Comparison of Application Methods on Deposition and Redistribution of Chlorothalonil in a Potato Canopy and Potential for Control of Late Blight

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ABSTRACT

Hamm, P. B., and Clough, G. H. 1999. Comparison of application methods on deposition and redistribution of chlorothalonil in a potato canopy and potential for control of late blight. *Plant Dis.* 83:441-444.

The effect of application method by aircraft (fixed wing), ground, and chemigation on deposition of chlorothalonil in a potato canopy was compared over 2 years. Initial chlorothalonil deposition was greatest with ground application, less by aircraft, and least with chemigation. After application by aircraft or ground, the upper canopy had more chlorothalonil than the middle, and the lower canopy had the least. With chemigation, the upper canopy also had more chlorothalonil, but amounts in the lower and middle canopy were similar. Redistribution occurred with time as material from the upper canopy moved downward. With a 9-day application frequency using ground or aircraft methods, residue levels throughout the treated potato canopy were maintained, even if distribution of the fungicide within the canopy was poor from the initial application. With chemigation, low initial chlorothalonil levels were further decreased due to redistribution, increasing the likelihood that levels could fall below that which may be needed to adequately control late blight, particularly beyond 7 days after application.

Late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is a serious disease of potato and tomato. Cultural and chemical control methods must be used to prevent substantial yield reductions. Repeated fungicide applications are mandatory, particularly under moderate to heavy disease pressure. Fungicides are applied in commercial fields by three methods: (i) aircraft (fixed wing or helicopter) with spray booms, (ii) ground, with spray booms attached to either self-contained or tractor-pulled equipment, and (iii) chemigation, where the material is injected into the irrigation system and distributed with the irrigation water. Chemigation may use moveable hand lines, wheel lines, or most frequently, a self-propelled center pivot irrigation system. The amount of water applied during a center pivot application depends primarily on the speed at which the pivot moves and to a lesser degree on the sprinkler used.

Aircraft application is quick, inexpensive, and uses very little water (47 to 94 liters·ha⁻¹), but it can be impeded by natural or man-made obstructions such as trees,

power lines, and buildings, and cannot be used during moderate or high winds. Use of this method requires scheduling with a commercial applicator. Center pivot chemigation can be scheduled and performed by trained personnel employed by the grower, using grower owned equipment already on-site, during periods when wind speeds would preclude aircraft application. However, approximately 9 h is required to complete each center pivot-irrigated field, and tremendous water volumes (48,000 to 58,400 liters·ha⁻¹ or a depth of 0.48 to 0.58 cm·ha⁻¹) are used. Ground application takes more time to complete than aircraft but less than chemigation, can be accomplished in higher velocity winds than the other methods, and uses little water (200 to 1,400 liters·ha⁻¹). Application by ground equipment requires either the purchase of expensive specialized equipment or contracting with a commercial applicator. Most fungicide applications in the Columbia Basin of Oregon and Washington are by aircraft (75%), with fewer but significant areas treated by chemigation (25%) and very little application with ground equipment (9). The method used to apply fungicides may depend more on availability of equipment than on how well the fungicide is delivered.

The Columbia Basin of Oregon and Washington produces 65,000 ha of potatoes annually. With the recent replacement of the metalaxyl-sensitive strain (US1) by a more aggressive metalaxyl-resistant strain (US8) (13,14), and with higher than average precipitation during

the crop season during the last 7 years (9), the region has experienced low to high incidence and severity of this disease and difficulty of control. In a year with high disease incidence (1995), growers made up to 18 applications of protectant fungicides (average 10) to full-season potatoes (9). However, because of the epidemiological nature of the disease, differing cultural practices, cultivar susceptibility, and field locations, in a low-disease-incidence year, the maximum number of applications is nearly the same but the average number is reduced (P. B. Hamm, *unpublished data*).

Methods of fungicide application for general disease control have been compared. In a nonreplicated trial, Wyman et al. (15) simultaneously compared center pivot chemigation, ground, and aircraft application methods in potatoes and found that all application methods provided acceptable levels of early blight control. Lowest disease severity and highest yields in peanuts were reported by Brenneman and Sumner (1) by using ground application. An attached boom (an additional boom attached to the main irrigation apparatus) or normal chemigation treatment was not as effective. In two trials, one comparing center pivot and ground application, the other comparing solid set chemigation, ground, and aircraft methods, McMaster and Douglas (12) reported all methods equally controlled early blight in potato.

Application method should affect disease control by influencing the amount of deposition of residue to and within the canopy and subsequent redistribution. One report suggests only 10% of the applied chlorothalonil was retained on foliage after chemigation (7). Bynum et al. (4) compared aircraft, center pivot chemigation, and an attached boom in corn and sorghum treated with lithium sulfate. They found more residue in the canopy just after application by low water amounts with the attached boom, less after application by aircraft, and least when high water volumes were used during traditional center pivot chemigation. McMaster and Douglas (12) reported more chlorothalonil deposited by ground application than by center pivot chemigation in one trial, and aircraft and ground equal but greater than solid set chemigation in another.

Application methods also differ in their penetration within the canopy. Bruhn and

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Oregon State University Agricultural Experiment
Station Technical Paper 11361.

Accepted for publication 2 February 1999.

Publication no. D-1999-0308-03R
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Fry (3), when comparing ground and aircraft (helicopter) applications in potatoes, found greater levels of chlorothalonil in the upper canopy. Similar tests by McMaster and Douglas (12) reported higher levels of chlorothalonil in the upper canopy than in the lower canopy, using ground application. Chemigation using moveable lines (wheel lines) resulted in residues that were equal at both canopy locations investigated. Bynum et al. (4) found higher levels of lithium sulfate in the upper canopy after aircraft use and low-water-rate chemigation than with high water rates. Lower canopy areas had more chemical residues when high water rates were used during chemigation. Deonier (5) found considerably more tracer dye in the upper portions of corn and potato canopies than in lower levels after application by aircraft.

Movement and/or loss of fungicide occurs in the canopy. Bruhn and Fry (3) reported that residue levels of chlorothalonil in the lower canopy are maintained by redistribution of chemicals from the upper canopy. They reported movement of chlorothalonil was greatest when irrigation and/or rain occurred on the day of application. Elliott and Spur (6) reported that rain and/or irrigation water had the greatest effect on movement. One report (3) suggested temperature was involved with loss by volatilization of the chlorothalonil, while another (6) found no temperature relationship.

No previous work has compared all three common application methods simultaneously, using a replicated experimental design to compare initial deposition of fungicides through repeated application, or followed the redistribution through repeated applications of material within the potato canopy.

The purpose of this study was to compare commercial potato fungicide application methods commonly used in the Columbia Basin to control late blight. Comparisons of specific interest were: (i) the initial amount of chlorothalonil residue

applied to the canopy, (ii) distribution of chlorothalonil in the potato canopy after initial application, and (iii) redistribution of chlorothalonil in the potato canopy after the initial application and irrigation.

MATERIALS AND METHODS

Field plots were established on a research farm near Paterson, Washington, in 1994 and 1995. The experimental design was a randomized complete block with three replicates. Experimental units consisted of 15 rows of Russet Burbank potatoes (0.86-m row spacing). Plots were 22 m wide and 231 m long. In both years, fungicide applications began after plant canopies closed rows. Chlorothalonil (0.94 liters a.i.·ha⁻¹, Bravo 720, ISK Biosciences Corp., now marketed by Zeneca Ag Products) was applied by aircraft using 65 liters of water per ha⁻¹, CP nozzles (CP Products Company Inc., Tempe, AZ), 316 Pa, at an air speed of 201 km·h⁻¹. Chemigation used a lateral-move irrigation system (system typical of a center pivot water apparatus) with low pressure spinner spray nozzles (Nelson Irrigation Corp., Walla Walla, WA).

In 1994, high (28 liters·min⁻¹) and low (12 liters·min⁻¹) water volume nozzles delivering 58,400 and 27,900 liters·ha⁻¹ (a depth of 0.58 and 0.28 cm·ha⁻¹), respectively, were compared. In 1995, all treatments were applied with high volume nozzles. Ground application used 280 liters of water per ha⁻¹, 316 Pa, TeeJet flat fan 8006 nozzles (Spraying Systems Co., Wheaton, IL), with 0.43-m spacing at 8.1 km·h⁻¹. Buffer areas between treatments prevented drift between collection sites. Normal commercial production practices were followed. Over the course of the trial, water deposition (primarily from irrigation) averaged 9.6 mm·day⁻¹, and mean maximum and minimum temperatures were 31.1 and 14.1°C, respectively.

At each sample time, five leaves that were fully expanded at the most recent fungicide application were selected from

the upper, middle, and lower canopies, and a single 1.1 cm² disk was removed from each. Disks were placed in a scintillation vial, put on ice, and later frozen until the addition of 10 ml of analytical grade toluene (1994), or placed in vials already containing 10 ml of toluene (1995). Foliage samples were taken from the center of each experimental unit on the day of application (1 to 3 h after treatment, before any water application) and 2 and 5 days after application. The fungicide was applied three times on a 7-day schedule. At 7, 9, 12, and 14 days after the final fungicide application each year, additional foliage samples were collected as before. Chlorothalonil levels were determined by gas chromatography, using electron capture detection. Each sample was analyzed twice, and mean values were determined. Laboratory analyses and quantifications of chlorothalonil in leaf disk samples were performed by others (Ricerca, Inc., Painesville, OH).

Data were analyzed by SAS GLM procedures (SAS Institute, Cary, NC), with Duncan's multiple range test used to separate treatment means.

RESULTS

Statistical analysis confirmed no differences in chlorothalonil levels in the same treatment between years or between the two chemigation water volumes, so data were combined for water volumes and years.

Very low chlorothalonil levels in untreated buffered areas indicated little drift occurred between treated areas (averaged 0.11, 0.07, 0.02, 0.05, 0.04, 0.01, and 0.02 µg·cm⁻² at 0, 2, 5, 7, 9, 12, and 14 days after application, respectively).

Chlorothalonil deposited in the potato canopy and levels of residue at all subsequent sample times were consistently greater for ground application treatments (Table 1). More chemical was deposited to the canopy and more was retained in the foliage at 0, 2, 5, and 9 days after aircraft application than with chemigation.

Table 1. Chlorothalonil level on potato foliage by application method, canopy position, and days after application in potato

Treatment	Chlorothalonil (µg·cm ⁻²) at various times after application ^y						
	0	2 day	5 day	7 day	9 day	12 day	14 day
Application method (M)							
Aircraft	1.50 b ^z	0.93 b	0.51 b	0.97 b	0.64 b	0.50 b	0.53 b
Chemigation	0.71 c	0.47 c	0.24 c	0.57 b	0.22 c	0.29 b	0.20 b
Ground sprayer	3.20 a	2.18 a	1.46 a	2.91 a	2.14 a	1.86 a	3.31 a
	****	****	****	****	****	****	****
Canopy position (C)							
Upper	2.70 a	1.43 a	0.79	1.21	0.79	0.72	0.84 b
Middle	1.45 b	1.08 b	0.69	1.51	0.81	0.66	1.31 a
Lower	0.80 c	0.76 c	0.55	1.34	0.81	1.02	1.03 ab
	****	****	NS	NS	NS	NS	*
M × C	****	***	NS	NS	NS	NS	*

^y Days after application. 0 sample followed chlorothalonil application by 1 to 3 h. Samples at 0, 2, and 5 days combined data from three repeated fungicide applications, applied on a 7-day application schedule. Remaining sample times are a single replicated sample date following the third application each year.

^z NS, not significant; ****, significant at $P = 0.0001$; **, significant at $P = 0.01$; *, significant at $P = 0.05$. Means followed by different letters are significantly different at $P = 0.05$ (Duncan's multiple range test).

Differences in chlorothalonil levels occurred within the canopy. Initial deposition in the canopy and residue measured 2 days after application were highest in the upper canopy, intermediate in the middle, and lowest in the lower canopy (Table 1). Residues throughout the canopy were equal 5, 7, 9, and 12 days after the last application, but at 14 days after application, residue levels were less in the upper than in the middle canopy.

Ground application initially deposited significantly more chlorothalonil at all levels within the canopy than did aircraft and chemigation treatments (Table 2). Aircraft application deposited approximately twice the material to the upper and middle canopies as did chemigation but was not different from chemigation in the lower canopy.

There were significant interactions between application methods and canopy position (Table 1). On the day of treatment, chlorothalonil levels decreased from upper to middle to lower canopies with all application methods, but with chemigation, the values were similar for the upper and middle, and middle and lower canopies (Table 3). Higher levels also were detected in the upper canopy at day 2, but only with aircraft and ground applications. Although there was an interaction between application method and canopy position at 14 days after application, the effect was slight. Ground sprayer residue was significantly greater than either chemigation or aircraft application for all three canopy positions; the level of significance of the effect varied slightly with canopy position (data not shown).

Chlorothalonil residue levels decreased with time. Just after application, average levels were $1.65 \mu\text{g}\cdot\text{cm}^{-2}$, decreasing significantly to $1.09 \mu\text{g}\cdot\text{cm}^{-2}$ and $0.68 \mu\text{g}\cdot\text{cm}^{-2}$ at 2 and 5 days after application, respectively.

DISCUSSION

Chlorothalonil application by ground sprayer was the most effective method for depositing greater residue levels of fungicide to the potato canopy, next was aircraft, and least was center pivot chemigation. A compilation of previous reports (1,2,4,12,14) supports our conclusion.

Finding higher chemical residue in the upper canopy after application, regardless of application method, was expected. Previous researchers (2,11) found more chlorothalonil in the upper and middle canopy locations after application, as did Bynum et al. (4), who reported more lithium sulfate marker in the upper canopy.

Maintaining a minimum disease control level of fungicide in the canopy is important for controlling plant diseases, particularly late blight. Weekly application of fungicides maintained high residue levels in the canopy, while irrigation apparently spread the chemical throughout the canopy.

Because chlorothalonil redistributed from upper to middle to lower canopies, a greater amount of initial deposition created a larger reservoir for redistribution, so the effect (maintaining fungicide level) was greatest for ground, intermediate for aircraft, and least for chemigation. Lukens and Ou (11) reported an increase or constant level of chlorothalonil in the lower canopy of tomatoes and concluded this was the result of either buildup in the canopy from repeated sprays or redistribution. A more recent report (3) documented this movement as redistribution in the canopy and showed that rain, especially on the day of treatment, was responsible for downward movement in the canopy. In determining the half-life of chlorothalonil in a peanut canopy, rain was the most important variable for residue loss (6). Application of water in the 2-day period after fungicide application during our study averaged $9.1 \text{ mm}\cdot\text{day}^{-1}$. Subsequent sample periods had similar irrigation amounts. This amount of irrigation undoubtedly contributed to a downward fungicide movement. Temperature during this trial may have caused volatilization of chlorothalonil in the canopy, but the literature differs on the importance of this factor (3,6).

Fungicide redistribution would suggest that uniform coverage of the upper canopy during application is a more important consideration in the frequently irrigated Columbia Basin than is complete canopy coverage. Current recommendations in the Columbia Basin suggest two applications of fungicides on a weekly basis prior to late blight exposure (8). This ensures adequate protection from fungicide redistribution when the application method initially deposited low chlorothalonil levels to the lower canopy. Subsequent weekly applications maintain the fungicide level throughout the canopy by the addition of residue in the upper level, allowing for the subsequent movement downward.

Chemical control recommendations for late blight, particularly with the advent of new, aggressive genotypes, include weekly or more frequent application of protectant fungicides to achieve the same level of protection as previously obtained (10).

Table 2. Chlorothalonil residues on potato foliage at three canopy positions when applied by three application methods

Application method	Residue ^y ($\mu\text{g}\cdot\text{cm}^{-2}$)		
	Upper	Middle	Lower
Aircraft	2.57 b ^z	1.31 b	0.63 b
Chemigation	0.94 c	0.68 c	0.51 b
Ground sprayer	5.46 a	2.75 a	1.41 a
	****	****	***

^y Foliage sample from leaflets the day of fungicide application.

^z ****, significant at $P = 0.0001$; ***, significant at $P = 0.001$; **, significant at $P = 0.01$. Means followed by different letters are significantly different at $P = 0.05$ (Duncan's multiple range test).

However, the work reported here suggests longer fungicide application intervals may be justified at certain periods of the growing season when applied by aircraft or ground methods, but not by chemigation. While extensive foliage growth during early and mid-season would require weekly or more frequent reapplication, with little new growth in late season, 2-week intervals may be adequate. Lukens and Ou (11), after studying chlorothalonil deposition, redistribution, and fungicide residue needed for control, concluded that intervals between applications in tomatoes could be increased to 10 days and still ensure adequate control of early blight. A reduction in late blight control costs and decreased chemical use could be achieved, based on the amount of and redistribution of residue reported here, if the residue level necessary to maintain control of this disease was known.

Total residue levels within the canopy decreased with time, with the lowest levels found in the chemigation treatment, presumably due to low initial levels at application. Levels needed to control late blight have not been reported. However, chemigation residue levels apparently are high enough through the recommended 7-day spray interval most years to prevent infection in the Columbia Basin of Oregon and Washington, since the disease has been controlled by this application method (P. B. Hamm, unpublished data). The much lower residue levels 9 days and longer after application by chemigation may not be adequate to control late blight. More frequent treatments when fungicides are applied by chemigation may be necessary to maintain critical residue levels, particularly during periods favorable to late blight development and rapid plant growth.

Even though application methods may not deposit fungicide equally, all methods

Table 3. Chlorothalonil residues over time on three potato canopy positions when applied by three different application methods

Time Canopy position	Application method ($\mu\text{g}\cdot\text{cm}^{-2}$)		
	Aircraft	Chemigation	Ground sprayer
3 h after application			
Upper ^y	2.57 a ^z	0.94 a	5.46 a
Middle	1.31 b	0.68 ab	2.75 b
Lower	0.63 c	0.51 b	1.41 c
	***	**	****
2 days after application			
Upper	1.33 a	0.45	2.92 a
Middle	0.86 b	0.61	2.18 ab
Lower	0.61 b	0.66	1.45 b
	***	NS	**

^y Foliage samples from leaflets within each canopy position that were fully expanded at the last fungicide application.

^z NS, not significant; ****, significant at $P = 0.0001$; ***, significant at $P = 0.001$; **, significant at $P = 0.01$. Means followed by different letters significantly different at $P = 0.05$ (Duncan's multiple range test).

of application may control some disease problems equally. McMaster and Douglas (12) found less residue after center pivot or solid set chemigation, but they reported equal early blight control compared with chemigation by ground or ground and aircraft methods, respectively. Wyman et al. (15) did not measure fungicide levels, but they compared center pivot chemigation, ground, and aircraft application, and found that all three controlled early blight equally. Apparently, in these cases, the minimum level of fungicide needed to control early blight was maintained, regardless of application method. In contrast, Brenneman and Sumner (1) reported better control of leaf spot (*Cercosporidium personatum*) in peanuts by ground application than by chemigation when on a 14-day fungicide treatment schedule. They concluded that growers should use application methods other than chemigation or an underslung boom or reduce the treatment interval when conditions favored the disease to ensure adequate protection. The information reported here showing reduced fungicide deposition due to chemigation would support their conclusions. The choice of application method and/or the frequency of application becomes an important consideration when controlling some plant diseases.

In our study, the use of a chemigation system specially equipped to reduce water volume (27,900 liters·ha⁻¹) did not result in higher chlorothalonil levels anywhere in the canopy compared with typical chemigation methods (58,400 liters·ha⁻¹). Others have investigated the use of very low volumes of water with fungicides applied by

attaching an additional boom to a center pivot irrigation system, with mixed success (1,4,15). These systems may provide a substantial benefit through ease of application and higher fungicide residue levels, but none have been thoroughly tested for their efficacy in controlling late blight.

ACKNOWLEDGMENTS

We thank Mike Hassel and Suzanne Bauscher for field assistance during this trial. We also thank AgriNorthwest, Ag Northwest, and Columbia Basin Spreaders for the application of materials. Financial contributions were made by Zeneca Ag Products (formerly ISK Biosciences Corp.), Novartis (formerly Ciba Crop Protection), and the Oregon Potato Commission. Special thanks to John French, Carl Bucholtz, Robert K. Thornton, Gene Maas, and Alan Cleaver for their assistance in this study and D. A. Johnson and W. E. Fry for their comments on the manuscript.

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