Comparison of Deposition Patterns in Two Programs for Applying Protectant Fungicides to Potato Stems and Leaves for the Control of Late Blight (*Phytophthora infestans*)

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ABSTRACT

Fungicides are applied by air, chemigation, and ground in the Columbia Basin of Oregon and Washington. These methods of fungicide application differ in deposition of fungicide to the canopy and cost. This study compared the alternate use of air and chemigation application of fungicides (AIRCHEM) with chemigation alone (CHEM), by either measuring chlorothalonil or manganese (mancozeb) amounts in three canopy levels (upper, middle, lower), both on leaflets and stems, after multiple fungicide applications on a 7-day schedule. Greater amounts of chlorothalonil or mancozeb were usually found on the leaflets in the upper and middle canopy locations from AIRCHEM compared to CHEM, the day of fungicide application and 7 days later. Deposition of fungicides on stems generally follow the same pattern as leaflets, but the amount deposited and maintained on stems was significantly less than leaflets. Mancozeb deposition in the three canopy levels followed the same pattern as was found for chlorothalonil. The greater the amounts of chlorothalonil on leaflets and stems resulted in better disease reduction during inoculation assays. Reduced fungicide amounts on stems compared to leaflets may be the reason for increased stems infections in recent years by more aggressive strains of late blight. This is the first report quantifying chlorothalonil or mancozeb amounts on potato stems and the first to report amounts of mancozeb on potato foliage after fungicide application.

RESUMEN

En el valle del Columbia en Oregon y Washington se aplican funguicidas por aire y por tierra. Estos métodos de aplicación difieren en la deposición del funguicida y en el costo. Este estudio comparó el uso alternado de la aplicación por aire (AIRCHEM) y por tierra (CHEM) midiendo las cantidades de clorotalonil y de manganeso (mancozeb) en tres niveles de la parte aérea de la planta (superior, media, inferior), tanto en los foliolos como en los tallos, después de múltiples aplicaciones con intervalos de siete días. Mayor cantidad de clorotalonil o de mancozeb se encontró generalmente en los foliolos localizados en el tercio superior del tratamiento AIRCHEM, comparado con CHEM, el día de la aplicación y siete días después. La deposición de los funguicidas sobre los tallos siguió generalmente el mismo patrón que en los foliolos, pero la cantidad depositada y mantenida en los tallos fue significativamente menor que en los foliolos. La deposición de mancozeb en los tres niveles del follaje sigue el mismo patrón encontrado para el clorotalonil. Las mayores cantidades de clorotalonil dieron como resultado una mayor reducción de la enfermedad durante los ensayos de inoculación. La reducida cantidad de funguicida sobre los tallos en comparación con los foliolos puede ser la razón del incremento en años recientes de infecciones en tallos por variantes más agresivas de tizón tardío. Este es el primer reporte en que se cuantifican las cantidades de clorotalonil o

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mancozeb en tallos de papa y el primer reporte de la cantidad de funguicida sobre el follaje de papa, después de la aplicación del funguicida.

INTRODUCTION

Late blight of potato caused by *Phytophthora infestans* (Mont) de Bary is a serious disease of potato. Economic losses to potato growers in the Columbia Basin of Oregon and Washington has been estimated at $30 million (Johnson et al. 1997) and $22.3 million (Johnson et al. 2000) in 1995 and 1998, respectively. Losses are the result of reduced yields, storage losses, and the cost of chemical control (Johnson et al. 1997). Best management of late blight results from an integrated approach of cultural and fungicide practices (Johnson et al. 2000).

An important consideration when using fungicides is the method with which they are applied. Fungicides can be applied by one of three basic methods: air (helicopter or fixed wing), ground (self-contained or tractor-pulled equipment), or chemigation. Fungicide application by air is relatively quick, but is easily affected by environmental conditions such as wind, temperature, and humidity because of droplet size and distance from nozzle to canopy (Jacobsen 1986). Fungicide application by air is also expensive and can be impeded by natural or manmade obstructions such as trees, power lines, and buildings, but it uses little water. Scheduling with a provider is required. Chemigation requires no specialized equipment beyond the pump injecting fungicide into the system, and therefore is inexpensive, does not require scheduling with an outside business, uses high water volumes (Geary et al. 1999; Hamm and Clough 1999), and because of large droplet sizes, can be used when environmental conditions do not favor fungicide application by air.

In the Columbia Basin in 1995 growers used air most frequently (72%) to apply fungicides, compared to chemigation (28%) and ground (<1%) (Johnson et al. 1997). Three years later, growers had reduced their reliance on fungicide application by air to 59%, but increased the use of chemigation to 37% (Johnson et al. 2000). Increased chemigation use was due to the reduced costs of using this method as growers looked for ways to reduce expenses for late blight control (Johnson et al. 2000).

Both air and chemigation application methods reduce late blight, but they do not necessarily apply fungicide equally. When the fungicide was applied by air, more residue was found in the upper canopy and less in the lower canopy when applied after canopy closure (Geary et al. 2004; Hamm and Clough 1999). Chemigation resulted in uniform distribution of fungicide in the canopy, but at reduced amounts, and after 7 days the amounts were below that thought to provide adequate protection against late blight (Hamm and Clough 1999). Greater residue amounts resulted in greater disease control when detached leaves were exposed to late blight in the laboratory (Geary et al. 1999, 2004).

Water rates used during fungicide application may contribute to the amount of fungicide residue found in the canopy. Aircraft generally apply fungicides in 47 L/ha of water whereas chemigation uses high water volumes (48-58,400 L/ha), which may be the reason for reduced amounts of fungicide in the canopy after application, as the fungicide is basically washed through the canopy with the movement of water (Geary et al. 2004; Hamm and Clough 1999).

Redistribution of fungicide downward in the potato canopy occurs due to repeated watering between weekly fungicide applications, regardless of fungicide application method (Geary et al. 1999, 2004; Hamm and Clough 1999). In the case of chemigation where fungicide amounts were already reduced, by 7 days after the last fungicide application, redistribution had reduced residues throughout the canopy to near zero. Similarly, high fungicide residues found in the upper canopy after air application moved downward, substantially maintaining amounts in the middle and lower canopy (Geary et al. 1999, 2004; Hamm and Clough 1999).

The most commonly used fungicides for the protection against late blight in the Columbia Basin are chlorothalonil and mancozeb-based (EBDC - ethylene bis-dithiocarbamate + zinc + manganese) products, presumably due to their efficacy and reduced cost (Johnson et al. 1997, 2000). Johnson et al. (2000) reported the use of chlorothalonil to be decreasing in the Columbia Basin, dropping in use from 36% to 28% between 1995 and 1998. During that same period, the use of mancozeb increased from 23% to 41%. Expense was a factor for this shift. The average cost of applying a single treatment of chlorothalonil in 1995 was $22.18/ha, increasing to $26.80/ha in 1998, whereas the cost of applying mancozeb was $15.23/ha in 1995, increasing to $17.30/ha in 1998 (Johnson et al. 1997; 2000). Although products that contain mancozeb are widely used and their use is increasing, little is known about how the method of fungicide application and water affect residue amounts.

An important consideration in late blight control is the protection of potato stems. Once they are infected, stems can be long-term sources of inoculum and/or sites that allow secondary infection by *Pectobacterium* (*Erwinia*) sp. (unpublished data). In addition, the potential greater incidence of stem infection by the newer, reportedly more aggressive strains (Miller et al. 1998) of *P. infestans* suggests that controlling stem infections is particularly important. No work, however, has reported fungicide residue amounts on stems after fungicide application or watering.

Currently air is the recommended method for applying fungicides in the Columbia Basin for late blight management because the air method can more quickly deposit fungicide residues over large areas of the potato canopy compared to chemigation. The use of chemigation, however, is increasing because it is less expensive. Alternating the methods of fungicide application between air and chemigation would reduce application costs compared to air application alone. However, the quantity of fungicide residue on foliage from alternating the two application methods is not known. The objectives of the work reported here were (1) to determine if the alternate use of an air and chemigation (AIRCHEM) fungicide application program would deposit and maintain a greater amount of fungicide in the canopy, providing a more effective control of late blight than CHEM through a repeated 7-day fungicide application program, using either chlorothalonil or mancozeb and (2) to determine the level of chlorothalonil and mancozeb deposited on stems and leaflets, 1 day and 7 days after the application of fungicides by AIRCHEM and CHEM application programs.

MATERIAL AND METHODS

Field Information

Experiments were conducted in commercial potato fields near Pasco, WA, planted to cv Russet Burbank in 1999 and 2000. Certified seed potatoes were planted at a spacing of 0.23 m within the row and 0.86 m between rows. Each field was at least 51 ha in size and irrigated by a center-pivot system. Foliar fungicides were not applied prior to application of treatments. Fields within each year were in close proximately to one another, had a single manager, similar soil types, were nearly the same age (days after planting) when the test began, and had received identical nutrients, herbicides, irrigation and insecticides, following standard commercial potato production practices used in the Columbia Basin.

Application of Fungicides

Fungicides were applied either by CHEM (applying fungicides only by chemigation through the center-pivot irrigation system at a 7-day interval) or by AIRCHEM (applying fungicides first by air then alternated with chemigation through the center-pivot irrigation system on a 7-day interval). In 1999, four applications of chlorothalonil (Bravo Weatherstik 1.76 L/ha) were repeatedly applied by CHEM to three fields and by AIRCHEM to three fields. In 2000, three applications of chlorothalonil (Bravo Weatherstik 1.76 L/ha) were applied by CHEM to one field and by AIRCHEM to two fields, and four applications of mancozeb (Dithane M45 2.2 lbs/ha) were applied by CHEM to one field and by AIRCHEM to two fields. The same amount of water was used by each fungicide application method each year (25,442 L and 65 L/ha, for chemigation and air application, respectively).

Plant Tissue Collection

Plant tissue samples were collected within 24 h (before the application of irrigation water) and 7 days after each fungicide application. Leaf samples were collected from the upper, middle, and lower levels of the potato canopy each year. Upper leaves that were collected existed at the previous fungicides application, if a previous fungicide application had been made. Stems were also collected from the same three canopy levels. Five leaf and five stem (20 cm in length) subsamples per canopy level were collected from three randomly selected areas in each field. Subsamples within a canopy level were collected at distances of approximately 50 m from each other and were collected from the same general area at each sample time. The three areas sampled per field were approximately one-third sections of the field (circle). Each field was considered a replication for a method of fungicide application.

Fungicide Assays

Excised leaves and stems were placed in plastic bags in the field and then transported to the laboratory in a cooler containing ice. A 1.25-cm-diameter leaf disk was removed with a cork borer from each of the five terminal leaflets and five stem sections (1 cm length from the center 20 cm) were removed from each sample collected. Stem diameters were determine and averages used to calculate surface area. For chlorothalonil determinations, leaf disks or stems were placed in clean sample vials containing 10 mL toluene, and shipped by freezer shipment for analysis to Ricerca, Inc., Painesville, OH.

Chlorothalonil amounts were determined by gas chromatography using electron capture detection. Each sample was analyzed twice and a mean value for chlorothalonil residue was obtained. Amounts of chlorothalonil on leaflets or stems were calculated as level/cm^2 of tissue. Methods were identical to those used in previous reports (Geary et al 1999, 2004; Hamm and Clough 1999).

A direct analytical test for mancozeb (ethylene bisdithiocarbamate + zinc + manganese) was not available. Therefore the amount of mancozeb residue was determined by the amount of manganese present. For this method leaves and stems were collected as indicated above, placed in zip locked bags, cooled, and shipped refrigerated overnight for analysis. On arrival, wet leaf weights were measured, and the leaves and stem were placed in jars. Samples were then shaken for 2 minutes with a mechanical shaker in 0.1 molar tetrasodium EDTA (approximately 4 ml/g leaf). Ten milliliters of the rinsates were filtered through 0.2-µm Gelman Acrodisc CR PTFE filters. The filtered rinsates were analyzed for µg/mL manganese by Wavelength Dispersive X-Ray Fluorescence Spectroscopy (WDXRF). The amount of manganese/g tissue was calculated with the formula: µg Mn/g tissue = (EDTA volume × µg/mL Mn)/g tissue. The level of manganese/g of leaf tissue or stem calculated as level/cm^2 of tissue was determined by multiplying this number by 4.8.

In Vitro Pathogenicity Testing

In the 1999 trial excised leaves and stems collected from the same locations as identified above were also exposed to an isolate of *P. infestans* of the US 8 clonal lineage collected in the Columbia Basin in 1999. Inoculum was increased at 18 C on excised leaves of cv Norkotah Russet in humid chambers. Sporangia were washed from the leaflets with distilled water, and then chilled at 4 C for 2 h. Sporangia were quantified using a hemacytometer, and the concentration was adjusted to 1×10^4 sporangia/mL. Petioles of detached leaves with five attached leaflets were placed prior to inoculation in test tubes containing a nutrient solution to maintain leaf vigor (Geary et al. 1999). Leaves and stems were inoculated by placing 0.05 mL of a sporangium suspension on a 1-cm filter paper square and transferring the square to either the center of five leaflets per leaf sample or the center of each 20-cm stem segment. The filter paper surface receiving inoculum was placed against the plant tissue; surface tension held the square in place. Inoculated leaf tissues were placed in a mist chamber for 18 h at 17 to 21 C and then moved to a greenhouse for 6 days at 23 to 27 C during the day and 18 to 21 C at night until lesions developed. Natural photoperiod in the greenhouse was at least 14 h; supplemental lighting was not used. Stems were placed in sealed plastic bags and placed in an incubator at 18 C with fluorescent light at an intensity of 34 $\mu E \cdot m^{-2} \cdot s^{-1}$ and a 12-h photoperiod. Five days after inoculation the percentage of leaves with late blight symptoms was noted and severity determined, based on the mean area of lesion (cm^2). Incidence of stem infection and length of stem lesions were observed and measured.

Statistical Analysis

The experimental design was a one-way treatment (method of fungicide application) with each field being a replication. In 1999, there were three replicates (fields) for each of the two fungicide application program (AIRCHEM vs CHEM). In 2000, the AIRCHEM treatment was replicated twice, and the CHEM treatment was replicated once for both the trial using chlorothalonil and in the trial using mancozeb. Leaf and stem data were analyzed separately.

Data for quantity of fungicide residue on leaflets and stems were analyzed as a completely random design with doubly repeated measures. Main treatment effect was the method of fungicide application: CHEM vs AIRCHEM. Each main treatment effect (method of fungicide application) was assigned to an irrigated potato field. The first repeated measure is a factorial of number of fungicide applications, where each fungicide application is divided into two canopy collection times, 1 day and 7 days after each fungicide application. The second repeated measure is the level of response within each collection (1 and 7 day) at three canopy levels.

Data for severity of late blight on leaves and length of stem lesion in the 1999 chlorothalonil trial were similarly analyzed except that the levels of canopy data were pooled and analyzed by method and method × collection.

Fungicide residue values were square root transformed to fit the best model and satisfy normality and variance assumptions when determining P values and significance. Data are reported as actual mean residues and actual mean disease severity and incidence. Since there were interactions between method of fungicide application and canopy levels for residue, significance within level of canopy was reported within each method of fungicide application by collection day. Since there was no significant interaction between method of fungicide

application and collection day for residue on leaflets or stems, canopy levels were combined and significance was reported for method of fungicide application by collection day. T-tests using least square means at $P = 0.05$ was used to separate treatment means, otherwise main treatment effects and interactions were reported with P values.

Comparisons of interest were method of fungicide application (method) for day of collection (collection) within a canopy level (canopy). Number of fungicide applications was not a comparison of interest, but was used in the analyses as a repeated measure term to which increased the degrees of freedom and satisfied variance assumptions. Since residue amounts on leaflets and stems were analyzed separately, 95% confidence intervals were constructed for each method of fungicide application in each trial to directly compare residue amounts between similar method of fungicide application for leaflets and stems. If there was no overlap between the leaf and stem confidence intervals, values were considered significantly different. Data were analyzed using analysis of variance, hypothesis tests, and Least Square Means in the GLM procedure in SAS® statistical software (version 9.1 SAS Institute, Cary, NC).

RESULTS

Fungicide Assays

Significant ($P < 0.05$) interactions were observed for fungicide application method × canopy level of chlorothalonil residue on leaflets and stems in 1999, manganese level on leaflets in 2000, collection period (1 day vs 7 day) × canopy level for chlorothalonil residue on leaflets and stems in 1999, and chlorothalonil and manganese amounts on leaflets and stems in 2000 (Table 1).

More chlorothalonil and manganese were deposited on leaf samples when the application method was by AIRCHEM than by CHEM (Table 2). Mean chlorothalonil and manganese residue amounts were numerically greater 1 day after application compared to 7 days after application for both leaflets and stems in all trials (Table 2). The mean amount of fungicide residue on leaflets within 1 day after fungicide application was two to six times more, regardless of fungicide, when fungicides were applied by AIRCHEM vs CHEM, and was significant for all trials. Mean residue on leaflets 7 days after fungicide application, regardless of fungicide, was nearly two to 10 times more when fungicides were applied by AIRCHEM than by CHEM and was significant in the 1999 and 2000 chlorothalonil trials (Table 2). While residue amounts of both fungicides on stems were generally numerically greater after AIRCHEM compared to CHEM, differences were not as great as compared to differences found on leaflets.

The highest residue levels of chlorothalonil and manganese detected at the 1-day collection for AIRCHEM, regardless of stem or leaflets, was on the upper canopy in all trials ($P < 0.05$) (Table 2). Greater chlorothalonil and manganese amounts were found in AIRCHEM in the middle canopy than in the lower canopy, on leaflets or stems, regardless of sample time, except for the mancozeb treatment on stems in 2000. Residue amounts on leaflets did not vary significantly in any trial at either sample time among canopy levels for CHEM, except in 1999, 7 days after fungicide application (Table 2). Fungicide amounts on stems after CHEM, regardless of fungicide, canopy location, or sampling time, were generally equal within trials except for the greater chlorothalonil amounts in the upper canopy in 1999 and 2000.

The residue level was significantly greater on leaflets than stems, regardless of fungicide, by similar method of fungicide application and by similar collection day in all trials using a 95% confidence interval (Table 2). After AIRCHEM, fungicide amounts on leaflets were five to 18 times greater than on stems, 1 day after fungicide application, and four to 29 times greater 7 days after fungicide application. After CHEM, differences between leaflets and stems were not as great. One day after CHEM fungicide application, two to seven times greater amounts of fungicide were found on leaflets compared to stems, and one to 10 times more 7 days later.

Chlorothalonil residue amounts on leaflets were numerically greater in the middle canopy compared to other canopy levels at the 7-day collection with AIRCHEM (Table 2). Seven days after CHEM the largest chlorothalonil residues were found on leaflets in the lower canopy. Greater chlorothalonil amounts were found in the upper canopy location on stems 7 days after AIRCHEM and on lower leaves 7 days after CHEM (Table 2).

In Vitro Pathogenicity Testing

Mean late blight severity and incidence for leaves and stems show an inverse relationship between amount fungicide residue vs disease severity and incidence (Table 3). Mean disease severity on late blight inoculated leaflets ($P = 0.07$) and incidence on stem samples ($P < 0.01$) was lower when fungi-

TABLE 1—*Analysis of variance table for fungicide residue on leaflets and stems of potato by method of fungicide application, number of fungicide applications, collection time, and canopy level in 1999 and 2000 (important comparisons are in bold).*

Year/fungicide[1]	Source	df	Mean square		*F* value		*P>F*	
			Leaf	Stem	Leaf	Stem	Leaf	Stem
1999/	Method[2]	1	17.8656[3]	0.6663	79.64	10.34	0.0009	0.0324
Chlorothalonil	Field (Method)	4	0.2243	0.0644	4.49	3.12	0.0029	0.0207
	Collection[4]	1	3.4715	1.4060	32.54	68.20	<.0001	<.0001
	Applications[5]	3	0.7806	0.6813	7.32	4.69	0.0009	0.0089
	Applications × Collection	3	0.0506	0.0074	1.01	0.36	0.3934	0.7843
	Method × Collection[6]	1	0.2051	0.0190	1.92	0.39	0.1766	0.5362
	Applications × Method[6]	3	0.4296	0.0185	4.03	0.38	0.0168	0.7660
	Applications × Method × Collection[6]	3	0.1616	0.0070	1.51	0.15	0.2325	0.9319
	Field (Applications × Method × Collection)	28	0.1067	0.0484	2.13	2.35	0.0064	0.0025
	Canopy	2	0.2004	0.6171	4.01	29.93	0.0230	<.0001
	Method × Canopy	**2**	**1.0195**	**0.1212**	**20.38**	**5.88**	**<.0001**	**0.0045**
	Collection × Canopy	**2**	**0.7153**	**0.2174**	**14.30**	**10.54**	**<.0001**	**0.0001**
	Applications × Canopy	6	0.3083	0.0351	6.16	1.70	<.0001	0.1350
	Applications × Collection × Canopy	6	0.1043	0.0304	2.08	1.47	0.0672	0.2015
	Method × Collection × Canopy	**2**	**0.5649**	**0.0471**	**11.29**	**2.28**	**<.0001**	**0.1102**
	Applications × Method × Canopy	6	0.1962	0.0502	3.92	2.44	0.0021	0.0349
	Applications × Method × Collection × Canopy	6	0.1093	0.0173	2.18	0.84	0.0558	0.5456
2000/	Method[3]	1	2.8780	0.0002	21.86	0.05	0.1340	0.9341
Chlorothalonil	Field (Method)	1	0.1316	0.0218	2.00	4.28	0.1824	0.0607
	Collection[4]	1	2.0949	0.2933	16.72	57.70	0.0095	0.0014
	Applications[5]	2	0.0852	0.0171	0.68	3.37	0.5478	0..5373
	Applications × Collection	2	0.0690	0.0013	1.05	0.26	0.3800	0.7723
	Method × Collection[6]	1	0.0492	0.0005	0.39	0.01	0.5585	0.9299
	Applications × Method[6]	2	0.0223	0.0527	0.18	10.37	0.8421	0.0287
	Applications × Method × Collection[6]	2	0.0188	0.0159	0.15	3.13	0.8644	0.0808
	Field (Applications × Method × Collection)	5	0.1253	0.0067	1.91	1.32	0.1668	0.3194
	Canopy	2	0.3875	0.2826	5.90	55.60	0.0164	<.0001
	Method × Canopy	2	0.1732	0.0114	2.64	2.24	0.1125	0.1492
	Collection × Canopy	**2**	**0.8218**	**0.1062**	**12.51**	**20.89**	**0.0012**	**0.0001**
	Applications × Canopy	4	0.1429	0.0267	2.18	5.25	0.1336	0.0111
	Applications × Collection × Canopy	4	0.0163	0.0060	0.25	1.18	0.9055	0.3666
	Method × Collection × Canopy	2	0.1508	0.0008	2.30	0.16	0.1432	0.8499
	Applications × Method × Canopy	4	0.1612	0.0062	2.45	1.22	0.1026	0..1891
	Applications × Method × Collection × Canopy	4	0.0884	0.0066	1.35	1.30	0.3093	0.3254
2000/	Method[3]	1	7.9503	0.0025	4.76	0.00	0.2736	0.9645
Mancozeb	Field (Method)	1	1.6708	0.8119	10.53	19.46	0.0051	0.0005
	Collection[4]	1	16.9952	1.1967	30.08	17.76	0.0009	0.0040
	Applications[5]	3	2.9477	0.2357	5.22	3.50	0.0333	0.0782
	Applications × Collection	3	0.1402	0.1365	0.88	3.27	0.4707	0.0507
	Method × Collection[6]	1	0.5789	0.1447	1.02	2.15	0.3452	0.1863
	Applications × Method[6]	3	0.9953	0.0904	1.76	1.34	0.2417	0.3360

TABLE 1—*Continued.*

Year/fungicide[1]	Source	df	Mean square Leaf	Mean square Stem	*F* value Leaf	*F* value Stem	*P*>*F* Leaf	*P*>*F* Stem
2000/ Mancozeb	Applications × Method × Collection[6]	3	0.4698	0.1148	0.83	1.70	0.5176	0.2526
	Field (Applications × Method × Collection)	7	0.5650	0.0674	3.56	1.61	0.0168	0.2061
	Canopy	2	1.8222	0.0187	11.48	0.45	0.0008	0.6468
	Method × Canopy	**2**	**3.2799**	**0.0964**	**20.67**	**2.31**	**<.0001**	**0.1336**
	Collection × Canopy	**2**	**1.8126**	**0.2049**	**11.42**	**4.91**	**0.0008**	**0.0229**
	Applications × Canopy	6	0.4682	0.0284	2.95	0.68	0.0391	0.6674
	Applications × Collection × Canopy	6	0.1782	0.1188	1.12	2.85	0.3927	0.0469
	Method × Collection × Canopy	**2**	**0.6055**	**0.0149**	**3.82**	**0.36**	**0.0442**	**0.7052**
	Applications × Method × Canopy	6	0.4025	0.0456	2.54	1.09	0.0641	0.4107
	Applications × Method × Collection × Canopy	6	0.2088	0.0481	1.32	1.15	0.3062	0.3764

[1]Based on µg chlorothalonil/cm^2 tissue or as µg Mn/g tissue for mancozeb.
[2]Method is chemigation alone (CHEM) or alternation of air applied and chemigation (AIRCHEM) with the hypothesis test using Field (Method) as an error term.
[3]Fungicide residue values were square root transformed to satisfy normality and variance assumptions when determining *P* values and significance.
[4]Collection is two canopy collections 1 and 7 days after a fungicide application with the hypothesis test using Field (Applications × Method × Collection) as an error term.
[5]Applications is a repeated measure of three or four applications of fungicide with the hypothesis test using Field (Applications × Method × Collection) as an error term.
[6]Hypothesis test using Field (Applications × Method × Collection) as an error term.

cides were applied by AIRCHEM than with CHEM (Table 4). Greater incidence and disease severity resulted on inoculated leaves collected 7 days after CHEM fungicide application compared to AIRCHEM. A greater incidence of late light occurred on inoculated stems treated by CHEM compared to AIRCHEM.

DISCUSSION

These trials over 2 years quantified the relative deposition of fungicide residue between two programs of fungicide applications over time of collection (1 vs 7 days), canopy levels, and between leaflets and stems. The patterns of residue deposition showed both similarities and differences between the AIRCHEM and CHEM fungicide application programs in regards to amount and/or significance of residue at collection time and canopy level. Also shown in these trials was the significant reduction of fungicide deposition on stems compared to leaflets.

More residue of chlorothalonil was detected on leaflets when applied by AIRCHEM than applied by CHEM. Redeposition of chlorothalonil did not differ in this study from that reported in previous studies (Geary et al. 1999, 2004: Hamm and Clough 1999). Mancozeb deposition from 1 year's data, as determined by manganese concentration, did not differ from chlorothalonil in relative amounts by canopy location or fungicide application method. Mancozeb is likely deposited and moved similarly to chlorothalonil. It was not the intent of this study to compare deposition rates between the two fungicides. What was found, regardless of fungicide application method, was more residue, regardless of fungicide, on leaflets compared to stems. This is the first report describing fungicide amounts on leaflets compared to stems, and the first to suggest mancozeb amounts in a potato canopy, after fungicide application and 7 days later.

Maintaining fungicide amounts is important in managing potato late blight. Geary et al. (1999) reported the LD 50 values to control US 8 genotypes by chlorothalonil to be 1.35-1.63 µg/cm^2 leaf. Minimum amounts have also been reported (Lukens and Ou 1976) for early blight in tomato and *Alternaria alternate* in passion fruit (Ko et al. 1975). Selecting a fungicide application method to maximize fungicide amounts (initial concentration and duration) in the canopy may provide greater periods of late blight control. This is particularly important when environmental factors such as tem-

TABLE 2—*Mean fungicide residue on leaflets and stems of potato by method of fungicide application, collection days after each fungicide application, and canopy level for three trials in 1999 and 2000.*[1]

Year/ Fungicide	Method	Canopy Level	Leaflet mean(n)[2]	Leaflet collection[3] 1 day	Leaflet collection[3] 7 day	Stem mean(n)[2]	Stem collection[3] 1 day	Stem collection[3] 7 day
1999/ Chlorothalonil	AIRCHEM	Upper		3.29 a[4]	0.76 b[4]		0.76 a[4]	0.20 a[4]
		Middle		1.99 b	1.35 a		0.36 b	0.15 b
		Lower		0.89 c	0.90 b		0.12 c	0.09 b
		means	1.53(72)[5]	2.06 A[6]	1.00 B[6]	0.28(72)[5]	0.41 W[6]	0.14 Y[6]
	CHEM	Upper		0.23 x	0.05 y		0.23 x	0.07 x
		Middle		0.31 x	0.08 xy		0.23 x	0.07 x
		Lower		0.43 x	0.18 x		0.08 y	0.06 x
		means	0.21(72)	0.32 C	0.10 D	0.12(72)	0.18 X	0.06 Z
2000/ Chlorothalonil	AIRCHEM	Upper		5.02 a	0.96 a		0.33 a	0.07 a
		Middle		1.84 b	1.31 a		0.09 b	0.03 ab
		Lower		1.29 b	1.20 a		0.02 c	0.01 b
			1.94(36)	2.72 A	1.16 B	0.09(36)	0.15 W	0.04 X
	CHEM	Upper		1.37 x	0.29 x		0.28 x	0.05 x
		Middle		0.92 x	0.42 x		0.07 y	0.02 x
		Lower		0.65 x	0.53 x		0.05 y	0.04 x
		means	0.70(18)	0.98 BC	0.41 C	0.08(18)	0.13 W	0.04 X
2000/ Mancozeb	AIRCHEM	Upper		23.74 a	6.23 a		1.81 a	1.27 a
		Middle		9.95 b	4.39 b		1.49 ab	0.81 a
		Lower		6.09 c	4.38 b		1.23 b	1.21 a
			9.13(48)	13.26 A	5.00 BC	1.31(47)	1.51 W	1.10 X
	CHEM	Upper		6.10 x	2.06 x		1.81 x	0.75 x
		Middle		6.51 x	2.63 x		1.90 x	0.84 x
		Lower		5.75 x	3.74 x		1.52 x	1.00 x
		means	4.47(24)	6.12 B	2.81 C	1.30(23)	1.74 W	0.86 X

[1]Based on µg chlorothalonil/cm^2 tissue or as µg manganese/g tissue for mancozeb.
[2]Leaflet and stem means are the overall canopy means by fungicide application method for both 1 and 7 days after fungicide application.
[3]Residue values represent mean repeated collections within fields 1 day and 7 days after fungicide application.
[4]Values followed by the same letter are significantly different. Significance of residue values ($P < 0.05$) based on SQRT transformation using Least Square Means. Statistical comparisons are between canopy levels within each method by collection day (a-c for AIRCHEM and x-y for CHEM).
[5]Comparisons are between leaflets and stem means by year and fungicide application method with significance determined by 95% confidence intervals. All values were significantly different from each other.
[6]Values followed by the same large letter within each year and leaflet (A-D) or within each year and stem (W-Z) are significantly different. Significance of residue values ($P < 0.05$) based on SQRT transformation using Least Square Means. Statistical comparisons are between methods of fungicide application and day of collections using Field (Applications × Method × Collection) as an error term.

perature (Bruhn and Fry 1982a), rainfall (Bruhn and Fry 1982a; Elliott and Spurr 1993; Ko et al. 1975) or cultural factors such as potato cultivar, plant growth, fungicide application dosage, fungicide application methods (Bruhn and Fry 1982b; Geary et al. 2004; Hamm and Clough 1999), water rate (Geary et al. 1999; Hamm and Clough 1999), and canopy closure (Geary et al. 2004) affect fungicide amounts. Not everyone is in agreement that loss of chlorothalonil is related to rainfall, plant growth, or crop age (Lukens and Ou 1976) or temperature (Elliott and Spurr 1993).

Finding reduced amounts of fungicide after chemigation was not surprising. Others have reported reduced amounts of fungicides (Geary et al. 2004; Hamm et al. 1999) or lithium sulfate (Archer et al. 1991) after chemigation or reported greater disease and reduced yields in peanut after fungicide applications by chemigation compared to ground (Brenneman and Sumner 1990), to ground and underslung boom (Sumner et al. 2000), or to ground during high early blight pressure in potatoes (Wyman et al. 1986). In contrast, others have reported no differences between ground and chemigation based on symptom development of leaf spot in peanuts (Culbreath et al. 1993), air and chemigation to control anthracnose in tomato (Potter 1981), or between ground, underslung boom and chemigation under reduced disease pressure due to early blight in potato (Wyman et al. 1986). These reports did not measure fungicide residue amounts, but used disease control as the measure of chemigation effectiveness. Reduced fungicide amounts likely resulted from chemigation, but were high enough, under those conditions and fungicide programs, to control the respective diseases. Chemigation for the control of

TABLE 3—*Analysis of variance for severity and incidence of late blight disease on leaflets and stems of potato in response to method of fungicide application (chlorothalonil), number of fungicide applications, and collection time in 1999.*

Type	Source	df	Mean square		*F* value		P>F	
			Severity	Incidence	Severity	Incidence	Severity	Incidence
1999/ Leaflet	Method[1]	1	9.1153	0.5734	5.89	1.34	0.0722	0.3122
	Field (Method)	4	1.5473	0.4294	1.48	1.70	0.2195	0.1622
	Collection[2]	1	26.7080	0.5734	17.9	2.79	0.0004	0.1106
	Applications[3]	2	4.8845	0.2791	3.27	1.36	0.0590	0.2802
	Applications × Collection	2	0.6276	0.0487	0.60	0.19	0.5519	0.8251
	Method × Collection[4]	1	18.8930	0.8750	12.70	4.25	0.0020	0.0524
	Applications × Method[4]	2	0.0089	0.0140	0.01	0.07	0.9940	0.9344
	Applications × Method × Collection[4]	2	0.9000	0.2345	0.60	1.14	0.5569	0.3398
	Field (Applications × Method × Collection)	20	1.4928	0.2057	1.43	0.81	0.1452	0.6876
1999/ Stem	Method[1]	1	6.1454	0.8438	1.87	40.50	0.2437	0.0031
	Field (Method)	4	3.2935	0.0208	0.95	0.18	0.4443	0.9467
	Collection[2]	1	0.6724	0.0104	0.19	0.05	0.6685	0.8209
	Applications[3]	3	3.8771	0.3993	1.08	2.00	0.3735	0.1365
	Applications × Collection	3	8.6712	0.0104	2.50	0.05	0.0725	0.9647
	Method × Collection[4]	1	0.0931	0.0104	0.03	0.61	0.8732	0.8209
	Applications × Method[4]	3	2.8364	0.1215	0.79	0.61	0.5095	0.6145
	Applications × Method × Collection[4]	3	1.9067	0.1215	0.53	1.06	0.6646	0.6145
	Field (Applications × Method × Collection)	28	3.5890	0.1994	1.04	1.74	0.4501	0.0449

[1]Method is chemigation (CHEM) alone or alternation of air applied and chemigation (AIRCHEM) with the hypothesis test using Field (Method) as an error term.
[2]Collection is two canopy collections 1 and 7 days after a fungicide application with the hypothesis test using Field (Applications × Method × Collection) as an error term.
[3]Application is a repeated measure of three or four applications of fungicide with the hypothesis test using Field (Applications × Method × Collection) as an error term.
[4]Hypothesis test using Field (Applications × Method × Collection) as an error term.

late blight in the Columbia Basin is efficacious, but may be only when disease pressure is low to moderate and when a 7-day fungicide application program is followed.

Chemigation with reduced water amounts via an attached boom has been shown to be an effective way to apply fungicides. Geary et al. (1999) found comparable late blight control 1 day after fungicide application between chemigation and an attached (underslung) boom, but that foliage was more susceptible to infection after 7 days. They reported chlorothalonil amounts three times greater in the attached boom vs chemigation treatment. An underslung boom was found to be better than chemigation for the control of potato leaf spot (Brenneman and Sumner 1990). Only Wyman et al. (1986) reported comparable disease control between chemigation and the use of an underslung boom. While this method has been shown effective, using an attached boom has not been accepted by growers, possibly due to costs, reliability, availability, technical issues, time required, or the difficulty in scheduling irrigation with a fungicide application.

In this study the amount of residue on leaflets and stems, from repeated sampling after repeated fungicide applications, decreased considerably from the 1-day collection to the 7-day collection, regardless of fungicide application methods or fungicide (Table 2). The highest level of chlorothalonil residue after 7 days was found on leaflets in the middle canopy using AIRCHEM. Apparently the high level of residue from AIRCHEM on the upper canopy level is the result of the initial fungicide application by air, as described by Hamm and Clough (1999), which is then washed down to the middle canopy level after 7 days. Beginning with chemigation and alternating with air resulted in lower fungicide residues in preliminary trials, presumably due to the lower beginning amounts due to CHEM (unpublished data). In this study the 7-day CHEM method, though only significant in 1999, had con-

TABLE 4—*Severity and incidence of late blight on potato leaflets and stems in response to method of fungicide application (chlorothalonil), and days after fungicide application in 1999.*[1]

Tissue Type	Source	Severity[2]	P>F	Incidence	P>F
Leaflet	Method (n)		0.07		0.31
	AIRCHEM (52)	0.51 a[3]		0.44	
	CHEM (44)	1.13 b		0.59	
	Collection × Method[4]		<0.01		0.05
	AIRCHEM 1 day (26)	0.41 a		0.46 a[3]	
	AIRCHEM 7 day (26)	0.60 a		0.43 a	
	CHEM 1 day (21)	0.15 a		0.42 a	
	CHEM 7 day (23)	2.03 b		0.74 b	
Stem	Method (n)		0.24		<0.01
	AIRCHEM (46)	1.90		0.73 a[3]	
	CHEM (43)	2.36		0.92 b	
	Collection × Method[4]		0.87		0.82
	AIRCHEM 1 day (23)	1.73		0.83	
	AIRCHEM 7 day (23)	2.07		0.83	
	CHEM 1 day (22)	2.43		0.92	
	CHEM 7 day (21)	2.29		1.00	

[1]Tissue from leaflet and stems collected and pooled from three canopy locations in the potato canopy, 1 day and 7 days after fungicide application and inoculated with *P. infestans* US 8.

[2]Leaflet severity based on mean area of lesion (cm^2) and stem severity based on mean length of lesion (cm) after inoculation.

[3]Numbers followed by the same number are not significantly different at the *P* level indicated.

[4]Significance determined by Least Square Means using Field (Application × Method × Collection) as an error term.

sistently the highest amount of residue on leaflets in the lowest canopy level and the lowest residue in the upper canopy, demonstrating the effect of normal irrigation washing down the residue from the earlier collection. Others have reported or suspected redistribution of fungicides in the plant canopy (Bruhn and Fry 1982a; Geary et al. 1999, 2004; Hamm and Clough 1999).

Interaction between method of fungicide application, collection day, and canopy level demonstrated the complex dynamics of fungicide concentrations within a commercial potato canopy and the response over time and method of fungicide applications. The interaction for method of fungicide application × canopy level and collection day × canopy level on leaflets can be explained by more mean residue being collected within 1 day of fungicide application on the upper leaf canopy by AIRCHEM than in the other canopy levels by either fungicide application method and collection times. This resulted presumably from less dilution of fungicide by aerial application (applied in 65 L/ha of water) portion of AIRCHEM than by CHEM alone (applied in 25,442 L/ha of water), and more residue being deposited on the upper canopy with an air application, even with the diluting factor of alternating with chemigation. Fungicide, regardless of chlorothalonil or mancozeb, is more evenly distributed through the canopy with CHEM, evidenced by no significant differences between the canopy levels within the CHEM method except on the 7-day collection in 1999 on leaflets where reduced residue values were found (Table 2). Previous work has shown similar results with the use of chlorothalonil (Archer et al. 1991; Geary et al. 1999; Hamm and Clough 1999), but no one has reported redistribution from the use of mancozeb. Regardless of distribution of residue through the canopy on leaflets, AIRCHEM had greater residue amounts for every canopy level within each collection day compared to CHEM.

The response of method of fungicide application by collection day (no interaction) when canopy levels are combined showed a significant difference in residue amounts on leaflets (Table 2). The hierarchy of residue response on leaflets from highest to lowest is as follows: AIRCHEM/1 day > AIRCHEM/7 day > CHEM/1 day > CHEM/7 day except for 2000 mancozeb trial where AIRCHEM/7 day < CHEM/1 day. In the two trials in 2000, the AIRCHEM/7 day and the CHEM/1 day residue values were not significantly different. Stems had less residue, but followed a similar hierarchy as leaflets. The AIRCHEM/1 day residue was significantly greater than the CHEM/7 day residue, for both leaflet and stems, in all trials.

Deposition of chlorothalonil or mancozeb on potato stems has not been previously measured. Even though residue amounts deposited on stems followed the same residue distribution pattern as on leaflets for method of fungicide application or day of collection, the amount of residue deposited or maintained on stems was substantially and significantly less (95% confidence intervals) than leaflets during these trials. This may be explained by plant architecture. Leaves in a potato canopy extend outward from stem and intercept droplets from above. This is in contrast to the stems, which are vertical and shielded by the leaves. Interestingly, when US 1 was the predominate genotype found in the Columbia Basin

and sensitive to the widely and successfully used systemic fungicide containing mefenoxam, the occurrence of *P. infestans* on stems was low in contrast to leaf infections. However, when US 8 became the predominate genotype, stem infections became common. This could be explained by more aggressive strains (Miller et al. 1998) and/or the lack of sufficient protectant fungicide amounts on the stems to prevent infection. No reports have compared relative susceptibility of potato stems vs leaves nor have comparisons been reported on relative aggressiveness of US 1 or US 8 to stems and leaves. However, Geary et al. (1999) reported more disease from US 8 genotypes on fungicide treated leaves than from US1. Others have suggested that fungicide programs directed at new strains would require shortened fungicide application intervals or more aggressive use of fungicides (Mayton et al. 2001; Miller et al. 1998). Insufficient amounts of protectant fungicides in the canopy may have contributed to the rapid change from US 1 to aggressive US 8 genotypes in the Columbia Basin reported by Miller et al. (1997). Fungicide amounts may have been adequate to control US 1 genotype but not US 8.

Inoculation of leaves and stems in 1999 with *P. infestans* confirmed results from the residue analysis. The expected inverse relationship between mean chlorothalonil fungicide residue and disease severity and incidence was evident from disease severity on leaves ($P = 0.07$) and incidence on stems ($P < 0.01$). Disease severity and incidence were significantly greater on leaflets at the 7-day collection period after CHEM (Table 4), which inversely compared with the lowest amount of chlorothalonil residue from the similar 1999 7-day collection (Table 1). Others have reported that greater amounts of fungicide on leaves results in greater late blight control (Geary et al. 1999, 2004) and while inoculation of leaves and stems treated with mancozeb was not attempted during the work reported here, a similar inverse relationship is likely between residue amounts and infection. The substantially reduced amounts of chlorothalonil when applied by CHEM after 7 days (Table 2) may further suggest poor disease control is likely without another fungicide application. Disease incidence on stems ($P \leq 0.01$) was more conclusive than disease severity on stems.

The objectives of this work to compare two fungicide application programs for their ability to deposit fungicide on stems and leaves of potato were achieved. The two fungicides used served as a medium to evaluate the treatments and both supported the conclusions. Greater levels of fungicide resulted in the use of AIRCHEM compared to CHEM and that greater fungicide residues were found on leaves vs stems. Both materials are broad spectrum in activity, function as contact fungicides, and the deposition and redistribution patterns of chlorothalonil and mancozeb were expected to be similar, as was demonstrated in this study. Mancozeb was used only one year in this study, and the cost of an additional year did not seem justified given that deposition patterns of the two fungicides were similar and similar to three earlier studies that described the deposition and redistribution of chlorothalonil on leaves in a potato canopy (Geary et al. 1999, 2004, Hamm and Clough 1999). These distinct similarities were found even with the use of one to two replications the second year of the study. However, the use of repeated measures, which provided multiple data collection $\times$ 1 day and $\times$ 7 days after fungicide application, each with in-field replications, provided valid statistical comparisons. In addition, there is considerable value in collecting research data to fulfill the objectives of this study from commercial fields using commercial application methods vs data from small plots using methods that simulated commercial fungicide applications.

Fungicide applications using AIRCHEM is a cost-saving means for applying fungicides to control late blight. A mean total cost for one late blight fungicide application in the Columbia Basin of Washington is currently approximately $42.08/ha (unpublished data). In a program where 12 fungicide applications are necessary to control late blight, by using AIRCHEM growers could save $51.98/ha (or $8.66/ha/fungicide application, the difference in cost/treatment between air and chemigation when chemigation is used during six of those fungicide applications) compared to air application alone. Late-season fungicide applications could be accomplished at no additional cost using savings from a rotation AIRCHEM reported here, which would result in better disease control and reduced tuber damage in storage.

Of greater value than the cost savings may be the greater fungicide residue and better protection in the canopy by using AIRCHEM compared to CHEM alone. The work reported here found the amount of fungicide residue on leaflets by alternating fungicide application methods to be nearly two to 10 times greater (Table 2). Greater level of fungicides relate to better disease control (Geary et al. 1999, 2004). This added amount of protection in the canopy may reduce late blight infection and/or damage, reducing the risk at the end of the growing season when some growers stop their applications of late blight fungicides. Growers are resistant to late-season fungicide

applications because of the high costs they have already expended, particularly when potato values are soft, late blight incidence in the area has been low, and open canopy conditions due to natural plant senescence suggests lower humidity and conditions less conducive for disease development. However, risks actually are increasing later in the season due to moisture on foliage maintained by dew, irrigation, reduced temperatures, reduced evaporation, and reduced solar radiation (Harrison 1992). In addition, reduced temperatures encourage zoospore formation thought to be important for infecting tubers (Crosier 1934; Harrison 1992).

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