas, due to the volatility of the metam sodium breakdown products and high application rates of 160 pounds or more of active ingredient per acre. The number of such incidences has increased over the years to the point where the public has pressured the Environmental Protection Agency to reexamine the use of metam sodium in agriculture.

Metam sodium acts as a soil fumigant by breaking down into the active ingredient methyl isothiocyanate (MITC) when exposed to water. MITC is highly toxic and is responsible for most of the fumigant properties of metam sodium. Metam sodium is highly water soluble with a low vapor pressure, while MITC has low water solubility with high vapor pressure. Therefore, MITC is a volatile compound and prone to drift. MITC is lost during application because of its lack of solubility in water and through soil emissions.

MITC is responsible for most of the eye and respiratory complaints by the public during and after metam sodium application. This is especially true in crop production where metam sodium is used near housing, schoolyards, and other urban areas.

Problems with Chemigation of Metam Sodium

The agricultural practice of injecting a chemical into an operating irrigation system and applying it to a field with the irrigation water is known as chemigation. Farmers often use the chemigation of metam sodium by sprinkler irrigation from center pivots in fields prepared for potato production. Metam sodium is applied via chemigation across the entire field at a constant rate of 37 to 45 gallons per acre in eastern Idaho.

While this is a common practice, there are three main problems with the chemigation of metam sodium.

1. The variable and unknown application rates when end guns and/or corner catchers are in use.
2. The volatility and off-gassing (soil emissions) of MITC during and after chemigation.
3. The increase in drift during high temperatures and wind.

Impact of End Guns and Corner Catchers on Product Application

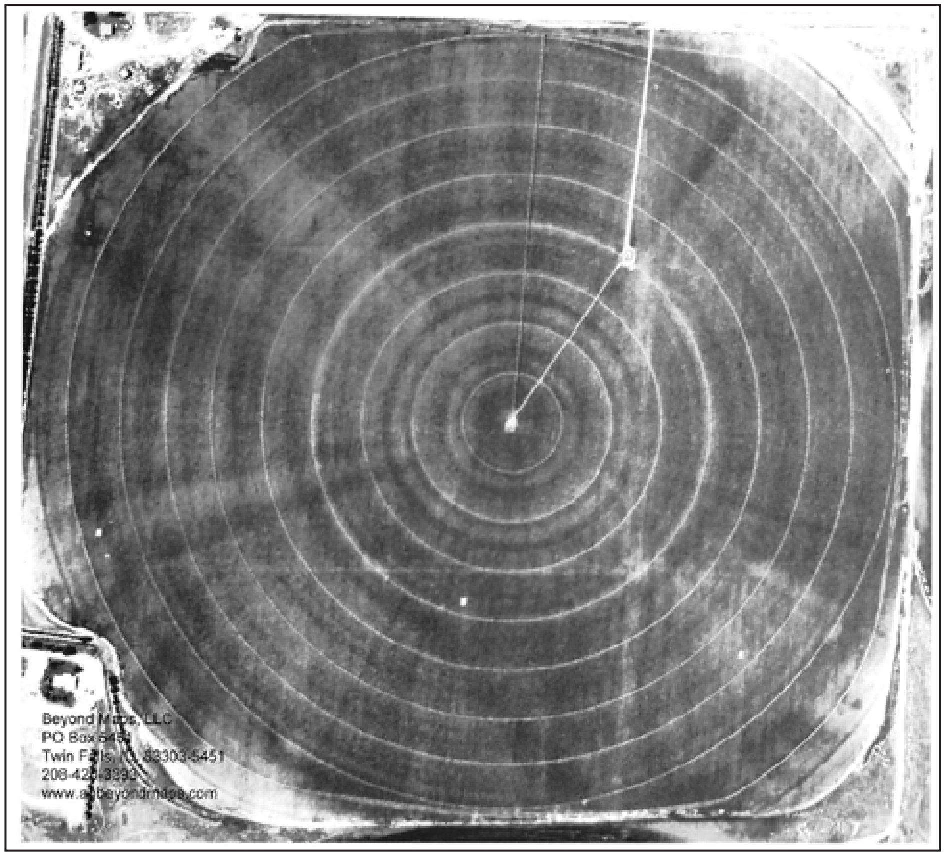
Product application rates during chemigation are based on the time it takes an irrigation system to complete a rotation. If a farmer wants to chemigate 40 gallons per acre of metam sodium on a 136-acre field requiring 52 hours to apply the necessary water for the application, then the chemigation equipment is set to deliver 105 gallons per hour ([40 gal/ac x 136 ac] / [52 hr] = 104.6 gal/hr).

When end guns and/or corner catchers are used during chemigation, the product application rate is not constant. The added volume of water through the system for the end guns and/or corner catchers dilutes the concentration of metam sodium applied to those portions of the field. Application errors of 7 to 21% can result, depending upon the system design and field size (King et al., 2009).

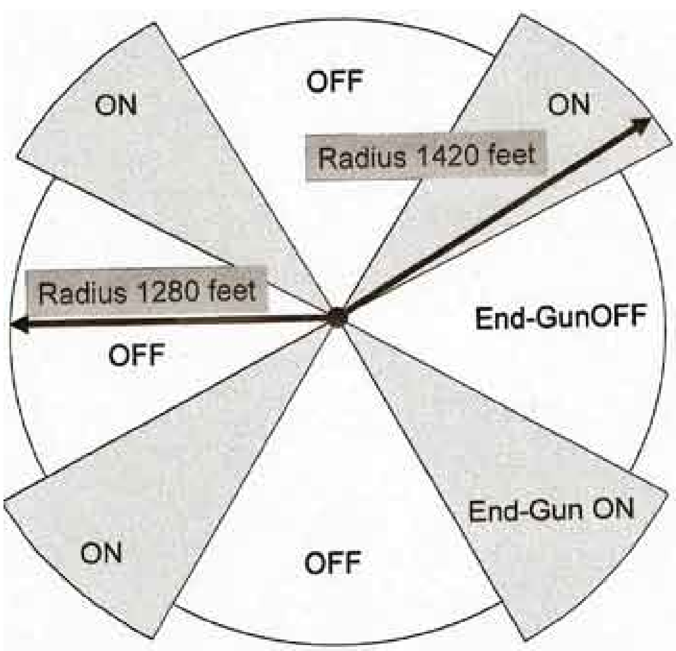
Urban sprawl has increased the difficulty of chemigation with metam sodium.

The application error is proportional to the increase in water flow when the end guns and/or corner catchers are engaged and not compensated for by the chemigation pump. Newer technology, such as variable frequency drive chemigation systems, compensate for some of the errors in traditional chemigation, since it allows the output of the pump to be adjusted while the irrigation system is in operation. Use of this technology is growing, but it is still minor as compared to the traditional method of injection at uniform rates.

For example, end guns are usually in use for 15 to 45% of the time on a full rotation. A 136-acre field that has a center pivot system capacity of 1,000 gallons per minute and an end gun capacity of 150 gallons per minute will have an operating error of about 15% when the end gun is in use ([pivot 1000 gpm + end gun 150 gpm] / [pivot 1000 gpm]=1.15). If the same end gun system is used on an 80-acre field with a pivot water delivery system of 650 gallons per minute, the error rate increases dramatically to 23% when the end gun is in use during chemigation.



Chemigation problems due to water flow variability from the use of end guns and/or corner catchers are usually seen in aerial photographs as "spoke-wheels" and "wide-fans."



The product application rate drops when end guns and/or corner catchers are engaged during chemigation.

What is the significance of this error?

If a farmer is chemigating metam sodium at a constant rate of 38 gallons per acre on the 136-acre field described above, then 75% of the field is receiving 38 gallons per acre when the end gun is not in use and only 32 gallons per acre on the other 25% when the end gun is in use (Table I). Consequently, 102 acres received 38 gallons per acre and the remaining 34 acres received 32 gallons per acre.

On the 80-acre example field, the application rate is reduced from 38 gallons per acre to only 29 gallons per acre when the end gun is in use.

TABLE I: Impact of end gun (150 gpm) on product application rates during chemigation.

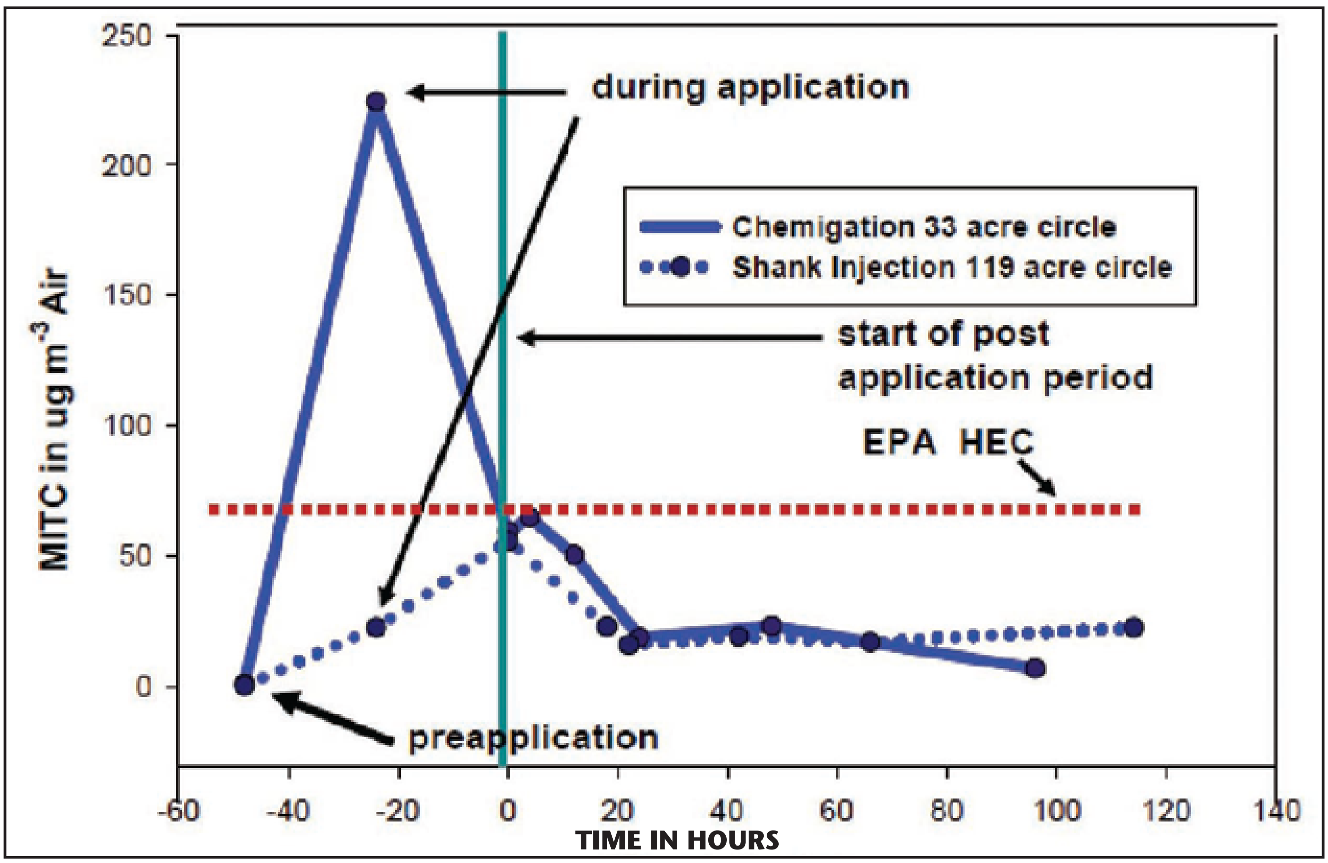
	WITHOUT END GUN	WITH END GUN	
Field Size	**Gallons applied/ac**	**Gallons applied/ac**	**Error rate**
136 acres	38	32	15%
80 acres	38	29	23%

This does not mean that pest control is reduced with these lower metam sodium application rates. Instead, it shows that many farmers are already applying metam sodium at varied rates when end guns and/or corner catchers are used during chemigation, with no apparent consequence to their crop production.

Volatility and Soil Emissions of MITC

Another problem with the chemigation of metam sodium is that MITC is produced as soon as metam sodium comes in contact with water. Some of this MITC can volatilize from the irrigation water before it ever reaches the soil surface.

2006 Whole Field MITC Emissions for BMP Chemigation and Shank Injected Circles



MITC concentrations during two different methods of metam sodium application. MITC emission during the application was greatest with chemigation and was reduced with the use of soil injection. This work was conducted by the Food and Environmental Quality Lab at Washington State University. Source: http://www.doh.wa.gov/ehp/pest/wsumitc-08.pdf.

Studies have shown that MITC diffusion into the atmosphere and MITC emissions from soil occur at a higher rate when metam sodium is applied by chemigation as compared to soil injection (Saeed et al., 2006). Soil injection is an application method where metam sodium is injected directly into the soil with field equipment at soil depths of five inches and greater. The equipment setup is similar to that of cultivation, including rippers, shanks, chisels, covering discs, and rollers.

A Washington State University (WSU-MITC group) study also showed the difference in volatility between chemigation and soil injection. The maximum off-target MITC concentration from two study fields were 90 and 320 parts per billion during chemigation, as compared to only 10 and 50 parts per billion during soil injection (http://www.doh.wa.gov/ehp/pest/wsumitc-08.pdf).

When MITC is in the soil it can be lost through another volatilization process known as soil emission. Both chemigation and soil injection of metam sodium are subject to soil emission of MITC. The closer MITC is to the soil surface, the more likely it could volatilize into the atmosphere and be lost, thus not available to impact pest populations in the soil.

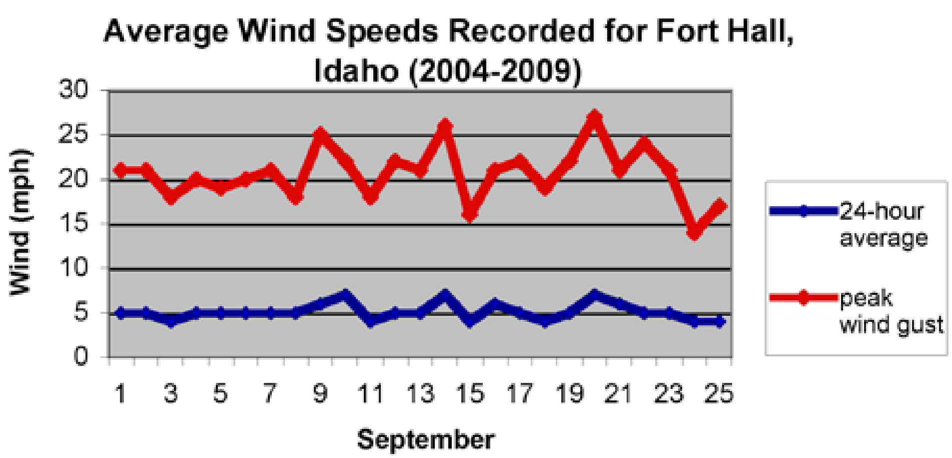
Application of metam sodium through soil injection places it directly in the soil, where the target pests are located. The longer that MITC resides in the soil, the greater the pest suppression.

Weather Conditions and MITC Drift

The third problem with chemigation is related to weather conditions. Drifting can occur with wind speeds as little as eight miles per hour (mph).

Weather records for a six-year period (2004 to 2009) in southeastern Idaho show that during the peak chemigation season (September 1 through October 20) approximately 15% of the days had an average wind speed of eight mph or more. These same weather stations also show that maximum wind gusts of 15 mph or more were almost a daily occurrence. To reduce metam sodium drift, the label for Vapam HL states that chemigation should cease if wind speeds exceed 10 mph.

It takes two to three days to chemigate metam sodium using center pivots. Consequently, chemigation occurs both day and night under varying weather conditions, which often results in drift. In contrast, soil injection on a 136-acre center pivot takes only eight to ten hours.



While the 24-hour average wind speed in the month of September from 2004 to 2009 ranged from 4 to 7 mph, the average peak wind gusts were much higher at 14 to 27 mph. These peak wind gusts exceeded the wind speed requirements for chemigation with metam sodium.

Reducing MITC Loss through Soil Injection of Metam Sodium

The best method of reducing MITC losses from drift and soil emissions is to replace chemigation with soil injection at depths of 8 to 12 inches, followed by a roller/packer to seal the soil. Application of metam sodium through soil injection places it directly in the soil, where the target pests are located. The longer that MITC resides in the soil, the greater the pest suppression.

MITC loss from soil emission using soil injection usually occurs when metam sodium is soil injected at depths of only two to five inches and with no roller/packer system following the injection.

MITC soil emission appears to be far less when soil injection is at eight inches or deeper and is followed by a soil packing system to seal the soil surface. The argument against this application depth is that *V. dahliae* is concentrated in the upper five inches of the soil. The soil injection process includes rippers and chisels, which mixes the soil to a depth greater than five inches. This mixing moves the top five inches, which may contain *V. dahliae*, deeper into the soil where the metam sodium is injected.

The value of soil injection over chemigation is that it places the desired amount of metam sodium more accurately, because it is injected directly into the soil with calibrated meters. Soil injection is also not impacted by weather conditions, as is chemigation.

Holley Brothers Custom Farming's equipment for soil injection of metam sodium. The injection tubing is connected to the rippers and "duck-foot" chisels, as a single injection port system set at a depth of 12 inches. The covering discs and the roller/packer (not pictured) are located behind the rippers and chisels and are used to seal the soil.

Seven Steps to GPS-Guided, Site-Specific Application of Metam Sodium

The technology of site-specific metam sodium application begins with soil sampling for plant-parasitic nematodes and *V. dahliae* using Global Positioning Systems (GPS). All soil sampling sites are geo-positioned using GPS and the pest data from those sites are incorporated into GIS (Global Information Systems) software, which is then used to create color-coded nematode and *V. dahliae* population density maps. These maps are then used to create the site-specific metam sodium application map. Metam sodium application rates vary across the field from zero to 50 gallons per acre, depending on the pest population densities. This application method uses soil injection in which metam sodium is applied directly into the soil at site-specific rates.

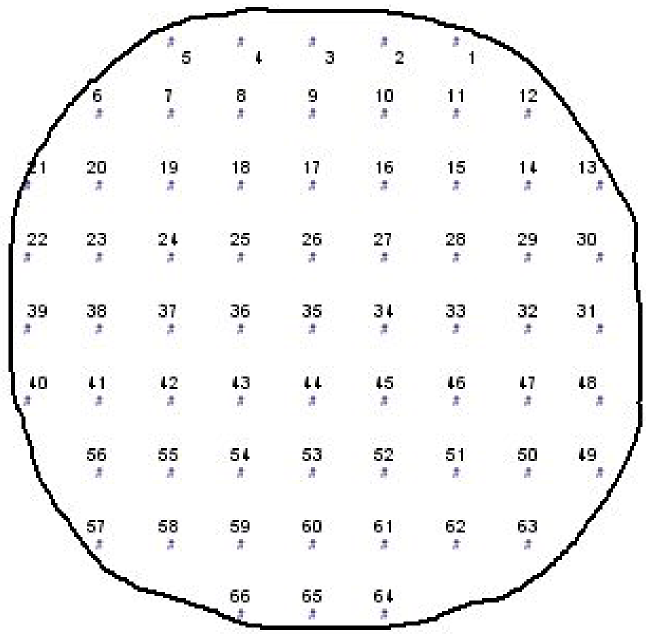
The following seven steps are followed by Western Ag Research LLC when we conduct GPS-guided, site-specific metam sodium applications.

Step 1 – Fixing Field Boundary and Soil Sampling Points by GPS

To lock in the field boundary, we drive a four-wheeler or truck around the edge of the field with a mounted GPS receiver. The field area is calculated by special GPS software. This method provides the most accurate acreage and identification of grid points within the field, with an error rate of only three to five feet. Other methods, such as aerial photos, often produce errors up to 30 feet or more.

A truck or four-wheeler with a mounted GPS receiver is driven around the perimeter of the field to lock in the field boundary.

Step 1: Geo-referenced grid points are established on a 136-acre field.



Once the field boundary is designated, most GPS data collection software packages will request the desired grid size for a soil sampling plan and then automatically fix the geo-referenced positions for the soil sampling sites within the designated field boundary.

Step 2 – Collecting and Analyzing Individual Soil Samples

The typical nematode sampling procedure often involves collecting several cores of soil from a 120- to 160-acre field and then combining the cores into one soil sample for a single nematode analysis. Growers then decide to treat the entire field based upon results of this single composite sample.

In grid-based sampling for nematodes, soil samples are collected individually on a grid that often varies from 1.85 to 3.00 acres. Western Ag Research LLC uses a two-acre grid for nematode mapping. The two-acre grid can be used for all nematode types that are common in potatoes—root lesion, stubby root, and root knot. The two-acre grid is also adequate for acquiring accurate spatial data of the *V. dahliae* population in the field.

A 136-acre pivot on a two-acre grid contains 60 to 70 individual soil sampling sites, depending upon field layout.

Each soil sample is actually a composite of five to ten soil cores collected within 45 to 65 feet of the geo-referenced grid point.

Step 2: Soil samples are collected for laboratory analysis of nematodes and *Verticillium.*

Each site of soil collection is mapped via GPS. The soil sample collected at each grid point is actually a composite of several sampling cores collected within 45 to 65 feet of the geo-referenced grid point.

For nematodes, especially root knot and stubby root, we suggest at least eight to ten sampling cores at each grid-point due to the patchy and sporadic nature of their distribution. Soil sampling for root-lesion nematode only requires five to seven sampling cores at each grid point, because of their wider distribution. Each composite sample is analyzed for root-lesion nematodes, other plant parasitic nematodes, and *V. dahliae* per 250 cc soil.

Step 3: Root-lesion nematode and *V. dahliae* counts and sampling sites are entered into GIS software.

Shape	Sampleid	Longitude	Latitude	RL	vert	PED	MS
Point	1	-112.36271240	43.41087744	250	120	3	50
Point	2	-112.36384519	43.41087744	780	132	3	50
Point	3	-112.36497834	43.41087744	400	28	2	40
Point	4	-112.36611148	43.41087744	420	38	2	40
Point	5	-112.36611148	43.41170060	240	21	2	40
Point	6	-112.36497834	43.41170060	1080	58	3	50
Point	7	-112.36384519	43.41170060	1020	38	2	40
Point	8	-112.36271204	43.41170060	420	35	2	40
Point	9	-112.36157890	43.41252375	40	3	1	30
Point	10	-112.36271204	43.41252375	80	0	1	30
Point	11	-112.36384519	43.41252375	260	53	3	50
Point	12	-112.36497834	43.41252375	720	12	2	40
Point	13	-112.36611148	43.41252375	60	14	1	30
Point	14	-112.36611148	43.41334676	80	3	1	30
Point	15	-112.36497834	43.41334676	600	16	1	30
Point	16	-112.36384519	43.41334676	60	60	2	40
Point	17	-112.36271204	43.41334676	300	20	1	30
Point	18	-112.36157890	43.41334676	720	33	2	40
Point	19	-112.36271204	43.41416975	80	38	2	40
Point	20	-112.36384519	43.41416975	1080	10	1	30
Point	21	-112.36497834	43.41416975	300	23	1	30
Point	22	-112.36611148	43.41416975	120	58	3	50
Point	23	-112.36611148	43.41499287	2400	19	3	50
Point	24	-112.36497834	43.41499287	120	37	2	40
Point	25	-112.36384519	43.41499287	600	48	2	40
Point	26	-112.36271204	43.41499287	300	13	1	30
Point	27	-112.36157890	43.41499287	240	16	1	30
Point	28	-112.36157872	43.41581598	960	20	1	30
Point	29	-112.36271186	43.41581598	660	8	1	30
Point	30	-112.36384501	43.41581598	300	7	1	30
Point	31	-112.36497834	43.41581598	420	0	1	30
Point	32	-112.36611148	43.41581598	240	14	1	30
Point	33	-112.36611148	43.41663920	960	1	1	30
Point	34	-112.36497816	43.41663920	960	0	1	30
Point	35	-112.36384501	43.41663920	840	21	1	30

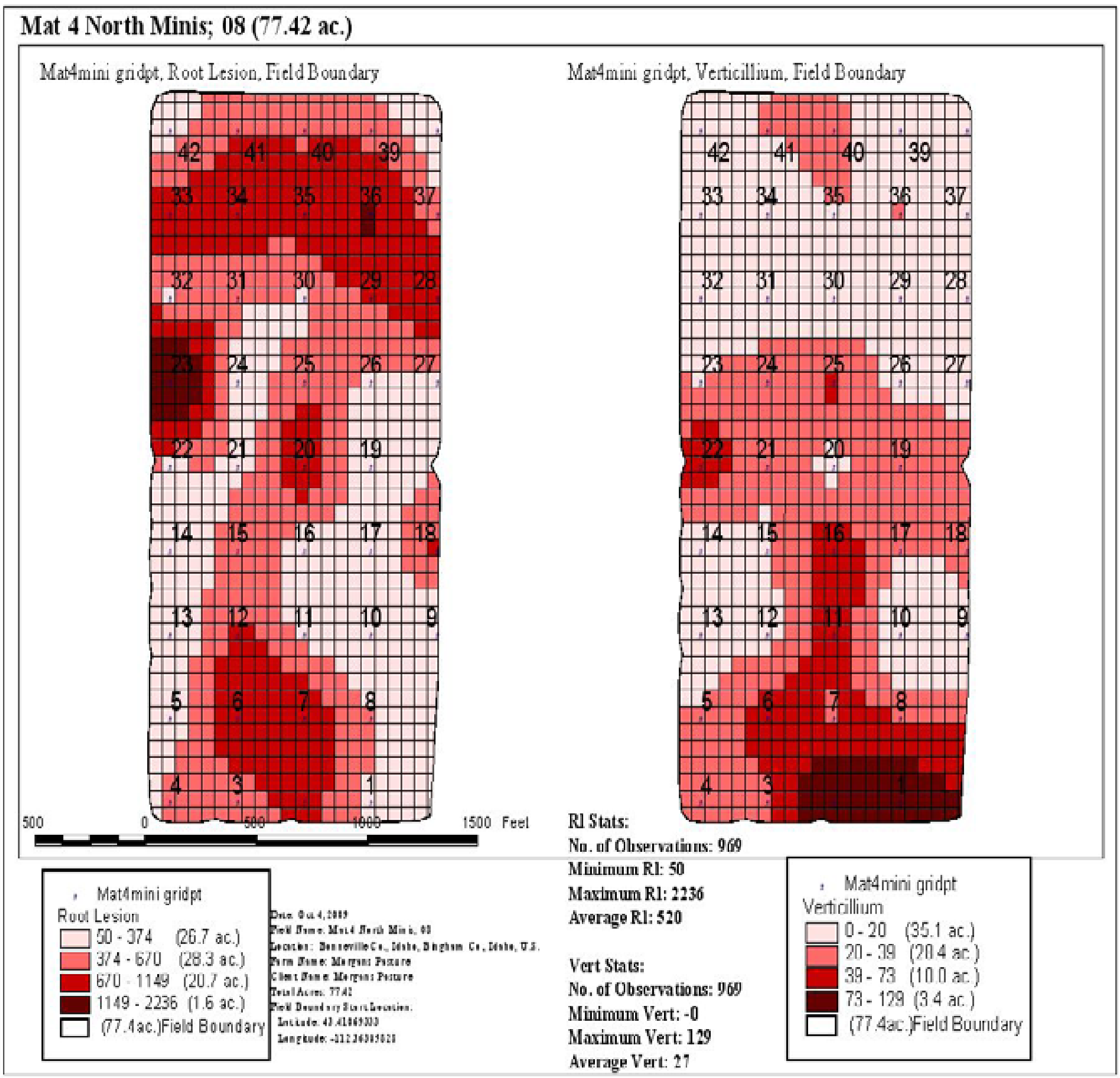
Step 3 – Entering Nematode and Verticillium Counts and Location in GIS Software

The number of root-lesion nematodes and *V. dahliae*, as well as the corresponding GPS location of each soil sample, is entered into a GIS software package. The root-lesion nematode and *V. dahliae* data are geo-referenced to the known GPS locations within the field. This information is used in the next step, to map the root-lesion nematode and *V. dahliae* populations.

Step 4 – Generating Spatial Maps of Root-Lesion Nematode and *V. dahliae* Populations

The next step is to create a map of the root-lesion nematode and *V. dahliae* populations across the field using a GIS software program and the data entered in step 3. These maps are developed using interpolation models based upon the pest population at each sampling point. Interpolation is a mathematical evaluation of pest populations in areas that were sampled and then autocorrelated to the areas that were not sampled, since they were located outside of the grid points.

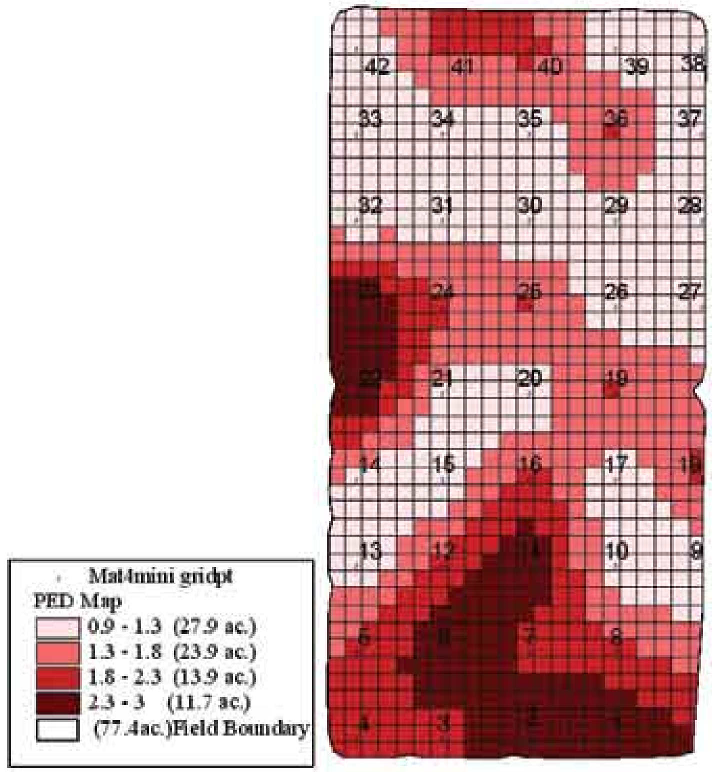
Step 4: Spatial maps of root-lesion nematode and *V. dahliae* populations are generated.



The most popular interpolation model in site-specific agriculture is kriging. Kriging is not simple mathematics. We rely on computers and the GIS software programs to quickly complete these complex calculations. Kriging is done between known nearby soil sampling points that were collected in the two-acre grids to generate values for areas in the field that were not directly sampled for nematodes and *V. dahliae*. These data, both the sampled values and GIS-software generated values, are used to make a color map that clearly shows the root-lesion nematode and *V. dahliae* populations in a field.

In the example map that was grid-sampled in 2008, the darker red areas indicate higher root-lesion nematode populations and the lighter red areas show lower root-lesion nematode population levels. The same color scheme is used to map *V. dahliae* populations within a field.

At the end of step 4, we have two separate maps showing the population densities of root-lesion nematode and *V. dahliae.*



Step 5: A single map is generated, called the Potato Early-Die (PED) risk map, from the population levels of both root-lesion nematodes and *V. dahliae.*

Step 5 – Generating PED Risk Map of Root Lesion and *V. dahliae* Data

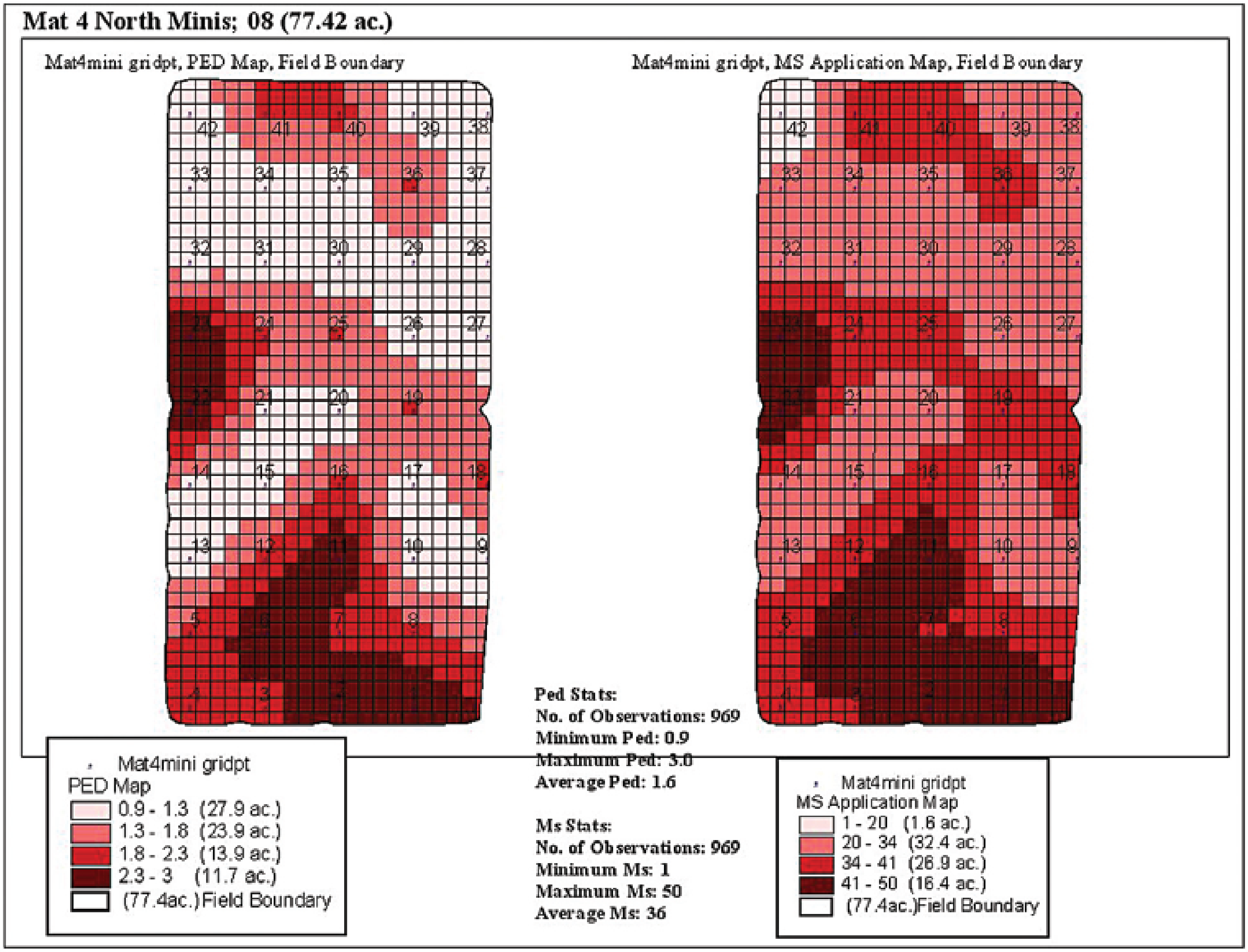
One of the difficulties of making a site-specific metam sodium application map is that the populations of root-lesion nematodes and *V. dahliae* are rarely similar across a field.

It is the interaction of these two pests that is important in potato early-die, which is characterized by early death of the potato plant and attributed to infection by *V. dahliae*. *V. dahliae* infection is exacerbated by infection of root-lesion nematodes, so it is important to develop a map for site-specific metam sodium application based upon both of these pests.

In 2001, Bird et al. addressed this issue by developing a map which represents both pests and is referred to as a Potato Early-Die (PED) risk map. Bird's PED risk map uses a three-level scaling system that shows the potential for potato early-die risk, based upon the population of root-lesion nematode and *V. dahliae* at each sampled and generated point. One is the lowest pest density and PED rating and three is the highest pest density and PED rating. The scaling system is unique in that it accounts for the often dissimilar distribution of root-lesion nematode and *V. dahliae* populations in a single map.

After the PED map is made, metam sodium rates are then assigned to this PED rating system in the next step.

Bird's three-level rating system was based on the metam sodium application rates of 0, 37.5, and 75 gallons per acre for the PED ratings of one, two, and three, respectively. Western Ag Research uses a four-scale system for most fields, where PED level one is not treated with metam sodium and PED level two is treated with 20 to 25 gallons per acre. PED levels three and four are treated with 30 to 50 gallons per acre, depending on the farmer's comfort level and the field history. Western Ag Research uses Bird's three-level scaling system in fields with higher pest densities, when all areas of the field are treated.



Step 6: A metam sodium application rate is assigned to each PED level and varies from field to field, based upon pest population levels and field history.

Step 6 – Making a Metam Sodium Application Map

The metam sodium application map is developed based upon the PED map from step 5 and the field history. We consult with the farmer or farm manager to determine if there are any variations we should make from the PED map based upon field history and the farmer's comfort level with the new technology. We also work with the farmer to determine which metam sodium rate to apply to each PED level.

In the example map shown here the pest levels are fairly high, so only three treatment levels were used. We treated with 30, 40, and 50 gallons per acre for the PED scales of one, two, and three, respectively. If PED levels were lower, then a possible scenario would be 0, 20, and 30 gallons per acre, respectively. The PED scale system is not fixed; it is field specific.

The full field view of the metam sodium application map on the display screen, located inside the tractor cab and in view of the operator.

Step 7—Sending the Map to a GPS Guided Applicator

The metam sodium application map created in step 6 is then saved as a "shapefile" (.dbf, .shp, .shx). The shapefile is usually sent via email to the applicator and is then used for the site-specific application. The shapefile system is a universal system that is accepted by almost all controller systems used in site-specific agriculture.

The shapefile map is used by the software located inside the tractor cab. The software system can be a Raven, John Deere, Ag Leader, or several others. The computer software such as the Raven Viper system recognizes the PED map and uses the prescribed rates to determine how much metam sodium is applied in each area of the field.

The display screen shows progress of the metam sodium application. The green-shaded area shows the portions of the field that have already been treated.

The Effect of Metam Sodium Application Method on Potato Yields and Pests

Table II is a summary of the effect of three metam sodium application methods on potato yield and the suppression of root-lesion nematode and *V. dahliae*.

We measured yields and pest levels in 36 fields treated with the different application methods for a total of 5,446 acres. Twelve fields were treated with each of the following application methods: (1) site-specific application of metam sodium using soil injection, (2) uniform metam sodium application using soil injection, and (3) chemigation of metam sodium. This work was funded in part by the U.S. Department of Agriculture and the Environmental Protection Agency.

The average metam sodium application for the 12 site-specific, 12 uniform, and 12 chemigated fields was 31.7, 36.0, and 36.9 gallons per acre, respectively. Thus, site-specific injection resulted in 65,815 pounds less metam sodium applied as compared to chemigation in the test fields.

On each of the 36 project fields, five separate soil samples were collected and each soil sample was a composite of seven to ten cores down to a 12-inch soil depth. This was done before the crop was planted and again four to six days before the vines were sprayed for harvest. The data show that there were no differences in root-lesion nematode or *V. dahliae* levels between the three application methods.

Yields were determined by the total number of trucks loaded at harvest for each field and with cellar measurements. We estimated the number of sacks per truck (10-wheeler) load at 240 and 265 for loam fields and sand fields, respectively, based on our experience. If 252 trucks were harvested on a loam soil, then there would be 60,480 sacks harvested from this field. On a 136-acre field, this would be 445 sacks per acre.

We then compared our in-field yield estimates to the quantity of potatoes loaded into the cellar. If the potatoes were loaded into a 70,000 sack cellar that had 20 plenums and 18.5 plenum areas were used, then [18.5/20 * 70,000] = 64,750 sacks, or about 476 sacks per acre.

We then used the two figures to provide a final estimate of the sacks per acre. In this example field, the estimate showed 445 sacks were loaded onto the trucks and 476 sacks were stored in the cellar, for a final estimate of 460 sacks per acre. We used this method of estimating yield on 32 of the 36 fields. Farmers provided actual truck weights on the other four project fields.

The site-specific metam sodium applied fields had the highest average yield, but all yields from the three metam sodium application methods were basically the same.

In summary, our study showed that soil injection was equal to chemigation in yields and the suppression of root-lesion nematode and *V. dahliae*.

TABLE II: Average nematode and Verticillium levels in soil samples collected from fields treated with three different metam sodium application methods. Fields were treated with metam sodium in the fall of 2008 and five soil samples were collected per field site in the spring and fall of 2009.

Site	Spring 2009		Fall 2009		Total Yield
	Root-Lesion Nematode	Verticillium	Root-Lesion Nematode	Verticillium	
Site-specific soil injection of metam sodium					
A1	18	7	0	1	484
A2	5304	27	324	2	407
A3	4	25	36	3	490
A4	194	14	26	9	515
A5	72	21	456	13	475
A6	24	18	74	4	510
A7	496	5	8	1	490
A8	40	33	456	3	440
A9	336	18	44	18	420
A10	112	13	8	2	355
A11	28	50	204	1	425
A12	2360	10	188	1	395
Average	**749**	**20**	**152**	**5**	**451**
Uniform soil injection of metam sodium					
B1	60	10	24	1	360
B2	244	23	4	1	465
B3	60	11	16	1	410
B4	8	17	98	1	475
B5	80	27	702	7	475
B6	20	22	600	1	475
B7	112	10	136	3	495
B8	44	12	892	2	460
B9	26	9	4	3	390
B10	68	39	0	1	385
B11	112	7	506	1	415
B12	24	11	196	10	395
Average	**72**	**17**	**265**	**3**	**433**
Chemigation of metam sodium					
C1	4370	21	142	6	426
C2	44	9	0	2	518
C3	4	28	6	2	445
C4	12	25	108	4	450
C5	4	4	0	45	490
C6	2	6	4	8	465
C7	0	16	4	16	395
C8	940	15	54	3	410
C9	52	25	100	6	425
C10	12576	8	1656	1	450
C11	22	0	32	2	330
C12	2028	14	492	14	420
Average	**1671**	**14**	**217**	**9**	**435**

Matching Metam Sodium Rates to Root-Lesion Nematode Levels

We were also interested in tracking root-lesion nematode levels in areas of the field that were treated with different rates of metam sodium. We collected soil samples on a two-acre grid before metam sodium application in the fall of 2008, as usual for site-specific injection. Then we collected from those same sites again in September to October 2009. We did this follow-up sampling to demonstrate whether or not reduced metam sodium rates were adequate for managing low root-lesion nematode population levels.

Olthof (1989) studied root-lesion nematode populations that were treated with two metam sodium rates. The study showed that a very high density of root-lesion nematodes (19,600 per 750 cc soil) treated with 37.5 and 20 gallons of metam sodium per acre was reduced by 90% and 63%, respectively. Olthof also studied the impacts of these two metam sodium rates on a root-lesion nematode population of 1,370 per 750 cc soil and found a 99% and 88% reduction, respectively.

TABLE III: Root-lesion nematode levels per 250 cc soil from grid sites treated with different rates of metam sodium by soil injection. Soil samples were collected before metam sodium application in fall 2008 and after the potato growing season in fall 2009. Soil type was silt loam.

25 gal/acre		
Grid	Fall 2008	Fall 2009
3	840	240
10	600	80
11	660	720
21	340	40
33	140	0
Ave:	**516**	**216**

30 gal/acre		
Grid	Fall 2008	Fall 2009
8	1080	120
28	1800	300
38	1200	0
44	1260	100
48	1200	0
Ave:	**1308**	**104**

35 gal/acre		
Grid	Fall 2008	Fall 2009
5	1500	60
6	1680	40
15	1740	40
18	1800	0
22	1800	200
24	1740	0
32	1620	0
34	1560	60
42	1740	20
45	1980	20
47	1500	40
51	1620	60
Ave:	**1690**	**45**

40 gal/acre		
Grid	Fall 2008	Fall 2009
2	2160	160
16	2160	40
20	2220	0
27	2040	20
31	2340	80
40	2460	20
41	2640	20
52	2220	0
55	2220	0
Ave:	**2273**	**38**

45 gal/acre		
Grid	Fall 2008	Fall 2009
14	2580	80
17	2940	20
50	2820	0
54	2520	60
Ave:	**2715**	**40**

50 gal/acre		
Grid	Fall 2008	Fall 2009
1	5040	60
4	5760	420
7	7920	1140
9	3660	80
12	6600	0
13	3840	100
19	3900	100
23	4680	20
25	5880	60
26	3840	0
29	4500	360
30	7800	20
35	3840	40
36	3120	0
37	3120	0
39	5340	0
43	4800	20
46	3180	100
49	3180	40
53	3840	60
Ave:	**4692**	**131**

In summary, Olthof found that the higher root-lesion nematode densities were suppressed with 20 gallons of metam sodium per acre, but not as much as with the 37.5 gallon rate. In contrast, the percent reduction at the lower root-lesion nematode densities was much more similar for the 37.5 and 20 gallons of metam sodium. This indicates that at lower root-lesion nematode levels, acceptable suppression can occur with reduced metam sodium rates.

When we looked at those areas of the field with the lower root-lesion nematode densities, Western Ag Research found similar results for our fields in eastern Idaho as did Olthof (1989). In the project field shown in Table III, we matched metam sodium rates with the different root-lesion nematode levels found in fall 2008 before application. Then we collected soil samples the following year and measured root-lesion nematode levels to see what effect the different site-specific metam sodium application rates had on nematode levels. These data showed that there was no difference in root-lesion nematode levels between the different metam sodium application rates after harvest in 2009.

Matching Metam Sodium Rates to *Verticillium dahliae* Levels

One of the biggest benefits of metam sodium is reducing the effects of *V. dahliae* on crop yields. We measured *V. dahliae* levels in soil samples collected after harvest in 2009 from all of the sites that were treated with different metam sodium rates. We found that the *V. dahliae* levels were the same, regardless of the metam sodium rate applied to the site (Table IV).

TABLE IV: *Verticillium dahliae* (Vd) levels from grid sites treated with different rates of metam sodium by soil injection. Soil samples were collected after the potato growing season in fall 2009. Soil type was silt loam.

25 gal/acre		30 gal/acre		35 gal/acre		40 gal/acre		45 gal/acre		50 gal/acre	
Grid	Vd cfu	Grid	Vd cfu	Grid	Vd cfu	Grid	Vd cfu	Grid	Vd cfu	Grid	Vd cfu
3	28	8	0	5	24	2	25	14	18	1	8
10	14	28	39	6	15	16	34	17	27	4	43
11	19	38	26	15	21	20	21	50	33	7	12
21	13	44	41	18	27	27	5	54	36	9	0
33	45	48	25	22	0	31	19	**Ave:**	**29**	12	29
Ave:	**24**	**Ave:**	**26**	24	53	40	17			13	13
				32	23	41	28			19	12
				34	42	52	34			23	39
				42	28	55	16			25	44
				45	34	**Ave:**	**22**			26	23
				47	13					29	31
				51	43					30	35
				Ave:	**27**					35	28
										36	45
										37	21
										39	6
										43	32
										46	58
										49	13
										53	0
										Ave:	**25**

Grid Size and Accurate Mapping of Nematode Populations

Western Ag Research has determined that a two-acre grid should be used for collecting soil samples and analyzing nematode populations in fields prepared for potatoes.

Using geo-statistical software, we have checked the spatial correlation of the two-acre grid, which now represents our database of more than 6,700 soil samples on 14,500 acres, for the main problem-causing nematodes affecting potatoes—root lesion, Columbia root knot, and stubby root. The software measures the correlation of the nematode density to the distance from the sampling point and is reported by the r^2 value and range. The closer the r^2 value is to 1.00, the higher the correlation. The correlation for nematodes in our 6,700 soil samples collected on two-acre grids is $r^2 = 0.60$ at a distance of 600 feet. Since a two-acre grid is 295 feet between soil sampling points, we actually have reliable spatial correlation to twice that distance, slightly surpassing eight acres (600 ft x 600 ft).

While our database of *V. dahliae* samples is not as extensive as our nematode database, the spatial correlation using two-acre grids is $r^2 = 0.74$ at a distance of 550 feet for 450 soil samples.

The debate on what is the most accurate size of grid for grid-based soil sampling for nematodes will always lead to an infinite regression. Someone could effectively demonstrate that one-acre grids are more accurate than two-acre grids. Then another could show half-acre grids are better. This would quickly grow to an unmanageable number of soil samples and thus unacceptable cost.

The key to the success of the two-acre grid is soil sampling technique and map interpretation. Soil samples should not be pulled at the grid point only as this will not account for variability in that area. The soil sampling technique should involve collecting five to ten cores while walking a radius of 45 to 65 feet from the grid point. This method will account for some of the variability in that area. Map interpretation is based on how one assigns the PED scales to the pest densities found in the soil samples.

We compared root-lesion nematodes with two grid soil sampling methods on a 34-acre mini pivot. We wanted to compare our two-acre grid regime with that of a more intensive soil sampling method using half-acre grids. We soil sampled in October 2008, before metam sodium application, and again in October 2009 using the same GPS coordinates after potato harvest (Table V).

TABLE V: Root-lesion nematodes were measured in 63 soil samples in the half-acre grid and 15 soil samples in the two-acre grid. The average of these soil samples is shown for each date. Soil type was sandy loam.

	HALF-ACRE GRID		TWO-ACRE GRID	
Sampling Date	Oct 2008	Oct 2009	Oct 2008	Oct 2009
Root-lesion nematodes	718 ± 740	35 ± 94	939 ± 658	183 ± 353
r^2	0.98	0.90	0.97	1.00
Range (ft)	1,480	490	560	890

The Future of Site-Specific Application of Metam Sodium

The future of site-specific application of metam sodium looks promising. Nearly all tractors owned by farmers are now equipped with GPS. Many farmers are now doing variable rate starter fertilizer applications themselves when they mark-out in fall beds. Farmers can also do site-specific application of metam sodium themselves, especially if done during fall bedding.

Fall bedding is a technique where farmers make their rows for potatoes using GPS in the fall months, instead of springtime. This allows the soil to dry quicker in spring so they can more quickly plant potatoes when conditions are favorable.

In the fall bedding process, farmers often choose to apply metam sodium using soil injection at uniform rates between 20 to 30 gallons per acre. Fall bedding has become a common practice and could easily be modified slightly to include the site-specific application of metam sodium.

Most farmers already have all of the hardware needed to do site-specific metam sodium applications: GPS-guided tractors and controllers. They only need to acquire the software to read the site-specific application maps, which costs approximately $2,000. The widespread adoption of GPS-guided tractors and the advancement in site-specific applications will likely support the rapid expansion of site-specific metam sodium injection for the management of root-lesion nematodes and *V. dahliae* in potato production.

A farmer applying metam sodium at uniform rates during fall bedding. His tractor and application equipment have the hardware for site-specific metam sodium application already in place. Only the software for reading site-specific application maps is needed in order to perform a site-specific metam sodium application.

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SPATIALLY DISTRIBUTED CONTROL NETWORK FOR FLOW PROPORTIONAL CHEMICAL INJECTION WITH CENTER PIVOT SPRINKLER IRRIGATION

B. A. King, R. W. Wall, J. P. Taberna Jr.

ABSTRACT. *The agricultural production practice of injecting a chemical into an operating irrigation system and applying it to the field area with the water is known as chemigation. Chemigation is a widely adopted practice with center pivot sprinkler irrigation. However, the practice of chemical injection at a constant rate with center pivot sprinkler irrigation systems equipped with an end gun and/or swing-arm corner watering system results in systematic chemical application errors ranging from 7% to 21% due to systematic changes in system flow rate. Chemical injection proportional to center pivot sprinkler system flow rate is one approach to reduce systematic chemical application errors. The objective of this project was to test the feasibility of using real-time monitoring of center pivot sprinkler irrigation system operating status to control chemical injection rate proportional to calculated system flow rate, thus minimizing systematic chemical application errors. A spatially distributed control network was developed to facilitate real-time monitoring of end gun and swing-arm corner watering system operating status and pressure. The spatially distributed control network consisted of three network nodes at specific locations along a center pivot sprinkler irrigation lateral that used the 480 VAC 3-phase power cable on the center pivot sprinkler irrigation system as the communication medium. The spatially distributed control network was installed on a commercial 460-m (1510-ft) long center pivot sprinkler system equipped with an end gun and swing-arm corner watering system. Performance of chemical injection proportional to calculated flow rate based on real-time center pivot sprinkler irrigation system operating status was evaluated by injecting Rhodamine WT dye into the center pivot sprinkler irrigation system water supply and measuring its concentration in the applied water. Mean dye concentration varied by 26% under constant rate chemical injection and 2% under flow proportional chemical injection due to systematic changes in center pivot sprinkler irrigation system flow rate. Use of the flow proportional chemical injection system reduced the coefficient of variability in measured dye concentration of applied water by 54% from 0.100 to 0.046. Use of the spatially distributed control network for calculating center pivot sprinkler system flow rate eliminates the need for straight sections of unobstructed piping at the chemical injection site. Display and/or data logging of real-time center pivot sprinkler operating status is an added benefit of using the spatially distributed control network. This information provides the ability to monitor, diagnose, and troubleshoot center pivot sprinkler system operation. Commercialization and adoption of the technology could reduce systematic chemical application errors and facilitate maintenance and operation of center pivot sprinkler irrigation systems equipped with an end gun and/or swing-arm corner watering system.*

Keywords. *Irrigation, Center pivot, Site-specific, Chemigation, Application uniformity.*

The agricultural production practice of injecting a chemical into an operating irrigation system and applying it to the field along with the water is generically known as chemigation (Threadgill, 1985). Chemigation is an effective means of economically and efficiently applying chemicals (Bynum et al., 1991; Sumner et al., 1991; Archer et al., 1991; Barnes et al., 1992; Weissling et al., 1992; Chandler and Sumner, 1993; Chalfant et al., 1993; Culbreath et al., 1993; Chandler et al., 1994; Brenneman et al., 1994; Waller et al., 1995; Hamm and Clough, 1999). When practiced with center pivot sprinkler irrigation, the primary advantages of chemigation include high application uniformity of applied chemical, timeliness of applying the chemical when needed, and avoidance of compaction and crop damage caused by conventional ground-based application equipment (Threadgill, 1985). Intuitively, the ability to periodically apply nitrogen fertilizer during the growing season according to crop need minimizes the potential for nitrogen leaching from over-irrigation or untimely rainfall events. The advantages of chemigation such as timing and frequency of application can make it part of a nitrogen Best Management Practice (BMP) for various crops (Scherer et al., 1999; Lamm et al., 2004). Beyond environmental advantages, in-season application of nitrogen fertilizer through the irrigation system can increase nitrogen use efficiency, crop yield, and

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quality. For example, application of nitrogen fertilizer after potato tuber initiation has been shown to increase marketable yield while increasing nitrogen use efficiency (Lauer, 1986, 1985; Westermann et al., 1988; Errebhi et al., 1998). In 1998, 35% of irrigated farms in the United States reported using chemigation for fertilizer application and 7% of irrigated farms reported using chemigation for chemical application (USDA, 1998).

High chemical application uniformity is a commonly cited advantage of chemigation with center pivot sprinkler irrigation (Threadgill, 1985). However, three criteria must be met in order to attain high chemical application uniformity using chemigation with center pivot sprinkler irrigation systems.

- Water application uniformity must be high by having a properly designed and installed sprinkler package as well as regular maintenance and visual inspection to correct clogging, nozzle wear, and pressure regulator failure.
- Travel speed of the system must be uniform across the field area by avoiding rutting and wheel slippage or significant differences in speed traveling uphill versus downhill.
- The chemical injection rate must be proportional to system flow rate to provide constant chemical concentration in the applied irrigation water.

This third criterion is not necessarily met in practice when use of end guns and/or swing-arm corner watering systems cause the water flow rate to change while the injection rate remains constant. This results in systematic chemical application errors due to the variable wetted radius of the irrigation system.

Eisenhauer and Bockstadter (1990) analyzed chemical application errors for center pivots equipped with a pressure regulated sprinkler package and an end gun and/or swing-arm corner watering system. They developed a series of equations to calculate average (area weighted) chemical application error for constant chemical injection rate with center pivot sprinkler irrigation systems. Based on the equations presented by Eisenhauer and Bockstadter (1990), average chemical application error for a center pivot sprinkler system equipped with an end gun located in the center of a square 65-ha (160-acre) field where the effective wetted radius of the system lateral is 396 m (1300 ft) with the end gun off and 427 m (1400 ft) with the end gun on, is 7.5% with a maximum error of 8.3%. Average chemical application error increases as the size of the square field area decreases and the end gun effective radius remains the same. Eisenhauer and Bockstadter (1990) calculated an average chemical application error for a pressure-regulated sprinkler package on a 390-m (1279-ft) center pivot sprinkler lateral equipped with an 80-m (262-ft) swing-arm corner watering system and an end gun with an effective radius of 20 m (66 ft) of 16% with a maximum error of 21%. This relatively high degree of variability in chemical application with center pivots equipped with a swing-arm corner watering system is rarely corrected or sometimes even recognized.

Proportional chemical injection systems are currently on the market that can be adapted to center pivot sprinkler irrigation systems but they are relatively expensive. These systems utilize a flow meter to measure the flow rate of the center pivot. The measured flow rate is then used to compute the chemical injection flow rate needed to maintain a set flow proportional injection rate. Modulating the speed of a motor or the stroke of the metering pump achieves the computed chemical injection flow rate. These systems work well when they are included in the initial design of the piping systems for turf irrigation, wastewater treatment, and industrial processes. However, their performance can be impaired when installed after the fact due to the presence of elbows, tees, and flow control valves which can create asymmetrical flow profiles and flow rotation. Closed conduit flow meters perform best when flow profiles are symmetric and do not rotate (James, 1988). Standard installation requirements for flow meters generally require unobstructed flow for a distance equivalent to 5 to 50 pipe diameters upstream and 5 to 10 pipe diameters downstream of the flow meter (James, 1988). Johnson et al. (2001) reported flow measurement accuracy's for an ultrasonic flow meter of ±5% when installed 10 pipe diameters downstream of flow disturbances and ±36.5% when installed close to flow disturbances. Water supply connections for center pivot sprinkler irrigation systems often do not include 10 to 60 pipe diameters in unobstructed flow length needed for accurate flow measurement. Neglected maintenance and the harsh outdoor environment can lead to calibration drift. Flow meters do not withstand the freezing and thawing cycles of cold climates and after a few years the bearings and other moving parts degenerate rendering the flow measurement device inoperable (Hla and Scherer, 2001).

The flow rate of a center pivot sprinkler irrigation system equipped with pressure regulators can be estimated based on knowledge of system operating pressure and sprinkler nozzle sizes. We hypothesize that by using spatially distributed control network technology for real-time measurement of end gun operating status and pressure and the operating status of valves along a swing-arm corner watering system, system flow rate can be calculated for pressure regulated sprinkler packages and subsequently used to control flow proportional chemical injection. This may allow for greater accuracy than using a flow meter, and at less cost and easier installation. The objective of this research was to evaluate the feasibility of using spatially distributed control network technology to control a flow proportional chemical injection system to minimize systematic chemical application errors.

Materials and Methods

A spatially distributed control network was developed for a center pivot sprinkler system by using the 480 VAC 3-phase power cable on the center pivot sprinkler irrigation system as the communication medium. The spatially distributed control network consisted of three network nodes operating in a master-slave configuration. The master network node was located at the pivot point and used to display current center pivot sprinkler operating state, log operational data at 5-min intervals, and control the flow rate of the chemical injection pump. One network slave node was located on the center pivot sprinkler lateral at the corner watering system swing joint and used to collect swing-arm sprinkler valve operating state and GPS location. The second network slave node was located on the center pivot sprinkler lateral at the drive wheel tower of the swing-arm and used to monitor pressure there and hence the operating status of the end gun.

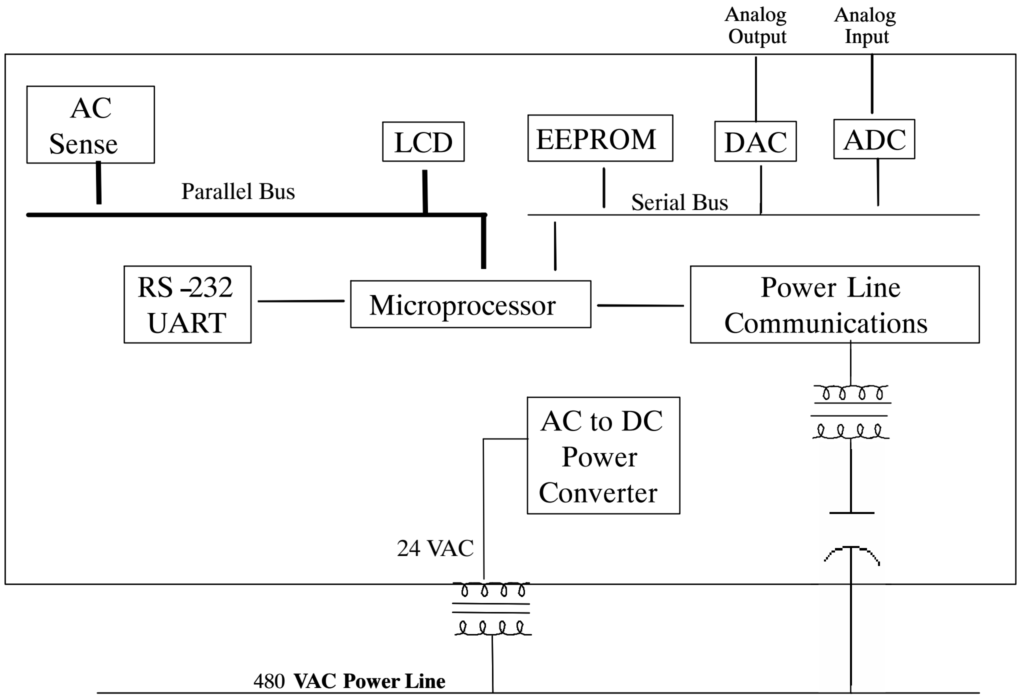

Figure 1. Block diagram of the PCB for network node that are fixed to the center pivot system and used for monitoring real-time operating status.

The electronic hardware for the control network was a single printed circuit board (PCB) that can function as either a master or slave network node. A block diagram of the key elements of the PCB is shown in figure 1. Power for the PCB is obtained from the 480-VAC power line using an external step-down transformer to provide nominal 24 VAC. Digital communications on the 480-VAC power line is implemented using proprietary integrated circuit chips from CEBUS (SSC P300 and SSC P111, Intellon Corp., Ocala, Fla.). A serial bus designed for communications between integrated circuits is used on the PCB for data transfers between the microprocessor and power line carrier interface. The same serial bus is used for data transfers between the microprocessor, EEPROM, a single-channel 10-bit DAC, and a single channel 10-bit ADC. A parallel bus on the PCB is used for data transfer between the microprocessor and a two-line, 16-character liquid crystal display (LCD) and sixteen 120-VAC sensing inputs. The AC sensing inputs are used to determine operating status of the sprinkler valve controller on the center pivot sprinkler swing arm. An asynchronous RS-232 serial interface provides for data transfer between a computer and other RS-232 serial devices such as a GPS receiver (GPS 17 HVS, Garmin International Inc., Olathe, Kans.) Software installed on the microprocessor determines whether the PCB functions as a master or slave network node. Based on real-time center pivot sprinkler system operating status collected using the spatially distributed control network, system flow rate was calculated as the sum of flow from each sprinkler along the center pivot sprinkler lateral up to the swing-arm joint, plus flow from each individual sprinkler on the swing-arm that was turned on, plus the flow from the end gun. Flow from the end gun was calculated based on verified nozzle size and measured pressure at the outlet of the booster pump.

The rate of chemical injection was controlled using a 0- to 5-VDC analog output from the master network node to control the motor speed of a positive displacement chemical injection pump (mRoy A/P, Agri-Inject, Inc., Yuma, Colo.) using a variable frequency drive (VLT MICRO 176F7312, Danfoss Drives, Loves Park, Ill.). Analog voltage output from the master node was determined based on calculated flow rates of the center pivot sprinkler irrigation system. The analog voltage output, A_{out}, was calculated based on real-time calculated flow rate of the center pivot sprinkler irrigation system, Q_c, and maximum calculated system flow rate, Q_{max}, as:

$$A_{out} = 5 \cdot \frac{Q_c}{Q_{\max}} \tag{1}$$

The spatially distributed control network was installed on a 10-span, 460-m (1510-ft) long center pivot sprinkler irrigation system equipped with an end gun and swing-arm corner watering system located near American Falls, Idaho, in May 2004. The field was planted to winter wheat. The center pivot sprinkler package was equipped with 138-kPa (20-psi) pressure regulators on each sprinkler to minimize variations in water application depth due to pressure fluctuations caused by multiple irrigation systems connected to the same water supply, and changes in flow rate and elevation as the center pivot sprinkler lateral traversed the field area. The nozzle size of every sprinkler on the system was determined by visual inspection. Based on the sprinkler manufacturer's nozzle flow rate data, the total design maximum flow rate of the center pivot sprinkler system was calculated as 4875 L/min (1288 gpm). The total maximum design flow rate of the swing-arm corner watering system and end gun combined was calculated as 1927 L/min (509 gpm) or 39.6% of total system flow rate. Constant rate chemical injection into this system can result in a 39.6% variation in chemical application rate between full extension and retraction of the swing-arm corner watering system and end gun operation.

Rhodamine WT dye was injected through the irrigation system to evaluate performance of the flow proportional chemical injection system. The dye was applied through the chemical injection system at a constant rate for one center pivot sprinkler system revolution beginning 5 June 2005 and at a flow proportional rate for one system revolution beginning 30 June 2005. Catch cans measuring 15.2 cm (6 in.) in diameter and 20.3 cm (8 in.) in height were placed on the ground within the crop canopy to collect water samples for dye concentration analysis. Crop canopy was fully developed and approximately 76 cm tall for both tests. The catch cans were placed at 5° angular increments around the field adjacent to the 7th center pivot tower wheel track. A 125-mL water sample from each catch can was collected and stored at 4°C until the dye concentration could be measured with a fluorometer (TD-7000, Turner Designs, Sunnyvale, Calif.). Water samples were collected twice daily at around 8 a.m. and 6 p.m. Average daily maximum and minimum air temperatures recorded at a weather station located within 19 km (12 miles) of the field test site were 25°C and 9°C, respectively, with a mean daily relative humidity of 59% over the field test duration. No precipitation occurred during the field tests.

A pressure sensor (PX209-100G5V, Omega Engineering Inc, Stamford, Conn.) located on the center pivot swing arm was hydraulically connected such that it measured the pressure at the outlet of the end gun booster pump. When the pump and end gun was on, the measured pressure represented end gun operating pressure and when the pump and end gun was off, the measured pressure represented the pressure in the center pivot swing arm lateral at that location.

Results and Discussion

Pressure at the outlet of the end gun booster pump logged by the spatially distributed control network as a function of center pivot lateral angular location determined from logged GPS location of the center pivot swing-arm pivot point (tower 9) is shown in figure 2A and 3A for constant and flow proportional injection tests, respectively. Operating status of the end gun is also shown in figure 2A and 3A to aid in interpreting system operation. Comparing figures 2A and 3A revealed that pressure and end gun operation of the center pivot sprinkler irrigation system were very similar for both injection tests. Center pivot irrigation system pressure was slightly lower on occasions during the constant injection test compared to the flow proportional injection test (e.g. 220° angular location). The sprinkler pressure regulator manufacturer recommends a minimum of 21 kPa (3 psi) above the pressure rating of the regulator for proper operation. The end gun pump added approximately 172 kPa (25 psi) to system lateral pressure when it was on. Thus, the minimum pressure for proper system operation was approximately 159 kPa (23 psi) when the end gun was off and 331 kPa (48 psi) with the end gun on. The center pivot lateral traversed the highest field elevations at about 190° to 260° angular location during which the center pivot swing-arm lateral sprinklers were fully on along with the end gun, representing the critical design condition for the center pivot sprinkler system. Examination of measured operating pressure for the constant injection test (fig. 2A) reveals that the center pivot sprinkler system briefly operated at pressures below the minimum design requirement, with the likely cause being startup of other irrigation systems connected to the same water supply. The consequence of this is that actual flow rate will be less than calculated flow rate based on 138-kPa (20-psi) sprinkler nozzle pressure. Thus, chemical injection proportional to calculated flow rate would be in error, resulting in a greater concentration of applied chemical than desired during this period.

Calculated center pivot irrigation system flow rate is shown in figures 2B and 3B for constant and proportional injection tests, respectively. Calculated flow rate ranged from a high of 4875 L/min (1288 gpm) when the swing-arm lateral sprinklers were fully on along with the end gun to a low of 3330 L/min (880 gpm) when the swing-arm was retracted and the end gun was off, resulting in a flow rate variation of 31.7%. The computed minimum flow is greater than the design minimum flow of 2952 L/min (780 gpm) because two of the sprinkler banks on the center pivot swing-arm were not functioning (turning off as designed). This potential problem was overcome by calculating flow rate of the system as it was operating rather than as designed. The producer was asked to correct the problem but was unsuccessful. Thus, the range in system flow rate shown in figures 2B and 3B is representative of actual field conditions and not actual system design specifications.

Measured dye concentration in the applied irrigation water as a function of center pivot lateral angular location is shown in figures 2B and 3B for the constant and flow proportional chemical injection tests, respectively. With constant chemical injection (fig. 2A), when center pivot sprinkler irrigation system flow rate increased or decreased,

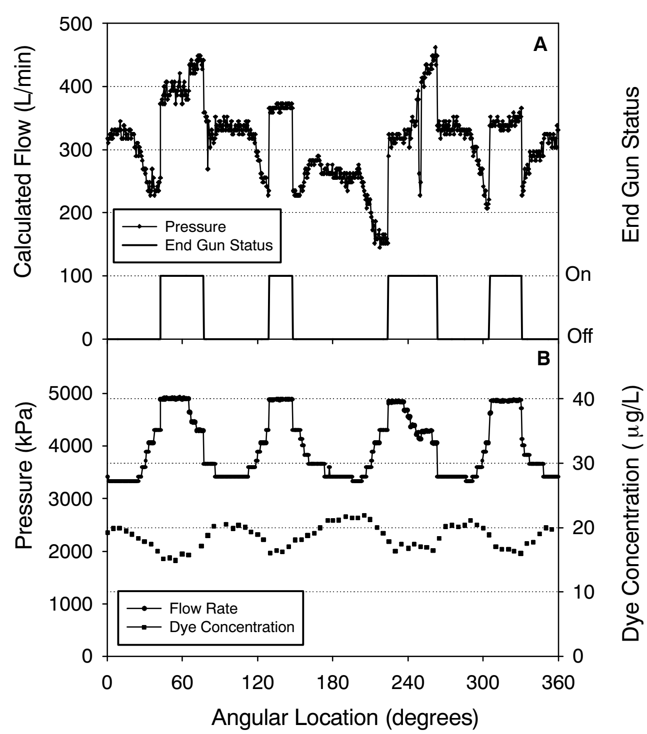

Figure 2. Pressure measured at outlet of end gun booster pump and end gun operating status (A) and calculated flow rate and measured dye concentration (B) as a function of system lateral angular location for constant rate chemical injection.

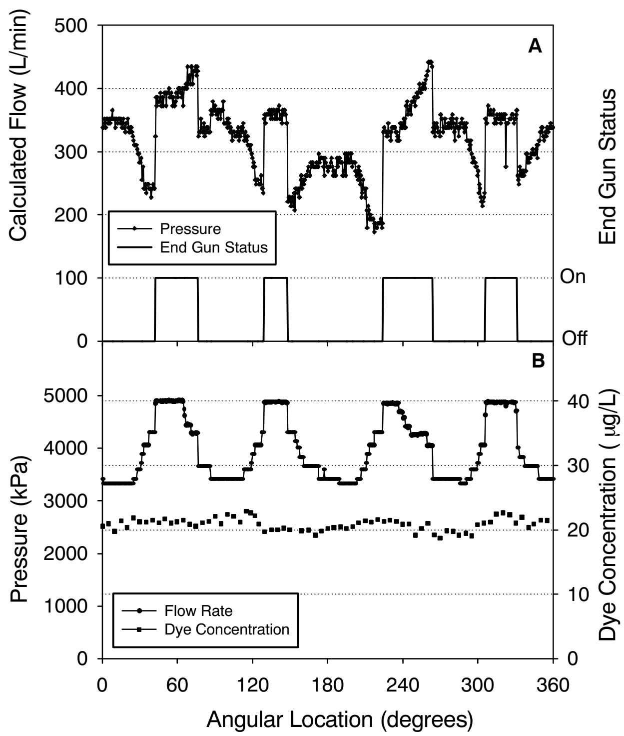

Figure 3. Pressure measured at outlet of end gun booster pump and end gun operating status (A) and calculated flow rate and measured dye concentration (B) as a function of system lateral angular location for flow proportional chemical injection.

measured dye concentration in the applied irrigation water decreased or increased accordingly in inverse proportion. The coefficient of variation in measured dye concentration with constant chemical injection was 0.10. Linear regression analysis of measured dye concentration with calculated center pivot sprinkler system flow rate for constant chemical injection results in an R^2 of 0.74 (fig. 4), thus calculated flow rate accounts for 74% of the variation in measured dye concentration. The variation in mean measured dye concentration with constant chemical injection over the calculated range in flow rate is 26%. With flow proportional chemical injection (fig. 3B), the mean measured dye concentration in the applied irrigation water varied 2% over the calculated range in center pivot sprinkler irrigation system flow rate. The coefficient of variation in measured dye concentration with flow proportional chemical injection was 0.046, a 54% reduction compared to constant rate chemical injection. Linear regression analysis of measured dye concentration with calculated center pivot sprinkler system flow rate for flow proportional chemical injection results in an R^2 of 0.04 (fig. 4), thus calculated flow rate accounts for only 4% of the variation in measured dye concentration. The small positive regression slope with flow proportional chemical injection is not significantly different ($p<0.01$) from zero. Thus, the method monitoring center pivot sprinkler irrigation system operating status to calculated flow rate eliminated systematic chemical application errors.

Considerable variation in measured dye concentration is present in figure 4 for both constant and flow proportional chemical injection despite removal of system flow rate variations due to the swing-arm corner watering system and end gun. The variation in measured dye concentration about the regression mean is approximately ±2 µg/L and consistent for both chemical injection tests. This variation in measured dye concentration can be the result of several potential sources of measurement error. The primary potential source of measurement error is due to evaporation from the catch cans. When water evaporated from the catch cans during the day, the dye concentration in the water sample increased. Thus, the amount of water evaporated from the catch cans between time of water application and water sample collection will affect the measured dye concentration. Since the water samples were collected an 8 a.m. and 6 p.m., the time for evaporation from the catch cans varied from 0 to 10 hours. For an irrigation application depth of 25 mm (1 in.), a potential evaporation estimate of 6 mm (0.24 in.) would

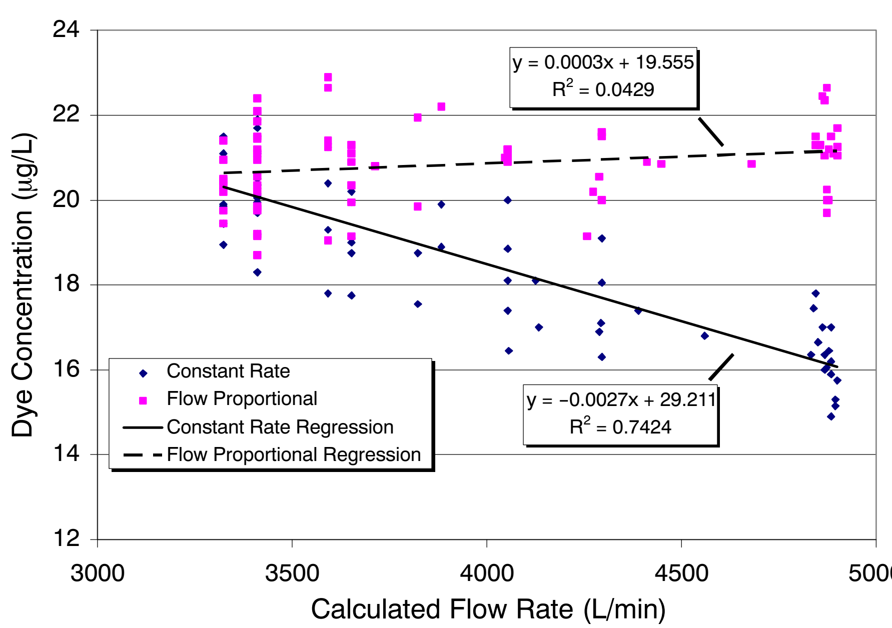

Figure 4. Linear regression equations for measured dye concentration versus computed center pivot flow rate with constant rate and flow proportional chemical injection.

result in a ±2.1 μg/L potential variation in measured dye concentration.

A second potential source of measurement error is calculation of center pivot sprinkler irrigation system flow rate. System flow rate is calculated based on the assumption that system operating pressure does not affect sprinkler flow rate due to the presence of pressure regulators on each individual sprinkler. The use of pressure regulators does reduce the effect center pivot sprinkler system pressure changes have on sprinkler flow rate but does not completely eliminate the effect. Changes in center pivot sprinkler system operating pressure do affect individual sprinkler flow rates, especially when system pressure is close to the pressure rating of the pressure regulator. Thus, pressure fluctuations due to end gun booster pump operation, elevation changes of the system lateral, and operation of irrigation systems connected to the same water supply along with occurrences of inadequate operating pressure are partially responsible for variations in measured dye concentration under flow proportional chemical injection. Using a center pivot sprinkler flow rate model that accounts for these pressure fluctuations could potentially reduce the effect of system pressure fluctuations on measured dye concentration.

A third potential source of measurement error for the constant rate chemical injection test is the manner in which the water samples were collected. The water samples were not instantaneous grab samples but rather samples collected over the time period required for the sprinkler pattern to completely pass over the catch can. Based on system speed, radial location of catch cans, and wetted diameter of the sprinklers, the collected water samples represent a 30-min average of dye concentration in the applied water. For a specific instantaneous calculated flow rate, the associated measured dye concentration will vary because the water sample corresponds to a range in flow rates over a 30-min period rather than the associated instantaneous flow. The crop canopy could have preferentially interfered with water entering the catch can from one or more directions adding to the variability in measured dye concentration.

Another potential source of error is the effect fluctuations in center pivot sprinkler irrigation system operating pressure have on the flow rate of the chemical injection pump. Kranz et al. (1996) found that chemical injection pump calibration curves change significantly with outlet pressure. Thus, the calibration of the chemical injection pump used in this study may have varied as pressure in the water supply for the center pivot sprinkler irrigation system changed due to operation of irrigation systems supplied by the same water source.

Use of the spatially distributed control network on center pivot irrigation systems provides the ability to monitor, diagnose, and troubleshoot system operation. For example, during field testing it became readily apparent that a producer has limited ability to verify correct operation of the valve banks on a swing-arm corner watering system. Currently, if water is coming out of the sprinklers, the corner watering system is assumed to be working. In our case, monitoring which valve banks were activated and comparing that with visual observations of sprinkler operation, we were able to determine that the swing-arm corner watering system was not operating correctly and identify which valve banks were faulty. The spatially distributed control network also allowed us to monitor operating pressure at the end of the system lateral, which enabled us to determine that operating pressure was occasionally below design specifications. Currently, there is no easy means to continuously monitor operating pressure at the end of a center pivot sprinkler system lateral and verify proper system operation. We included a GPS unit in the distributed sensor network and logged operational data throughout the irrigation season as a function of time and center pivot sprinkler system lateral location. This information provides a means to determine seasonal water application depth and water application depth per revolution of the center pivot sprinkler based on known system flow rate and actual travel speed. The logged GPS data also allows the travel speed of the center pivot sprinkler system to be evaluated for variations such as wheel slippage or equipment malfunctions. Efficient display and recording of various center pivot operating parameters can be valuable to the producer as a means to ascertain proper operation of the center pivot sprinkler system and diagnose problems when they occur.

The approached used in this study to control flow proportional chemical injection is subject to various sources of failure and error. The main components subject to failure are the spatially distributed control network node electronics, the pressure sensor, and the variable frequency drive. Use of a flow meter for flow proportional chemical injection includes a flow meter, variable speed controller, and variable frequency drive which are subject to failure and error as well. The biggest source of error in flow proportional chemical injection using the spatially distributed control network is in calculation of center pivot sprinkler irrigation system flow rate. Calculation of system flow rate assumes that the center pivot is well designed and operating as designed. Wear and failure of sprinkler pressure regulators, sprinkler nozzle plugging, swing-arm valve controller failure, and swing-arm sprinkler valve failure would all result in errors in calculation of center pivot sprinkler irrigation system flow rate. Overall, the approach used in this study to control flow proportional chemical injection is subject to more modes of failure and error than with use of a flow meter. The magnitude of a flow rate error would depend upon the difference between actual and calculated system flow rate. Failure of a swing-arm valve bank could result in a 5% error in calculated flow rate for the center pivot sprinkler irrigation system used in this study. A 10% drift in pressure transducer calibration could result in less than a 1% error in calculated flow rate for the center pivot sprinkler irrigation system used in this study.

Summary

The feasibility of using spatially distributed control network technology to determine real-time operating status of a center pivot sprinkler irrigation system to calculate system flow rate and control flow proportional chemical injection was evaluated. Field testing results show that this approach to control flow proportional chemical injection system eliminated systematic errors in chemical concentration in applied water caused by center pivot sprinkler system flow rate changes due to end gun and swing-arm operation. Errors in calculation of center pivot irrigation system flow rate could potentially be further reduced by using a center pivot sprinkler flow rate model that accounts for the effect system operating pressure fluctuations have on pressure regulated sprinkler flow rate. The distributed control network used for real-time center pivot sprinkler irrigation system monitoring is relatively easy to install and provides a means for distributed control and measurement as it uses the existing center pivot power cable for the communication medium. The spatially distributed control network also provides the ability to monitor, diagnose, and troubleshoot center pivot sprinkler system operation.

Acknowledgements

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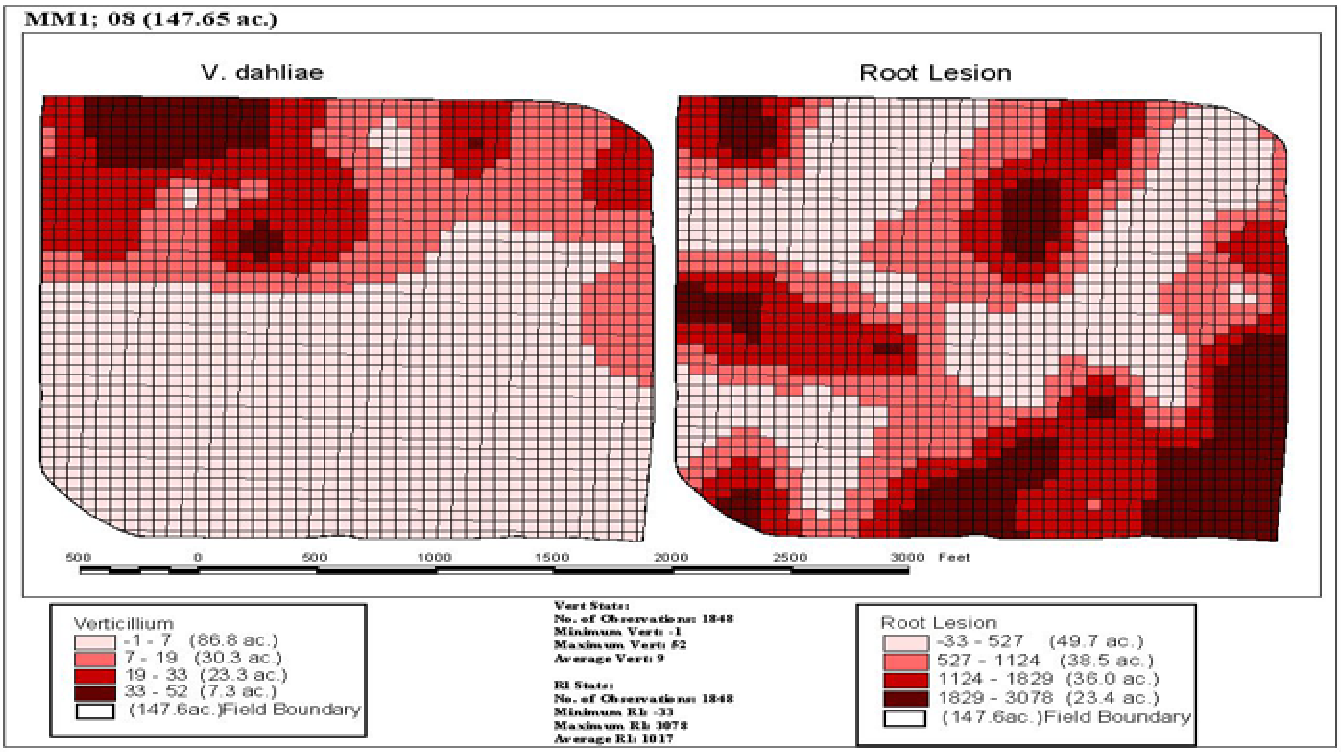
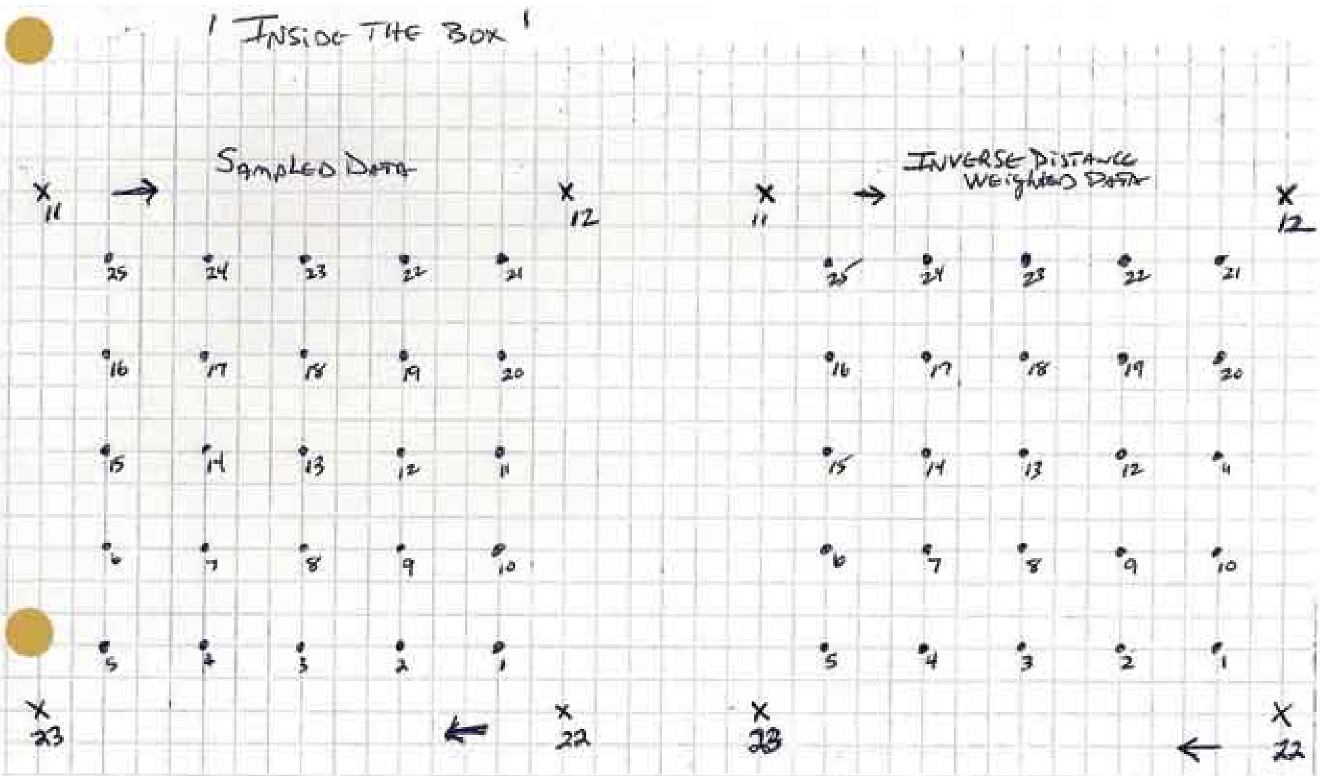
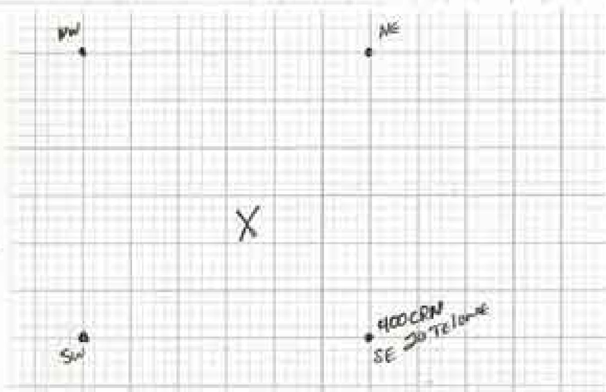




2-Acre Inside The Box

$$Z_i = \frac{\frac{n_{NW}}{d} + \frac{n_{NE}}{d} + \frac{n_{SW}}{d} + \frac{n_{SE}}{d}}{\frac{1}{d_{NW}} + \frac{1}{d_{NE}} + \frac{1}{d_{SW}} + \frac{1}{d_{SE}}}$$



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