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Containment of existing potato late blight (*Phytophthora infestans*) foliar epidemics with fungicides

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Abstract

Critical timing of application of foliar fungicides to limit further infection of potato foliage by *Phytophthora infestans* and the critical threshold of foliar infection level at which individual or combinations of specific fungicides limited further spread of infection with *P. infestans* were determined. In most seasons, key application timings at which the foliar late blight epidemic was contained to <50% of that in untreated control plots, were programs initiated 72 h before and 72 h after inoculation with *P. infestans*, and when foliar area with late blight lesions was estimated to be 1% or less. Delaying initiation of application of any fungicide until 5% and 10% estimated average foliar area with late blight lesions resulted in late blight development similar to the untreated control. Most fungicides and fungicide mixtures examined resulted in 30–50% reduction of late blight development in comparison to the untreated control as long as they were applied not later than 1% estimated average foliar area with late blight lesions. © 2002 Published by Elsevier Science Ltd.

Keywords: *Solanum tuberosum*; Oomycete; Disease control

1. Introduction

Potato late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is the economically most important potato disease in North America (Inglis et al., 1996). The asexual life cycle of *P. infestans* is short; and sporulating foliar lesions develop three to seven days after successful infection under conducive conditions (Maltese et al., 1995), resulting in a polycyclic epidemic (Zwankhuizen et al., 1998). Following the migration of phenylamide fungicide insensitive populations of *P. infestans* from Mexico to Europe and then to the rest of North America, estimated to have occurred during the early 1990s (Fry and Goodwin, 1997), control recommendations for potato late blight changed. This migration necessitated cultural control methods and crop protection strategies that relied primarily on protectant foliar fungicide applications (Secor and Gudmestad, 1999) as the characteristics of the replacement products required such usage patterns (Bruck et al., 1981; Schwinn and Margot, 1991; Schwinn and Staub, 1995).

Three basic types of foliar fungicide programs are typically used in North America; full-protectant, weather-based protectant and curative (Krause et al., 1975; Fry, 1977; Bootsma, 1979; Fry et al., 1979; Mackenzie, 1981; Raposo et al., 1993). Full-protectant foliar fungicide programs begin before the predicted or actual onset of potato late blight, consist of fungicide applications that continue throughout the growing season at regular intervals, and may be initiated by weather-based potato late blight prediction models (Mackenzie, 1981; Johnson et al., 1996). Full-protectant programs potentially require unnecessary input in seasons that are non-conducive to potato late blight development, and may have the most environmental impact; however, they have the least failure risk as fungicides are applied regardless of disease pressure.

Protectant fungicide programs that are fully weather-based are initiated like full-protectant programs, but the application interval and/or product rates vary depending on meteorological events (Krause et al., 1975; Stevenson, 1993). Weather modeled protectant programs can potentially reduce fungicide usage without increased foliar disease (Mackenzie, 1981), but may fail as many of the currently available potato late blight models in the United States were based upon the

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displaced clonal US1/A1 lineage (Mizubuti and Fry, 1998), were generally region specific (Grunwald et al., 2000) and may not account for local climatic variations (Johnson et al., 1996). During periods deemed non-conducive by weather models, lesions may remain viable and continue to sporulate at a reduced rate (Kable and Mackenzie, 1980) and without continued fungicide applications during these periods control failure is possible. During highly conducive conditions, weather-based programs can have fungicide application rates and schedules identical to full-protectant programs. Control failure factors common to both protectant schemes are: late blight contaminated seed (Inglis et al., 1999), highly conducive environmental conditions that enhance the epidemic rate (Baker, Kirk, and Stein, unpublished data, 2001), and fungicide misapplication or application at sub-effective rates (Kirk et al., 2001).

Curative programs are initiated following the discovery or predicted onset of late blight (Fry et al., 1979). These can have the lowest level of fungicide input, but have the highest potential for failure. Disease detection aptitude varies and current fungicide products are most efficacious with preventative usage (Schwinn and Margot, 1991; Secor and Gudmestad, 1999); therefore, attempts at controlling potato late blight curatively following establishment and spread may result in extensive fungicide application of more expensive products (Johnson et al., 2000) and increased fungicide resistance selection pressures (Brent, 1995). The prevention of infection with *P. infestans* of previously uninfected potato tissue from infected tissue located within the same canopy may be defined as containment of late blight.

The objectives of this study were to determine whether currently available fungicides and those close to market release applied alone or in combination were capable of limiting the spread of foliar late blight when applied relative to the inoculation event and when the plants reached various percent foliar infection thresholds.

2. Materials and methods

2.1. Experimental design and agronomic management

Cut potato seed (cv. Snowden) was planted at the Michigan State University Muck Soils Experimental Station, Bath, MI, USA between 3–10 June, 1996, 1998, 1999 and 2000 into two-row by 7.6 m plots (90 cm row and 23 cm plant spacing). Application initiation timings within each year were physically separated and treatments were replicated four times in a randomized complete block design within each timing. Inoculation, assessment of foliar late blight and maintenance pesticide application dates were similar for all years. The two-row beds were separated by a 1.5 m unplanted row. Plots were irrigated as necessary to maintain canopy and soil moisture conditions conducive for the development of foliar (Wallin, 1953) late blight with turbine rotary garden sprinklers (Gilmour Group, Somerset, PA, USA) at 10551 H_2O ha^{-1} h^{-1} and managed under standard potato agronomic practices for the region (Kudwa, 1999). Weeds were controlled by hilling and with metolachlor at 0.46 a.i. kg ha^{-1} ten days after planting (dap), bentazon salt at 0.12 a.i. kg ha^{-1}, 20 and 40 dap and sethoxydim at 0.05 a.i. kg ha^{-1}, 58–60 dap. Insects were controlled with imidacloprid at 1.4 a.i. kg ha^{-1} at planting, carbaryl at 1.4 a.i. kg ha^{-1}, 31 and 55 dap, endosulfan at 0.98 a.i. kg ha^{-1}, 65 and 87 dap and permethrin at 0.56 a.i. kg ha^{-1}, 48 dap.

2.2. Fungicides

Fungicides were applied with an ATV rear-mounted spray boom (R&D Sprayers, Opelousas, LA, USA) which traveled at 1 m s^{-1} and delivered 2301 H_2O ha^{-1} (3.5 kg cm^{-2} pressure) with three XR11003VS (Spray Systems, Pomona, CA, USA) nozzles per row positioned 45 cm above the canopy. Three applications were performed on seven-day intervals, commencing at 72 h before or 72 h after inoculation, or when the percent average foliar late blight level reached putative scouting thresholds (Kirk et al., 2000) of 1%, 5% or 10% (subjective estimations). Trade names, formulations, and active composition of treatments are listed in Table 1. Treatment, rate and application initiation thresholds for 1996, 1998, 1999 and 2000 are listed in Tables 2–5.

2.3. Inoculation

Inoculum for a mixed isolate zoospore suspension of phenylamide-insensitive *P. infestans* US8 genotype (Goodwin et al., 1995) and A2 mating type was produced by growing previously isolated and characterized isolates on modified rye B agar (Caten and Jinks, 1968) consisting of the filtrate of pre-rinsed rye (*Secale cereale* L.) seeds (100.0 g) boiled for 1 h, glucose (8.0 g), β-sitosterol (0.05 g) and agar (15.0 g) in petri plates. Cultures were grown for 21–28 days at 18–20°C with a 12-hour light/dark cycle to induce sporulation. Sporangia were harvested by scraping the mycelium into sterile de-ionized water and agitated with a magnetic stir rod for 15 min. The mycelial suspension was incubated at 8°C for 3 h to induce zoosporogenesis and filtered through four layers of cheesecloth to remove hyphae. Sporangia were counted with a hemacytometer and the concentration was diluted as required. Plots were inoculated by injecting the zoospore suspension into the irrigation system (1.76×10^6 zoospores ha^{-1}, 45–57 dap).

Table 1
Fungicides examined: trade names and formulation, manufacture names and addresses, active ingredients and formulation rates

Trade name	Manufacturer and address	Active ingredient(s) and rate
Acrobat 50WP	BASF Corporation, 26 Davie Drive, Research Triangle Park, NC 27709	Dimethomorph 500 g kg^{-1}
Acrobat MZ 69WP	BASF Corporation, 26 Davie Drive, Research Triangle Park, NC 27709	Mancozeb 600 g kg^{-1} + dimethomorph 90 g kg^{-1}
Banol 6.65SC	Aventis CropScience, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709	Propamocarb hydrochloride 720 g l^{-1}
Bravo WS 6SC	Syngenta Crop Protection, PO Box 18300, Greensboro, NC 27419	Chlorothalonil 720 g l^{-1}
Champ 2 4.6FL	Agtrol Chemical Products, 7322 Southwest Freeway Suite 1400, Houston, TX 77074	Copper hydroxide 550 g l^{-1}
Curzate 60DF	du Pont de Nemours and Co., Agricultural Products, Wilmington, DE 19898	Cymoxanil 600 g kg^{-1}
Curzate M8 72DF	du Pont de Nemours and Co., Agricultural Products, Wilmington, DE 19898	Mancozeb 660 g kg^{-1} + cymoxanil 60 g kg^{-1}
Dithane 75DF	Rohm and Haas, 100 Independence Mall West, Philadelphia, PA 19106	Mancozeb 750 g kg^{-1}
Omega 500F	Syngenta Crop Protection, PO Box 18300, Greensboro, NC 27419	Fluazinam 500 g l^{-1}
Polyram 80DF	BASF Corporation, 26 Davie Drive, Research Triangle Park, NC 27709	Metiram 800 g kg^{-1}
Quadris 2.08SC	Syngenta Crop Protection, PO Box 18300, Greensboro, NC 27419	Azoxystrobin 250 g l^{-1}
Quadris 80WDG	Syngenta Crop Protection, PO Box 18300, Greensboro, NC 27419	Azoxystrobin 800 g kg^{-1}
Ridomil Gold 4EC	Syngenta Crop Protection, PO Box 18300, Greensboro, NC 27419	Mefenoxam 480 g l^{-1}
Supertin 80WP	Griffin Corporation, P.O. Box 1847 Rocky Ford Rd., Valdosta, GA 31603^{-1}847	Triphenyltin hydroxide 800 g kg^{-1}
Tattoo C 6.25SC	Aventis CropScience, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709	Chlorothalonil 374 g l^{-1} + propamocarb hydrochloride 374 g l^{-1}

Table 2
Efficacy of fungicides against foliar potato late blight applied three times at a seven-day interval at three application initiation timings measured as RAUDPC$_N$; field results 1996: treatments listed as active ingredient(s), formulation and rate of application (kg ha^{-1})

Actives applied with formulation and rate of application (kg ha^{-1})	RAUDPC$_N$[a]		
	72 HAI[b]	1% FI[c]	10% FI
Azoxystrobin WDG (0.28)	0.150a[d]	0.474abc	0.983b
Chlorothalonil SC (1.27)\[e] mefenoxam EC (0.12)	0.109a	0.414abc	0.965ab
Chlorothalonil\propamocarb-HCl SC (2.02)	0.110a	0.190a	0.863ab
Chlorothalonil\propamocarb-HCl SC (2.02) + [f]triphenyltin-OH WP (0.13)	0.099a	0.187a	0.934ab
Copper-OH FL (1.77)	0.323b	0.714cd	0.973b
Mancozeb\copper-OH DF (1.31)	0.208ab	0.630bcd	0.989b
Mancozeb\cymoxanil DF (1.21)	0.093a	0.193a	0.944ab
Mancozeb\cymoxanil DF (1.21) + triphenyltin-OH WP (0.13)	0.088a	0.199a	0.831a
Mancozeb\dimethomorph WP (1.74) + triphenyltin-OH WP (0.13)	0.105a	0.200a	0.972b
Mancozeb\dimethomorph WP (1.74)	0.096a	0.293ab	0.918ab
Metiram DF (1.80) + triphenyltin-OH WP (0.13)	0.163a	0.397abc	0.944ab
Untreated control	1.000[g]c	1.000[g]d	1.000[g]b

[a] Relative area under the disease progress curve normalized to the untreated control.
[b] Hours after inoculation with *P. infestans* zoospores.
[c] Percent of foliage showing visible infection.
[d] Values followed by the same letter are NSD at $\alpha = 0.05$ (Tukey).
[e] Active ingredients separated by a "\" were pre-mixed.
[f] Active ingredients separated by a "+" were tank mixed.
[g] The RAUDPC value for the untreated control was 0.113, 0.279 and 0.294 for 72 HAI, 1% and 10% FI, respectively.

Table 3
Efficacy of fungicides against foliar potato late blight applied three times at a seven-day interval at two application initiation timings measured as RAUDPC$_N$; field results 1998: treatments listed as active ingredient(s), formulation and rate of application (kg ha^{-1})

Actives applied with formulation and rate of application (kg ha^{-1})	RAUDPC$_N$[a]	
	72 HAI[b]	1% FI[c]
Azoxystrobin SC (0.28) + [d]dimethomorph WP (0.22)	0.536a[e]	0.813a
Chlorothalonil SC (1.27)	0.638ab	0.954a
Chlorothalonil SC (1.27) + cymoxanil DF (0.15)	0.599a	0.966a
Chlorothalonil\[f] propamocarb SC (2.02)	0.630ab	0.923a
Dimethomorph WP (0.22)	0.851bc	0.847a
Dimethomorph WP (0.22) + triphenyltin-OH WP (0.13)	0.626ab	0.974a
Mancozeb\dimethomorph WP (1.74)	0.666ab	0.763a
Mancozeb DF (1.68) + triphenyltin-OH WP (0.13)	0.692ab	0.967a
Propamocarb SC (1.01) + imethomorph WP (0.22)	0.761ab	0.973a
Untreated control	1.000[g]c	1.000[g]a

[a] Relative area under the disease progress curve normalized to the untreated control.
[b] Hours after inoculation with *P. infestans* zoospores.
[c] Percent of foliage showing visible infection.
[d] Active ingredients separated by a "+" were tank mixed.
[e] Values followed by the same letter are NSD at $\alpha = 0.05$ (Tukey).
[f] Active ingredients separated by a "\" were pre-mixed.
[g] The RAUDPC value for the untreated control was 0.511 and 0.533 for 72 HAI and 1% FI, respectively.

2.4. Disease evaluation and data analysis

Subjective visual evaluations of percentage foliar late blight were made four to five days after inoculation and repeated on a four- to five-day interval until complete defoliation in untreated plots. The relative area under the disease progress curve (RAUDPC) metric was calculated for all plots using the following formula:

$$\mathrm{RAUDPC} = \frac{\sum_{i=0}^{\mathrm{final}}(T_i - T_{i-1})(P_{i-1}) + (T_i - T_{i-1})(P_i - P_{i-1})/2}{(T_{\mathrm{final}} - T_0)(100)}, \tag{1}$$

Table 4

Efficacy of fungicides against foliar potato late blight applied three times at a seven-day interval at four application initiation timings measured as RAUDPC$_N$; field results 1999: treatments listed as active ingredient(s), formulation and rate of application (kg ha^{-1})

Actives applied with formulation and rate of application (kg ha^{-1})	RAUDPC$_N$[a]			
	72 HBI[b]	72 HAI[c]	1% FI[d]	5% FI
Azoxystrobin SC (0.28)	0.476cd[e]	0.562c	0.698d	0.637a
Chlorothalonil SC (1.27)	0.487d	0.431bc	0.707d	0.630a
Chlorothalonil SC (1.27) + [f]cymoxanil DF (0.13)	0.346bc	0.350b	0.730d	0.602a
Chlorothalonil SC (1.27) + dimethomorph WP (0.22)	0.302ab	0.324ab	0.654cd	0.632a
Chlorothalonil\[g]propamocarb SC (2.02)	0.343bc	0.365b	0.573c	0.568a
Dimethomorph WP (0.22) + triphenyltin-OH WP (0.13)	0.437bcd	0.381b	0.577c	0.615a
Dimethomorph WP (0.33) + triphenyltin-OH WP (0.13)	0.426bcd	0.399b	0.566c	0.610a
Mancozeb DF (1.68) + triphenyltin-OH WP (0.13)	0.307ab	0.350b	0.466b	0.570a
Mancozeb DF (1.68) + triphenyltin-OH WP (0.26)	0.170a	0.216a	0.297a	0.581a
Untreated control	1.000[h]e	1.000[h]d	1.000[h]e	1.000[h]b

[a] Relative area under the disease progress curve normalized to the untreated control.

[b] Hours before inoculation with *P. infestans* zoospores.

[c] Hours after inoculation with *P. infestans* zoospores.

[d] Percent of foliage showing visible infection.

[e] Values followed by the same letter are NSD at $\alpha = 0.05$ (Tukey).

[f] Active ingredients separated by a "+" were tank mixed.

[g] Active ingredients separated by a "\" were pre-mixed.

[h] The RAUDPC value for the untreated control was 0.387, 0.252, 0.470 and 0.476 for 72 HBI and HAI, 1% and 10% FI, respectively.

Table 5

Efficacy of fungicides against foliar potato late blight applied three times at a seven-day interval at four application initiation timings measured as RAUDPC$_N$; field results 2000: treatments listed as active ingredient(s), formulation and rate of application (kg ha^{-1})

Actives applied with formulation and rate of application (kg ha^{-1})	RAUDPC$_N$[a]			
	72 HBI[b]	72 HAI[c]	1% FI[d]	5% FI
Chlorothalonil SC (1.27) + [e]azoxystrobin SC (0.28)	0.378a[f]	0.423a	0.412a	0.994a
Chlorothalonil SC (1.27) + cymoxanil DF (0.13)	0.403a	0.537a	0.541ab	0.854a
Chlorothalonil SC (1.27) + cymoxanil DF (0.15) + triphenyltin-OH WP (0.13)	0.384a	0.458a	0.496a	0.908a
Chlorothalonil\[g] propamocarb SC (2.02)	0.416a	0.508a	0.535a	1.077a
Chlorothalonil\propamocarb SC (2.02) + triphenyltin-OH WP (0.13)	0.483a	0.613a	0.401a	1.079a
Fluazinam FL (0.70)	0.348a	0.370a	0.377a	0.901a
Mancozeb\dimethomorph WP (1.74)	0.423a	0.503a	0.361a	0.782a
Mancozeb\dimethomorph WP (1.74) + triphenyltin-OH WP (0.13)	0.411a	0.488a	0.382a	1.062a
Mancozeb DF (1.68) + triphenyltin-OH WP (0.13)	0.452a	0.553a	0.536a	0.992a
Metiram DF (1.80) + dimethomorph WP (0.22)	0.523a	0.652a	0.391a	0.865a
Untreated control	1.000[h]b	1.000[h]b	1.000[h]b	1.000[h]a

[a] Relative area under the disease progress curve normalized to the untreated control.

[b] Hours before inoculation with *P. infestans* zoospores.

[c] Hours after inoculation with *P. infestans* zoospores.

[d] Percent of foliage showing visible infection.

[e] Active ingredients separated by a "+" were tank mixed.

[f] Values followed by the same letter are NSD at $\alpha = 0.05$ (Tukey).

[g] Active ingredients separated by a "\" were pre-mixed.

[h] The RAUDPC value for the untreated control was 0.287, 0.237, 0.288 and 0.241 for 72 HBI and HAI, 1% and 10% FI, respectively.

where T_0 was the day of inoculation (zero point for calculation), T_i was the ith day after inoculation when an estimation of percent foliar late blight was made, T_{final} was the number of days after inoculation at which the untreated controls reached 100% defoliation, and P_i was the estimated percent foliar late blight at T_i. To remove variability due to localized differences in disease pressure, the RAUDPC was normalized within each replicate block as a percentage of the untreated control ($\text{RAUDPC}_N = \text{RAUDPC}_{\text{treatment}}/\text{RAUDPC}_{\text{untreated control}}$). The range of RAUDPC$_N$ was from 0 (lowest) to 1 (highest = RAUDPC$_{\text{untreated control}}$) within each replicate block. Analysis of variance was calculated (SigmaStat, SPSS Inc., Chicago, IL, USA) at $\alpha = 0.05$ via pair-wise comparisons using Tukey's HSD.

3. Results

Treatments and the RAUDPC values normalized to the untreated control (RAUDPC_N) are shown in Tables 2–5 for 1996, 1998, 1999 and 2000, respectively. Treatments separated by a back slash "\" represent pre-mixed products, those separated by a plus sign "+" are tanked mixed at the time of application.

3.1. Field results 1996 (Table 2)

For treatments initiated 72 h after inoculation, all fungicide programs had a significantly lower RAUDPC_N than the untreated control. Fungicide programs were not significantly different (NSD) from each other except copper hydroxide [(1.77 kg ha^{-1}), $\text{RAUDPC}_N = 0.323$] which had a significantly higher RAUDPC_N than all fungicide programs except for the mancozeb\copper hydroxide [(1.31 kg ha^{-1}), $\text{RAUDPC}_N = 0.208$] program. At the 1% foliar infection initiation, only the copper hydroxide [(1.77 kg ha^{-1}), $\text{RAUDPC}_N = 0.714$] and mancozeb\copper hydroxide [(1.31 kg ha^{-1}), $\text{RAUDPC}_N = 0.630$] programs did not have a significantly lower RAUDPC_N than the untreated control. Remaining programs were NSD from each other and had a significantly lower RAUDPC_N than the copper programs except the azoxystrobin [(0.28 kg ha^{-1}), $\text{RAUDPC}_N = 0.474$], chlorothalonil + mefenoxam [(1.27 kg ha^{-1} + 0.12 kg ha^{-1}), $\text{RAUDPC}_N = 0.414$], mancozeb\dimethomorph [(1.74 kg ha^{-1}), $\text{RAUDPC}_N = 0.293$] and metiram + triphenyltin hydroxide [(1.80 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.397$] programs. At 10% foliar infection treatment initiation, only the mancozeb\cymoxanil + triphenyltin hydroxide [(1.21 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.831$] program had a significantly lower RAUDPC_N than the untreated control. Remaining fungicide programs were NSD from each other.

3.2. Field results 1998 (Table 3)

For treatments initiated 72 h after inoculation, only the dimethomorph [(0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.851$] program did not have a significantly lower RAUDPC_N than the untreated control. All other treatment programs were NSD from each other, except the azoxystrobin + dimethomorph [(0.28 kg ha^{-1} + 0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.536$] and chlorothalonil + cymoxanil [(1.27 kg ha^{-1} + 0.15 kg ha^{-1}), $\text{RAUDPC}_N = 0.599$] programs had a significantly lower RAUDPC_N than the dimethomorph [(0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.851$] program. At 1% foliar infection treatment initiation, none of the fungicide programs had a significantly lower RAUDPC_N than the untreated control and were NSD from each other.

3.3. Field results 1999 (Table 4)

For treatments initiated 72 h before inoculation, all fungicide programs had a significantly lower RAUDPC_N than the untreated control. The mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.26 kg ha^{-1}), $\text{RAUDPC}_N = 0.170$] program had a significantly lower RAUDPC_N than all fungicide programs except the mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.307$] and chlorothalonil + dimethomorph [(1.27 kg ha^{-1} + 0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.302$] programs. The chlorothalonil [(1.27 kg ha^{-1}), $\text{RAUDPC}_N = 0.487$] program had a significantly higher RAUDPC_N than all other programs except the azoxystrobin [(0.28 kg ha^{-1}), $\text{RAUDPC}_N = 0.476$], dimethomorph + triphenyltin hydroxide [(0.22 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.437$] and dimethomorph + triphenyltin hydroxide [(0.33 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.426$] programs. The remaining programs were NSD from each other. With treatment initiation 72 h after inoculation, all fungicide programs had a significantly lower RAUDPC_N than the untreated control. The mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.26 kg ha^{-1}), $\text{RAUDPC}_N = 0.216$] program had a significantly lower RAUDPC_N than all fungicide programs except the chlorothalonil + dimethomorph [(1.27 kg ha^{-1} + 0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.324$] program. The azoxystrobin [(0.28 kg ha^{-1}), $\text{RAUDPC}_N = 0.562$] program had a significantly higher RAUDPC_N than all programs except the chlorothalonil [(1.27 kg ha^{-1}), $\text{RAUDPC}_N = 0.431$] program. Remaining programs were NSD from each other. For treatments initiated at 1% foliar infection, all fungicide programs had a significantly lower RAUDPC_N than the untreated control. The mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.26 kg ha^{-1}), $\text{RAUDPC}_N = 0.297$] program had a significantly lower RAUDPC_N than all fungicide programs. The mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.466$] program had a significantly lower RAUDPC_N than remaining fungicide programs. The azoxystrobin [(0.28 kg ha^{-1}), $\text{RAUDPC}_N = 0.698$], chlorothalonil [(1.27 kg ha^{-1}), $\text{RAUDPC}_N = 0.707$] and chlorothalonil + cymoxanil [(1.27 kg ha^{-1} + 0.13 kg ha^{-1}), $\text{RAUDPC}_N = 0.730$], programs had significantly higher RAUDPC_N than all other programs except chlorothalonil + dimethomorph [(1.27 kg ha^{-1} + 0.22 kg ha^{-1}), $\text{RAUDPC}_N = 0.654$]. Remaining programs were NSD from each other. At the 5% foliar infection initiation timing, all fungicide programs had a significantly lower

$RAUDPC_N$ than the untreated control but were NSD from each other.

3.4. Field results 2000 (Table 5)

For treatments initiated 72 h before and after inoculation, all fungicide programs had a significantly lower $RAUDPC_N$ than the untreated control but were NSD from each other. At the 1% foliar infection initiation, all fungicide programs had a significantly lower $RAUDPC_N$ than the untreated control except the chlorothalonil + cymoxanil [(1.27 kg ha^{-1} + 0.13 kg ha^{-1}), $RAUDPC_N = 0.541$] program. All fungicide programs were NSD from each other. At the 5% foliar infection initiation, none of the fungicide programs was NSD from the untreated control.

4. Discussion

Containment of potato late blight in this study was defined as the prevention of *P. infestans* spread to uninfected tissue within the potato canopy. None of the treatments examined at any application timing completely prevented infection of disease-free tissue. Thus, containment may be redefined as the limitation of the epidemic to an extent significantly less than that measured in untreated controls and ranged from 8.8% to 83.1% (percent of $RAUDPC_N$, best to poorest), depending on the timing of initiation of the fungicide applications and seasonal potato late blight severity conditions. These results demonstrated that initiation of application of all fungicides and combinations 72 h before or after inoculation successfully contained potato late blight foliar epidemics in most instances. Containment failures occurred sporadically when programs were initiated at the 1% foliar infection level and consistently at the 5% foliar infection level. Therefore, the initiation of fungicide applications after observation of 1% estimated average foliar late blight was at risk of failure regardless of fungicide type and mode of action.

Initiation of fungicide applications 72 h before inoculation represented a program dependent on attainment of a weather-derived disease threshold. Fungicide applications initiated at this timing resulted in the lowest amount of late blight development through the presumed inhibition of infection, resporulation, and secondary infection events. Most commercially available fungicides used to control potato late blight disrupt the pre-infection stages of the asexual life cycle of *P. infestans* (Bruck et al., 1981; Schwinn and Margot, 1991; Schwinn and Staub, 1995) and the highest level of disease control for the pre-infection applications is consistent with this information. Few products disrupt resporulation from previously established lesions (Albert et al., 1991; Schwinn and Staub, 1995; Johnson et al., 2000; Matheron and Porchas, 2000), but any reduction in the sporangial production is likely to have a negative impact upon the epidemic rate.

The treatments that consistently failed to prevent or halt development of late blight were those based upon fungicides that are typically used in multiple active ingredient formulations, such as copper hydroxide and dimethomorph. The United States product label rates for these compounds were typically determined using mixtures with another active ingredient and the rate when used alone is not sufficient for late blight control. The only program that had a higher level of containment compared with the other fungicide programs across multiple application initiation timings and within the same year was the mancozeb + triphenyltin hydroxide [(1.68 kg ha^{-1} + 0.26 kg ha^{-1})] program in 1999 which was twice the label rate for an application of triphenyltin hydroxide in the United States. Applications initiated within 72 h pre- or post-inoculation reduced the amount and spread of late blight in comparison to applications delayed until foliar lesions could be observed. These field experiments emphasize the importance of preventative applications of effective fungicides for late blight prevention.

The current portfolios of active ingredients are not effective enough to support their use for containing epidemics occurring under conducive conditions and when applied in accordance with current labeled recommendations. As late blight epidemics remain the norm in many years in potato producing regions of North America, it may become necessary to re-evaluate application frequencies and establish rates of application of currently available fungicides for emergency use in order to manage and contain late blight after it has become established within the canopy.

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