Effect of Host Plant Resistance and Reduced Rates and Frequencies of Fungicide Application to Control Potato Late Blight

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ABSTRACT

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Field experiments were conducted during 1998 to 2000 to determine the response of commercial potato cultivars and advanced breeding lines (ABL) differing in susceptibility to foliar late blight (caused by *Phytophthora infestans*) to reduced rates and frequencies of residual, contact fungicide applications. When environmental conditions were most favorable for the development of late blight, the lowest application rate of the fungicides chlorothalonil or fluazinam (33% of the manufacturers' recommended application rate [MRAR]) gave unsatisfactory control of potato late blight. Under conditions moderately conducive for late blight development, effective control was achieved with 33 to 66% MRAR with either fungicide. The Michigan State University advanced selection, MSG274-3, was the least susceptible ABL tested and, during 1998 to 2000, late blight was effectively managed using reduced rates of fungicides. Application rates of chlorothalonil (33 to 100% MRAR) significantly reduced late blight in the cultivar Snowden (5-day application interval) compared with the nontreated control; whereas, late blight was not effectively controlled in Snowden even at 100% MRAR of chlorothalonil at either 10- or 15-day application intervals in 1999 or 2000. The ABL MSG274-3 was the least susceptible of all cultivars and ABL used in this study, and required minimal chemical protection against late blight. The study demonstrates that ABL with reduced susceptibility to late blight can be managed with reduced fungicide rates and longer application intervals, thus offering more economical control of this disease.

Additional keywords: advanced breeding lines, chlorothalonil, cultivar, fluazinam

Late blight of potato (*Solanum tuberosum*, L.) caused by *Phytophthora infestans* (Mont.) de Bary, is a major worldwide threat to the production of high quality potatoes (12). Unchecked, *P. infestans* can rapidly defoliate plants in the field and can infect potato tubers when spores are washed into the soil (15). Prior to the early 1990s, the population of *P. infestans* throughout much of the world was clonal, mefenoxam/metalaxyl sensitive, and US1/A1 (genotype/mating type; 13). Potato late blight control strategies changed following the migration of mefenoxam/metalaxyl-resistant populations of *P. infestans* from Mexico to North America in the 1990s (12) and necessitated cultural control methods and crop protection strategies that rely primarily on protectant foliar fungicide applications (12,18). Although fungicides have been used to manage late blight, both the efficacy and availability of commonly used fungicides have been threatened. This problem is compounded by the demand to reduce chemical input in agricultural systems (9) and the potential loss of commonly used protectant fungicides such as chlorothalonil (14) and metalaxyl/mefenoxam (17). In addition, the cost of protecting potato crops in the United States against late blight is estimated at $155 million annually (19). Therefore, crop production economics would suggest that more economical, yet still effective methods of disease control need to be developed.

There are several potential methods for reducing fungicide inputs in potato crop management. These include the use of fungicides with less active ingredient, reduced application rates, longer application intervals, and a combination of any of these strategies. In addition, Fry (10,11) observed that a combination of cultivar resistance and regular applications of protective fungicides reduced foliar late blight infection in potato. There are currently no late blight resistant potato cultivars that meet commercial standards in the United States. However, controlled environment and field trials at Michigan State University have identified certain foreign cultivars and advanced breeding lines (ABL) that are less susceptible to foliar late blight in the absence of fungicides than important cultivars grown and developed in the United States (e.g., Snowden, Atlantic, and Russet Burbank; 4–6,8). Typical fungicide application programs use a 5- to 7-day spray interval, depending on environmental conditions and grower preference. The frequent fungicide spray intervals and rates currently used by growers to control late blight are expensive and more economical control measures are needed. Therefore, the objective of this research was to determine if acceptable control of foliar late blight can be achieved by using increased fungicide spray intervals and reduced application rates of residual contact fungicides on potato germplasm with a range of susceptibility to late blight.

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MATERIALS AND METHODS

Five field experiments were performed during 1998 to 2000 to satisfy the objectives of this study. These are referred to as the "Cultivar/ABL by Fungicide Active Ingredient Trials" (three trials, 1998 to 2000) and the "Fungicide Application Interval and Reduced Dose Rate Trials" (two trials, 1998 and 2000).

Potato germplasm. Previous experiments (4–7) at Michigan State University have identified potato cultivars and ABL with different responses to foliar late blight. MSG274-3 has consistently been one of the most late blight resistant ABL in 4 years of testing, whereas Snowden has consistently been one of the most susceptible (4–7). In the present study, any cultivar or ABL with foliar late blight severity measured as the relative area under the disease progress curve (RAUDPC; 1) value that was not significantly higher than that of MSG274-3 was classified as late blight resistant (R). Any cultivar or ABL with a RAUDPC value significantly higher than that of Snowden or with a RAUDPC value that was not statistically different from that of Snowden was classified as late blight susceptible (S). Cultivars and ABL were classified as moderately resistant (M) if the

RAUDPC value was significantly higher than that of MSG274-3 but significantly lower than that of Snowden. The potato cultivars and ABL used to assess the efficacy of reduced fungicide application rate varied among years but always included late blight susceptible controls (e.g., Snowden and Atlantic) and cultivars and ABL classified as moderately resistant or resistant to late blight (4–7). The susceptible cultivar Snowden and the resistant ABL MSG274-3 were used in both 1999 and 2000 to assess the efficacy of increased fungicide application intervals in combination with reduced application rates of chlorothalonil against potato late blight. The cultivars and ABL included in the trials from 1998 to 2000 are listed in Table 1.

Residual contact fungicides. Field experiments to evaluate the efficacy of various fungicide protection strategies against late blight were conducted during 1998 to 2000. The fungicides chlorothalonil 6SC (Bravo WS 6SC; Syngenta Crop Protection, Inc., Greensboro, NC) and fluazinam 5SC (noncommercial formulation; ISK Biosciences Corporation, Mentor, OH) were used. The manufacturer's recommended applications rates (MRAR) for chlorothalonil are 0.87 kg a.i./ha/application and 9.2 kg a.i./ha/season (20) and for fluazinam are 0.15 a.i./ha/application and 1.5 kg a.i./ha/season (23). Fungicides were applied with an ATV rear-mounted spray boom (R&D Sprayers, Opelousas, LA) that traveled at 1 m/s and delivered 230 liters of H_2O/ha (3.5 kg/cm^2 pressure) with three XR11003VS nozzles per row positioned 30 cm apart and 45 cm above the canopy.

In the cultivar × fungicide active ingredient trials, chlorothalonil 6SC and fluazinam 5SC were applied at MRAR (20,23) of 0%, 33% (chlorothalonil 6SC at 0.29 kg a.i./ha and fluazinam 5SC at 0.05 kg a.i./ha), 66% (chlorothalonil 6SC at 0.57 kg a.i./ha and fluazinam 5SC at 0.1 kg a.i./ha), and 100% (chlorothalonil 6SC at 0.87 kg a.i./ha and fluazinam 5SC at 0.15 kg a.i./ha), resulting in seven different fungicide treatments that were applied to all cultivars and ABL on a 7-day spray interval. The trials received nine, eight, and eight fungicide applications in 1998, 1999, and 2000, respectively.

In the fungicide application interval and reduced dose rates trials, chlorothalonil 6SC was applied at 5-, 10-, and 15-day intervals at 0, 33, 66, and 100% MRAR (16) to both Snowden and MSG274-3. The first fungicide application occurred at 27 days after planting (DAP) (21 June 1998) and 22 DAP (2 July 2000) when potato plants were approximately 15 cm tall. Fungicides were applied until nontreated plots of susceptible controls reached about 100% diseased foliar area. The 5-, 10-, and 15-day interval treatments received 12, 8, and 6 applications, respectively, in 1998 and 2000.

Experimental design and agronomic practices. All experiments were conducted at the Michigan State University Muck Soils Research Station, Bath (90% organic muck soil). Soils were plowed to a 20-cm depth during October following harvest of preceding crops. Soils were prepared for planting with a mechanical cultivator in early May and fertilizer applied during final bed preparation on the day of planting. Cultivars and ABL were planted on 25 May 1998, 30 May 1999, and 9 June 2000 in two-row-by-8-m plots (0.9-m row spacing). Fertilizers were applied in accordance with results from soil testing carried out in the spring of each year and about 250 kg of N per hectare (total N) was applied in two equal doses at planting and hilling. Additional micronutrients were applied according to petiole sampling recommendations in all years. Boron, manganese, and magnesium at approximately 0.2, 0.3, and 0.2 kg/ha, respectively, were applied as chelated formulations. Cut and whole seed pieces (75 to 150 g) of selected cultivars and ABL were used in all experiments.

The experimental designs for the cultivar × fungicide active ingredient trials were split block with the four replications as blocks and the seven fungicide treatments as sub-blocks. Cultivars and ABL were randomized within blocks. Data were analyzed using the PROC MIXED function in SAS and least significant difference (LSD) at $P = 0.05$ was calculated using the appropriate error terms. LSD was used to determine if there were significant differences among treatments on the same cultivar or ABL and to compare different treatments on different cultivars and ABL.

The experimental design for the fungicide application interval and reduced dose rate trials were randomized complete block designs with four replications. In both trials, if a fungicide treatment on a cultivar or ABL resulted in a RAUDPC that was not significantly higher than nontreated MSG274-3, then it was classified as effective late blight control (E). Any fungicide treatment and cultivar or ABL combination in which the RAUDPC was significantly higher than or was not significantly different from that of nontreated Snowden was classified as a noneffective (NE) treatment. Furthermore, if a fungicide treatment on a cultivar or ABL resulted in an RAUDPC significantly higher than that of nontreated MSG274-3 but significantly less than that of nontreated Snowden, then the treatment was classified as providing intermediate late blight control (I).

When relative humidity (RH) dipped below 80% (measured with RH sensors

Table 1. Potato cultivars and advanced breeding lines (ABL) from Michigan State University potato breeding program included in cultivar × fungicide interaction trials from 1998 to 2000

	Trial				
	Cultivar × fungicide			Fungicide timing	
Cvs. and ABL[a]	1998	1999	2000	1999	2000
North American commercial	Atlantic	Atlantic	Snowden	Snowden	Snowden
	Snowden	Snowden	FL1625	…	…
	FL1533	FL1625	FL1930	…	…
	FL1625	FL1833	…	…	…
Foreign commercial	Lily	…	…	…	…
	Matilda	…	…	…	…
	Zarevo	…	…	…	…
	Picasso	…	…	…	…
ABL	MSA091-1	MSA091-1	MSE018-1	MSG274-3	MSG274-3
	MSC103-2	MSE018-1	MSF373-8	…	…
	MS018-1	MSE246-5	MSG050-2	…	…
	MSE230-6	MSG274-3	MSG124-8P	…	…
	MSE246-5	MSG274-3	…	…	…
	MSG007-1	…	…	…	…
	MSG141-3	…	…	…	…
	MSG274-3	…	…	…	…
	MSG297-4	…	…	…	…

[a] ABL from the Michigan State University potato breeding program.

mounted within the canopy), a mist irrigation system was turned on to maintain RH at >95% within the plant canopy. Plots were irrigated as necessary to maintain canopy and soil moisture conditions conducive for development of foliar late blight (16) with turbine rotary garden sprinklers (Gilmour Group, Somerset, PA) at 1,055 liters of H_2O per hectare per hour and managed under standard potato agronomic practices. Weeds were controlled by hilling and with metolachlor at 2.3 liters/ha, 10 DAP; bentazon salt at 2.3 liters/ha, 20 and 40 DAP; and sethoxydim at 1.8 liters/ha, 58 to 60 DAP. Insects were controlled with imidacloprid at 1.4 kg/ha at planting; carbaryl at 1.4 kg/ha, 31 and 55 DAP; endosulfan at 2.7 liters/ha, 65 and 87 DAP; and permethrin at 0.56 kg/ha, 48 DAP. The dates of application were similar for all years.

Pathogen preparation and inoculation. Zoospore suspensions were made from *P. infestans* cultures of a single isolate, (MI 95-7, US8 genotype, insensitive to mefenoxam/metalaxyl, A2 mating type; 13), the predominant biotype present in the major potato-growing regions of North America (12), grown on rye agar plates (3) for 14 days in the dark at 15°C. Sporangia were harvested from the rye agar plates by rinsing the mycelial and sporangial mat in cold (4°C), sterile, distilled water and scraping the mycelial and sporangial mat from the agar surface with a rubber policeman. The mycelial and sporangial suspension was stirred with a magnetic stirrer for 1 h. The suspension was strained through four layers of cheesecloth and the concentration of sporangia was adjusted to about 1×10^3 sporangia/ml using a hemacytometer. Sporangial cultures were incubated for 2 to 3 h at 4°C to stimulate zoospore release. All plots were inoculated simultaneously through an overhead sprinkler irrigation system on 25 July 1998, 23 July 1999, and 26 July 2000 by injecting the zoospore suspension of *P. infestans* into the irrigation water feed pipeline under 0.5 kg/cm^2 of CO_2 pressure and applied at a rate of about 150 ml of inoculum solution/m^2 of trial area. The amount and rate of inoculum applied was estimated from prior calibration of the irrigation system and was intended to expose all potato foliage to inoculum of *P. infestans*.

Disease evaluation and data analysis. As soon as late blight symptoms were detected (about 7 days after inoculation [DAI]), each plant within each plot was visually rated at 3- to 5-day intervals for percent leaf and stem (foliar) area with late blight lesions. The mean percent blighted foliar area per treatment was calculated. Evaluations continued until untreated plots of susceptible cultivars reached 100% foliar area diseased (33, 36, and 39 DAI in 1998, 1999, and 2000, respectively). These DAI were used as key reference points for calculation of RAUDPC (1). For each plot and assessment date, the area under the disease progress curve (AUDPC; 2,16) was estimated using the formula

$$\text{AUDPC} = \left(T_{i+1} + T_i\right) * \left(\frac{D_{i+1} + D_i}{2}\right)$$

where T was the time in days since inoculation and D was the estimated percentage of area with blighted foliage. As foliar late blight was assessed at various time intervals, the AUDPC was estimated with the area of a right triangle whose side lengths were based on the time interval and amount of late blight in the canopy. To accumulate AUDPC for the entire season and convert it to a rate over time, the formula was

$$\text{RAUDPC} = \frac{\sum \left(T_{i+1} - T_i\right) * \left(\frac{D_{i+1} + D_i}{2}\right)}{T_{\text{Total}} * 100}$$

Estimated AUDPCs for each interval were summed, divided by the total number of days to the 100% diseased foliar area reference point in the nontreated susceptible controls, and multiplied by 100, resulting in an accumulated assessment of seasonal disease estimated as a fraction of one (RAUDPC).

Microclimate measurement. Climatic variables were measured with a Davis Weather Station equipped with air temperature and humidity sensors located within the potato canopy on site (Spectrum Groweather ET Station; Spectrum Technologies, Inc., Plainfield, IL). Microclimate within the potato canopy was monitored beginning when 50% of the potato plants had emerged and ending when canopies of healthy plants reached 100% senescence. The Wallin Late Blight Prediction Model (22) was developed in the eastern United States under conditions similar to those in Michigan and was adapted to local conditions (1). Late blight disease severity values (DSV) were estimated from the Wallin Late Blight Prediction Model and accumulated from inoculation to final evaluation to estimate the conduciveness of the environment for late blight development.

Table 2. Mean relative area under the disease progress curve (RAUDPC; max = 100) in potato cultivars and advanced breeding lines (ABL) inoculated with *Phytophthora infestans* (US8, A2) and protected with reduced rates of chlorothalonil or fluazinam applied at a 7-day interval, sorted by order of susceptibility in nontreated control (1998)

		Mean RAUDPC					
		Chlorothalonil[a]			Fluazinam[a]		
Cv. or ABL	Nontreated	33	66	100	33	66	100
MSG274-3	3.05 (R)[b]	1.60 (E)	1.21 (E)	1.16 (E)	2.44 (E)	2.84 (E)	2.45 (E)
Zarevo	4.37 (R)	1.68* (E)	1.28* (E)	1.52* (E)	1.23* (E)	1.16* (E)	1.18* (E)
Lily	5.20 (R)	1.79* (E)	1.69* (E)	1.42* (E)	1.37* (E)	2.06* (E)	1.10* (E)
FL1625	9.30 (M)	1.40* (E)	1.28* (E)	1.26* (E)	1.06* (E)	1.33* (E)	0.98* (E)
MSE246-5	10.20 (M)	1.53* (E)	0.81* (E)	1.06* (E)	2.17* (E)	1.40* (E)	1.26* (E)
Matilda	10.34 (M)	1.60* (E)	1.01* (E)	0.96* (E)	2.31* (E)	1.91* (E)	1.20* (E)
Picasso	11.64 (M)	3.32* (E)	0.91* (E)	1.24* (E)	1.86* (E)	1.77* (E)	1.30* (E)
MSC103-2	12.12 (M)	1.54* (E)	1.30* (E)	1.67* (E)	1.38* (E)	1.79* (E)	1.53* (E)
MSA091-1	13.32 (M)	2.51* (E)	2.63* (E)	0.81* (E)	1.85* (E)	2.44* (E)	1.47* (E)
FL1533	17.70 (M)	3.15* (E)	1.21* (E)	1.75* (E)	2.91* (E)	2.67* (E)	1.41* (E)
MSE018-1	18.72 (M)	3.99* (E)	2.38* (E)	2.37* (E)	3.57* (E)	3.08* (E)	1.11* (E)
MSG141-3	19.76 (S)	7.57* (I)	7.29* (I)	4.69* (E)	8.46* (I)	4.22* (E)	4.33* (E)
MSG297-4	20.48 (S)	3.59* (E)	3.67* (E)	2.21* (E)	5.57* (E)	1.40* (E)	1.82* (E)
MSG007-1	21.01 (S)	5.79* (E)	4.66* (E)	1.46* (E)	5.12* (E)	3.60* (E)	1.59* (E)
Snowden	21.78 (S)	5.72* (E)	2.90* (E)	2.39* (E)	2.75* (E)	1.85* (E)	1.85* (E)
Atlantic	22.16 (S)	2.49* (E)	3.14* (E)	2.36* (E)	2.00* (E)	2.35* (E)	1.91* (E)
MSE230-6	23.63 (S)	4.98* (E)	1.82* (E)	1.28* (E)	2.49* (E)	1.84* (E)	2.02* (E)

[a] Chlorothalonil and fluazinam applied at 33, 66, or 100% of the manufacturer's recommended applications rates. Values followed by (E) = effective late blight control and (I) = intermediate late blight control; (*) indicates significantly different from the nontreated control of the same cultivar or ABL, P = 0.05. For comparing different treatments for the same cultivar or ABL, the least significant difference ($LSD_{0.05}$) = 2.913; for comparing different cultivars and ABL with the same treatment, $LSD_{0.05}$ = 2.789; and for comparing different treatments and different cultivars or ABL, $LSD_{0.05}$ = 2.757.

[b] Values followed by (R) = late blight resistant, (M) = moderately resistant, and (S) = susceptible.

RESULTS

Microclimate conditions. Late blight developed rapidly during August in 1998 to 2000; nontreated susceptible controls reached about 100% diseased foliar area 33, 36, and 39 DAI in 1998, 1999, and 2000, respectively. Accumulated DSV from inoculation to 100% senescence of healthy plants were 55, 78, and 109 in 1998, 1999, and 2000, respectively. This indicated that, in all years, environmental conditions were conducive to late blight development (DSV > 18; 22).

Cultivar or ABL × fungicide active ingredient trials. *1998.* Cultivars and ABL were significantly different in response to late blight and were classified and ranked based on mean RAUDPC of untreated plots (Table 2). Of the 17 nontreated cultivars and ABL, 3 were classified as resistant (MSG274-3, Zarevo, and Lily), 6 were classified as susceptible (Atlantic, Snowden, MSE230-6, MSG007-1, MSG297-4, and MSG141-3), and 8 were moderately resistant (FL1625, MSE246-5, Matilda, Picasso, MSC103-2, MSA091-1, FL1533, and MSE018-1). For each cultivar or ABL, all fungicide treatments significantly reduced the RAUDPC compared to the corresponding nontreated control, with the exception of MSG274-3. There were no significant differences among application rates of either fungicide on the cultivars and ABL that were classified as late blight resistant or moderately resistant, but there were significant differences among some of the fungicide treatments on the late blight susceptible cultivars and ABL. In all susceptible cultivars with the exception of Atlantic, one or both of the fungicides applied at 33% MRAR resulted in a significantly higher RAUDPC value than the 100% MRAR treatment. However, all application rates of both fungicides provided effective late blight control on all cultivars and ABL, with the exception of 33 and 66% MRAR of chlorothalonil and 33% MRAR of fluazinam on MSG141-3.

1999. Cultivars and ABL were significantly different in response to late blight and were classified and ranked based on mean RAUDPC of nontreated plots (Table 3). Of the nine nontreated cultivars and ABL tested, one was classified as resistant (MSG274-3), three were classified as susceptible (MSE246-5, Atlantic, and Snowden), and five were classified as moderately resistant (MSA091-1, FL1625, FL1533, FL1833, and MSE018-1). RAUDPC values in 1999 were higher than in 1998 and fungicide treatments were less effective, with most providing only intermediate late blight protection. At 33 and 66% MRAR, chlorothalonil only provided effective control in MSG274-3. However, even at 100% MRAR, chlorothalonil provided effective control for MSG274-3, FL1833, MSE246-5, and Atlantic but only intermediate control on all other cultivars and ABL. Fluazinam at 33% MRAR gave intermediate late blight control in all cultivars and ABL except MSG274-3, in which it provided effective control. At 66% MRAR, fluazinam gave effective control in four cultivars and ABL (MSG274-3, FL1625, FL1533, and MSE246-5) and intermediate control in all other cultivars and ABL. At 100% MRAR of fluazinam, late blight was effectively controlled in all cultivars and ABL except Atlantic.

There were no significant differences among application rates of either fungicide on MSG274-3, which was classified as resistant. For all cultivars and ABL, all fungicide treatments significantly reduced the RAUDPC compared with the corresponding nontreated control, with the exception of 33% MRAR of chlorothalonil on MSA091-1, FL1533, and Atlantic. In all cultivars and ABL classified as moderately resistant or susceptible, 33% MRAR of either fungicide resulted in RAUDPC values that were significantly higher than the 100% MRAR treatments. For both fungicides, 66% of MRAR was not significantly different from 100% of MRAR in some cultivars and ABL but was significantly different in others.

2000. Cultivars and ABL were significantly different in response to late blight and were classified and ranked based on RAUDPC of nontreated plots (Table 4). Of the eight nontreated cultivars and ABL, one was classified as resistant, five were classified as susceptible, and two were classified as intermediate. For each cultivar or ABL, all fungicide treatments significantly reduced the RAUDPC compared with the corresponding nontreated control. For both fungicides, 33% MRAR provided intermediate late blight control on most cultivars with the exception of MSG274-3, in which both fungicides gave effective control. Chlorothalonil applied at 33% MRAR provided effective control for FL1625 and Snowden but, at 66 and 100% MRAR, provided effective control on all cultivars and ABL. Fluazinam effectively controlled late blight on FL1625 at 66% MRAR and on FL1625, MSG124-8P, and MSF373-8 at 100% MRAR. There were no significant differences among application rates of either fungicide on MSG274-3, which was classified as resistant, or on FL1625, which was classified as moderately resistant. For the remaining cultivars and ABL, which were classified as moderately resistant or susceptible, 33% MRAR of either fungicide resulted in RAUDPC values that were significantly higher than at 100% MRAR, with the exception of 33% MRAR of chlorothalonil on MSF373-8 and Snowden. At 66% MRAR, both fungicides resulted in RAUDPC values that were not significantly different from those at 100% MRAR, with the exception of MSG124-8P.

Fungicide application interval and reduced dose rate trials. 1999. The mean RAUDPC for nontreated Snowden was 42.04 (susceptible) and the mean for nontreated MSG274-3 was 3.87 (resistant; Table 5). In Snowden, all fungicide

Table 3. Mean relative area under the disease progress curve (RAUDPC; max = 100) in potato cultivars and advanced breeding lines (ABL) inoculated with *Phytophthora infestans* (US8, A2) and protected with reduced rates of chlorothalonil or fluazinam applied at a 7-day interval, sorted by order of susceptibility in nontreated control (1999)

		Mean RAUDPC					
		Chlorothalonil[a]			Fluazinam[a]		
Cultivar/ABL	Nontreated	33	66	100	33	66	100
MSG274-3	6.38 (R)[b]	5.68 (E)	3.14 (E)	2.37 (E)	5.84 (E)	2.72 (E)	1.80* (E)
MSA091-1	22.52 (M)	24.32 (I)	14.59* (I)	14.10* (I)	29.36* (I)	14.03* (I)	8.40* (E)
FL1625	27.80 (M)	22.26* (I)	18.99* (I)	14.42* (I)	18.43* (I)	10.39* (E)	5.97* (E)
FL1533	31.90 (M)	28.49 (I)	14.54* (I)	13.04* (I)	14.37* (I)	10.10* (E)	5.61* (E)
FL1833	33.33 (M)	18.02* (I)	15.27* (I)	9.99* (E)	25.93* (I)	11.88* (I)	7.13* (E)
MSE018-1	37.09 (M)	26.37* (I)	26.63* (I)	20.70* (I)	27.78* (I)	18.39* (I)	6.38* (E)
MSE246-5	39.87 (S)	31.74* (I)	20.24* (I)	10.19* (E)	23.42* (I)	9.75* (E)	7.15* (E)
Atlantic	42.03 (S)	40.54 (NE)	19.15* (I)	8.79* (E)	26.22* (I)	18.35* (I)	11.91* (I)
Snowden	43.38 (S)	31.03* (I)	21.08* (I)	17.93* (I)	31.23* (I)	13.97* (I)	10.22* (E)

[a] Chlorothalonil and fluazinam applied at 33, 66, or 100% of the manufacturer's recommended applications rates. Values followed by (E) = effective late blight control and (I) = intermediate late blight control; (*) indicates significantly different from the nontreated control of the same cultivar or ABL, $P = 0.05$. For comparing different treatments for the same cultivar or ABL, the least significant difference ($LSD_{0.05}$) = 4.560; for comparing different cultivars and ABL with the same treatment, $LSD_{0.05}$ = 4.294; and for comparing different treatments and different cultivars and ABL, $LSD_{0.05}$ = 4.447.
[b] Values followed by (R) = late blight resistant, (M) = moderately resistant, and (S) = susceptible

application rates at all spray intervals significantly reduced the RAUDPC compared with the nontreated control. However, only 66 and 100% MRAR of chlorothalonil applied at a 5-day spray interval gave effective late blight control. In MSG274-3, all fungicide treatments significantly reduced the RAUDPC compared with the nontreated control. All application rates at all spray intervals gave effective late blight control, but there were no significant differences among the treatments.

2000. Snowden again was susceptible to late blight but, due to slower disease progression, the RAUDPC value in the nontreated control (16.67) was less than the RAUDPC value reported for 1999 (42.04; Table 6). All fungicide application rates at all spray intervals significantly reduced the RAUDPC compared with the nontreated control, with the exception of 33 and 66% MRAR of chlorothalonil applied at a 10-day spray interval for Snowden. The lowest RAUDPC values occurred with 66 and 100% MRAR of chlorothalonil applied at a 5-day spray interval and were classified as providing effective late blight control. In addition, 33% MRAR of chlorothalonil applied at a 15-day interval also resulted in effective late blight control, which was anomalous with the results from 1999.

The mean RAUDPC for nontreated MSG274-3 was 0.03, which was classified as resistant. In MSG274-3, none of the fungicide treatments significantly reduced the RAUDPC compared with the nontreated control. All treatments gave effective late blight control and there were no significant differences among the treatments.

DISCUSSION

The results of this study were consistent with previous studies and indicate that a combination of cultivar or ABL resistance and managed application of protective fungicides will reduce foliar late blight to acceptable levels in most situations (10,11,21). However, when environmental conditions were extremely favorable for the development of late blight (e.g., 1999), lower application rates (33 and 66% MRAR) provided unsatisfactory control for moderately resistant and susceptible cultivars and ABL. When conditions were moderately conducive to late blight development (e.g., 1998), reduced amounts of both chlorothalonil and fluazinam were effective at all application rates tested on most cultivars and ABL compared with the nontreated controls. Exceptions occurred, where 33% MRAR of either fungicide

Table 4. Mean relative area under the disease progress curve (RAUDPC; max = 100) in potato cultivars and advanced breeding lines (ABL) inoculated with *Phytophthora infestans* (US8, A2) and protected with reduced rates of chlorothalonil or fluazinam applied at a 7-day interval, sorted by order of susceptibility in nontreated control (2000)

		Mean RAUDPC					
		Chlorothalonil[a]			Fluazinam[a]		
Cultivar/ABL	Nontreated	33	66	100	33	66	100
MSG274-3	0.04 (R)[b]	0.03 (E)	0.03 (E)	0.02 (E)	0.02 (E)	0.03 (E)	0.04 (E)
FL1625	7.69 (M)	1.77* (E)	0.86* (E)	0.64* (E)	4.16* (I)	1.25* (E)	1.50* (E)
MSG124-3P	17.17 (M)	5.41* (I)	2.18* (E)	1.30* (E)	5.07* (I)	3.57* (I)	3.02* (E)
MSF373-8	19.13 (S)	3.20* (I)	3.00* (E)	0.47* (E)	7.88* (I)	3.17* (I)	2.43* (E)
MSG050-2	19.73 (S)	4.36* (I)	2.30* (E)	0.98* (E)	10.45* (I)	4.09* (I)	3.24* (I)
Snowden	21.39 (S)	2.64* (E)	2.52* (E)	1.16* (E)	11.03* (I)	4.06* (I)	3.26* (I)
FL1930	21.40 (S)	6.18* (I)	1.46* (E)	0.79* (E)	8.42* (I)	4.91* (I)	4.56* (I)
MSE018-1	22.77 (S)	4.29* (I)	1.59* (E)	0.94* (E)	14.54* (I)	5.27* (I)	4.98* (I)

[a] Chlorothalonil and fluazinam applied at 33, 66, or 100% of the manufacturer's recommended applications rates. Values followed by (E) = effective late blight control and (I) = intermediate late blight control; (*) indicates significantly different from the nontreated control of the same cultivar or ABL, P = 0.05. For comparing different treatments for the same cultivar or ABL, the least significant difference ($LSD_{0.05}$) = 3.298; for comparing different cultivars and ABL with the same treatment, $LSD_{0.05}$ = 3.025; and for comparing different treatments and different cultivars and ABL, $LSD_{0.05}$ = 3.029.

[b] Values followed by (R) = late blight resistant, (M) = moderately resistant, and (S) = susceptible.

Table 5. Mean relative area under the disease progress curve (RAUDPC; max = 100) in potato cultivars and advanced breeding lines (ABL) inoculated with *Phytophthora infestans* (US8, A2) and protected with reduced rates of chlorothalonil applied at 5-, 10-, or 15-day application intervals (1999)[a]

	MSG274-3				Snowden			
Interval (days)	0	33	66	100	0	33	66	100
5	3.87⁺ (R)	0.84* (E)	0.52* (E)	0.15* (E)	42.04⁺ (S)	8.83*⁺ (I)	5.75* (E)	5.08* (E)
10	3.87⁺ (R)	0.84* (E)	0.61* (E)	0.54* (E)	42.04⁺ (S)	30.16*⁺ (I)	23.3*⁺ (I)	17.07*⁺ (I)
15	3.87⁺ (R)	1.45* (E)	1.18* (E)	0.58* (E)	42.04⁺ (S)	33.65*⁺ (I)	32.23*⁺ (I)	25.99*⁺ (I)

[a] Chlorothalonil applied at 0, 33, 66, or 100% of the manufacturer's recommended applications rates (MRAR). Values followed by (⁺) are significantly different from the same cultivar or ABL treated with 100% MRAR at a 5-day application interval (least significant difference = 2.38); (*) indicates significantly different from the nontreated control of the same cultivar or ABL at P = 0.05; values followed by (R) = late blight resistant, (M) = moderately late blight resistant, and (S) = late blight susceptible; and values followed by (E) = effective late blight control and (I) = intermediate late blight control.

Table 6. Mean relative area under the disease progress curve (RAUDPC; max = 100) in potato cultivars and advanced breeding lines (ABL) inoculated with *Phytophthora infestans* (US8, A2) and protected with reduced rates of chlorothalonil applied at 5-, 10-, or 15-day application intervals (2000)[a]

	MSG274-3				Snowden			
Interval (days)	0	33	66	100	0	33	66	100
5	0.03 (R)	0.00 (E)	0.01 (E)	0.00 (E)	16.67*⁺ (S)	7.72*⁺ (I)	2.84* (E)	1.49* (E)
10	0.03 (R)	0.01 (E)	0.01 (E)	0.01 (E)	16.67*⁺ (S)	12.91⁺ (NE)	13.32⁺ (NE)	10.46*⁺ (NE)
15	0.03 (R)	0.02 (E)	0.01 (E)	0.02 (E)	16.67*⁺ (S)	6.01* (E)	10.36*⁺ (NE)	9.78*⁺ (I)

[a] Chlorothalonil applied at 0, 33, 66, or 100% of the manufacturer's recommended applications rates (MRAR). Values followed by (⁺) are significantly different from the same cultivar/ABL treated with 100% MRAR at a 5-day application interval (least significant difference = 2.38); (*) indicates significantly different from the nontreated control of the same cultivar or ABL at P = 0.05. Values followed by (R) = late blight resistant, (M) = moderately late blight resistant, and (S) = late blight susceptible; values followed by (E) = effective late blight control, (I) = intermediate late blight control, and (NE) = noneffective late blight control.

gave only intermediate late blight control. In some cultivars and ABL, 33% of the MRAR of either fungicide was sufficient to achieve acceptable control, whereas other cultivars and ABL required 66% MRAR of either fungicide to control late blight. However, there was rarely a further reduction in disease in any cultivar or ABL when either fungicide was applied at the 100% MRAR of either fungicide. In addition, the most resistant cultivars and ABL (e.g., MSG274-3, Zarevo, and Lily) did not respond to either fungicide applied at greater than 33% MRAR of either fungicide.

On late blight susceptible cultivars, applications of chlorothalonil at 10- and 15-day intervals were not effective for controlling late blight at any dose tested. However, in the resistant line MSG274-3, there was no significant reduction in foliar late blight after applications of chlorothalonil at any application rate or interval. In the cultivar Snowden, all fungicide treatments were significantly different (less foliar late blight) from the nontreated (Snowden) control. Differences between nontreated MSG 274-3 and the fungicide-treated MSG 274-3 treatments in 1999 may have been due to the severe late blight pressure experienced in 1999 in comparison with 2000.

The opportunity to manage late blight by applying reduced rates of fungicides at increased spray intervals to cultivars less susceptible to late blight was demonstrated in this study. However, more critical dose response studies will be required before effective rates of application can be established for new fungicides. In addition, the efficacy of reduced rates and increased application intervals of fungicides against other potato pathogens, such as early blight, has not been established and may prove to be a major constraint in the adoption of managed fungicide applications.

The application rates and application frequencies of fungicides used in this study were selected to cover the range of responses likely to be exhibited by the range of cultivars and ABL used over the period of the study. In addition, microclimatic conditions at the experimental site were likely to differ over the study period; therefore, it was important to have high- and low-level fungicide input treatments. The study largely supported the dose rates recommended by the manufacturer but also showed that less susceptible potato cultivars required lower levels of input for effective late blight control.

As new cultivars with enhanced late blight resistance are developed and released, it will be important to provide growers with recommendations for the most effective and economical chemical control of late blight in these new cultivars. In the future, the type of information gathered in this study will be used to develop models, based on cultivar resistance and response to fungicide application, to advise and guide growers as to which fungicide, rate, and frequency of application is required to provide protection against late blight. Climatic conditions within the canopy will also impact choice of fungicide and rate and frequency of application (1). Therefore, new cultivars will need to be carefully screened in the manner described in this study, over several seasons, in order to develop accurate models for fungicide application.

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