Disease Control and Pest Management

Field and Computer Simulation Evaluation of Spray-Scheduling Methods for Control of Early and Late Blight of Potato

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ABSTRACT

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Field experiments corroborated a reduced-sprays strategy which had previously been devised through analysis of experiments using complex computer simulators. The reduced-sprays strategy was designed to efficiently suppress both early and late blight in potato foliage. Tuber blight was not included in the analysis. Early sprays were confirmed to be unimportant for early blight, but essential for late blight if early season weather favored disease development. Sprays applied 1 or 2 wk before the end of the season contributed very little to efficient suppression of either disease. Simulation models were used to compare the efficiency of the reduced-sprays strategy and several other methods for suppressing potato early and late blight. In these analyses, the reduced-sprays strategy scheduled two to three fewer sprays, but suppressed early and late blight as well as the other methods. Savings were achieved mainly at the beginning and the end of the seasons. A specific spray-scheduling method for early blight controlled early blight well, but failed to suppress late blight well when there were severe late-blight epidemics. A late-blight-specific spray-scheduling method and a method of scheduling sprays for both diseases suppressed both diseases as well as did weekly sprays (the conventional method) and with the same average number of applications as with weekly sprays.

Additional keywords: Alternaria solani, epidemiology, models, *Phytophthora infestans.*

Potato early blight, caused by *Alternaria solani* (Ellis & Martin) Jones & Grant, and potato late blight, caused by *Phytophthora infestans* (Mont.) de Bary, are the two most important fungal diseases of potato (*Solanum tuberosum* L.) in the northeastern United States. Late blight is sporadic, but potentially devastating, whereas early blight inflicts a lower, but more constant, level of damage (6,8,9). Large amounts of fungicides are applied by potato growers to suppress these two diseases. Growers in the northeastern United States typically initiate spraying when plants are 15–20 cm in height and spray once a week until the vines are killed (11), applying 7–10 sprays in all.

Although the weekly spray strategy has proven to be reliable for disease suppression, it may result in inefficient use of fungicide, since sprays are applied regardless of existing disease levels, cultivar resistance, weather, etc. A number of methods for improving the efficiency of fungicide use have been advanced. Blitecast (12) and a simulation forecast (8) schedule fungicides for late-blight suppression. However, they do not deal with early blight. Potato Disease Management (PDM), developed in the University of Wisconsin, initiates and schedules fungicide applications for control of both diseases (20). PDM has not been tested in the northeastern United States.

Based on analysis done with simulation models describing potato early-blight development, potato late-blight development, and chlorothalonil dynamics, we have proposed a reduced-sprays strategy for controlling early and/or late blight in potato foliage (18). This strategy is based on optimal initiation and termination dates of sprays. According to this strategy, sprays should be initiated when late blight is predicted by a forecast system (i.e., Blitecast) or when early blight is predicted to become important (which is 6–7 wk after planting), whichever comes first. Subsequent spray intervals during the first 6–7 wk would be determined according to the resistance of the cultivar to late blight (11), and, after 7 wk, on a weekly schedule. The last spray would be applied approximately 3 wk before vine kill. The use of this strategy could save up to 2–4 sprays in a growing season, without substantially increasing disease in the foliage (relative to the common grower practice described above) (18). The reduced-sprays strategy still needs to be evaluated and compared to other existing spray-scheduling methods in the field before being recommended to commercial potato growers.

The availability of cultivars moderately resistant to late blight (7,8) and an eradicant fungicide for late-blight suppression could lower the amount of fungicide needed to control that disease. However, the exclusive use of methods aimed at late-blight suppression would probably result in inadequate suppression of early blight (14,19).

Because of the importance of early and late blight for potato production and the variety of approaches now possible for their control, integrated guidelines for their management are needed. Simulators are potentially valuable tools for evaluating the benefits of spray-scheduling methods. The purpose of this work was to evaluate the reduced-sprays strategy relative to other strategies. Both field experiments and simulation experiments were used.

MATERIALS AND METHODS

Field evaluation of the reduced-sprays strategy: cultural practices. The control of early blight (EB) and late blight (LB) was investigated in separate field experiments done in 1988, and of both diseases (EBLB) in 1989. Experiments were done at the Homer C. Thompson Research Farm at Freeville, NY. Certified potato seed (whole tubers or pieces, each weighing about 50 g) were machine planted on 12 May (cv. Norchip, EB experiment) and 17 May 1988 (cv. Katahdin, LB experiment) and on 23 May 1989 (cvs. Norchip and Katahdin, EBLB experiment). In 1988, plots consisted of four rows, each 3 m long; and in 1989, they were 4 m long. There was 0.9 m between rows, and plants were spaced about 23 cm apart within a row. Plots were separated from each other by fallow areas about 4 m wide. Fertilizer (175 kg N, 175 kg P, and 175 kg K/ha) was applied at planting. Herbicide (Linuron 50WP, 1.7 kg a.i./ha, DuPont Co., Wilmington, DE) was applied after planting but prior to plant emergence. Insecticides were applied in each experiment every 10–14 days, starting on the second week of June. Plants were hilled during the last week in June of 1988 or the first week in July of 1989. The broad spectrum protectant fungicide, chlorothalonil (Bravo 720, Dimond Shamrock Corp., Painesville, OH) was applied at the rate of 0.84 kg a.i./ha, in water at 470 L/ha and 860 kPa with a tractor-mounted boom sprayer. Vines were killed mechanically (by mowing) in early September, and tubers were harvested 2 wk later. In the EB experiment, four plants having three main stems each were hand harvested; and in the LB and EBLB experiments, the two middle rows were machine harvested. The LB and EBLB harvest was rated visually for late-blight infections 10 days after harvest.

Experimental design. In 1988, components of the reduced-sprays strategy were evaluated (i.e., initiation and termination dates of spraying). Treatments consisted of the application of chlorothalonil in schedules differing in initiation and termination dates (Table 1). In 1989, the strategy was compared to the conventional method. Treatments consisted of three fungicide-scheduling methods: 1) conventional; 2) reduced-sprays strategy; and 3) untreated control (Table 1). Treatments were arranged in randomized complete blocks with three (in 1988) or four (in 1989) replicates per treatment.

Plots in the LB experiment were inoculated by applying one drop (approximately 0.05 ml per drop) of a mixture of *P. infestans* isolates, race 0 (isolate numbers 163, 182, and 183; 20,000 sporangia per milliliter), on 12 and 13 July 1988 to each of four plants in the outer rows of each plot. In the EBLB experiment, four seed tubers infected with *P. infestans* were hand planted in each plot. Seed tubers were inoculated by injecting a 0.01 ml-drop of inoculum (containing approximately 500 sporangia of *P. infestans*) to a depth of 7 mm at the base of two eyes with a side-port 16-gauge needle attached to a Hamilton repeating dispenser syringe (Hamilton Co., Reno, NV). Inoculated tubers were stored at room temperature 2 wk prior to planting. Before planting, all tubers were checked for infection. Any tubers with noticeable soft rot were discarded. Plots in the EB and EBLB experiments were not artificially inoculated with *A. solani*, because soil at the test site was already heavily infested.

Disease assessments. Disease was assessed visually. In the LB and EBLB experiments, defoliation of the two middle rows of each plot was estimated every 3–7 days using a modification of a blight assessment key published by the British Mycological Society (9). No attempt was made to distinguish between lesions of *A. solani* and *P. infestans*. In the EB experiment, assessments of defoliation were made on four randomly selected main stems per plot every 6–8 days. Percent defoliation per plot was calculated as the mean of the percent defoliation of each of the four stems. Assessments started in each experiment after symptoms first became apparent (early July) and continued until vines were killed (early September). For some analyses, the area under the defoliation progress curve (AUDPC), as calculated by Shaner and Finney (17), was used. The duration of the period used for calculating AUDPC was from the date of first appearance of noticeable disease symptoms in any plot until the last assessment. AUDPC units are proportion days.

TABLE 1. Schedules of fungicide applications[a] in the field experiments conducted in 1988 and 1989 at Freeville, NY, to control early blight (EB), late blight (LB), or both (EBLB)

Experiment	Year	Fungicide treatment	No. of sprays	Date of spraying	
				First	Last
EB	1988	Untreated	0	···	···
		Early termination	6	6/16	7/22
		Late initiation	6	6/30	8/4
		7 days	12	6/16	9/1
LB	1988	Untreated	0	···	···
		Early termination	5	7/14	8/10
		Late initiation	7	7/28	9/8
		7 days	9	7/14	9/8
EBLB	1989	Untreated	0	···	···
		Reduced-sprays strategy	8	6/29	8/18
		Conventional	10	6/29	8/31

[a] Chlorothalonil (Bravo 720) was applied at the rate of 0.84 kg a.i./ha.

Comparison of spray-scheduling methods via simulation analysis. Models which simulate the effects of environment and cultivar resistance on the development of *A. solani* (15,18) and *P. infestans* (1), and which include the initial deposition of the fungicide chlorothalonil (3) and its subsequent weathering, redistribution, loss, and efficiency (2), were used. Both models are operated on an IBM-PC microcomputer. Simulation experiments used 6 yr of meteorological data (1977–1981, 1983) recorded at Freeville, NY, and had the following common parameters: the length of the season (from date of planting until vine kill) was 102 days; median emergence occurred on the 18th day after planting; and the initial level of early or late blight was one lesion per 10 plants. The protectant fungicide chlorothalonil was applied at the rate of 1.34 kg a.i/ha. Simulations were done with a susceptible and a moderately resistant cultivar for each disease.

Dates of initial appearance were calculated independently for each disease. The initial appearance of *A. solani* was set to occur after accumulation of 235 ± 39 (mean ± standard deviation [SD]) physiological days (PDAYS) (16) since median emergence because this is the time of early-blight appearance we had observed in 13 crops over 4 yr with eight cultivars (Shtienberg and Fry, *unpublished data*). The initial appearance of *P. infestans* was set to occur 6 ± 2 days after the accumulation of 18 Blitecast severity values because this is the observed mean time of late-blight appearance (5,19). These means and error terms were used to generate five dates of initial occurrence for each weather data set for each disease: the mean, the mean plus or minus one SD, and the mean plus or minus two SD.

The efficiency of several spray-scheduling methods in suppressing early and late blight was evaluated. Schedules for fungicide applications were determined separately for each spray-scheduling method and were then simulated in both pathogen models. One hundred and twenty different runs (five disease-initiation dates × 6 yr × two susceptibility groups of cultivars × two diseases) were conducted for each of the following spray-scheduling methods:

Conventional. Weekly sprays were initiated 35 days after planting (when plants were approximately 15–20 cm in height) and continued until the end of the season (11).

Reduced-sprays strategy. Initiation was according to Blitecast or on wk 7, whichever came first. Intervals were according to late-blight susceptibility early in the season (7 days for a susceptible cultivar and 10 days for a moderately resistant cultivar), and weekly after wk 7. The last spray was applied approximately 3 wk before the end of the season (18).

Potato Disease Management (PDM). PDM was developed for scheduling sprays for the control of both early and late blight (20). It was built out of two forecasting components: PDM/EB (early blight) and Blitecast (late blight [12]). PDM schedules sprays separately for each disease; therefore, in our simulation experiments, the more conservative recommendations from each of the components was adopted. A conservative recommendation was the one for earlier or more frequent application.

PDM/EB. This is the early-blight component of PDM. Sprays were initiated after the accumulation of 300 PDAYS since median emergence. Subsequent applications were timed according to modified FAST (13) rating values and the maturity of the cultivar (20).

Blitecast. This is a forecast system for late blight. Sprays were initiated when 18 severity values accumulated since median emergence. Subsequent applications were timed according to the accumulation of rain and severity values (12).

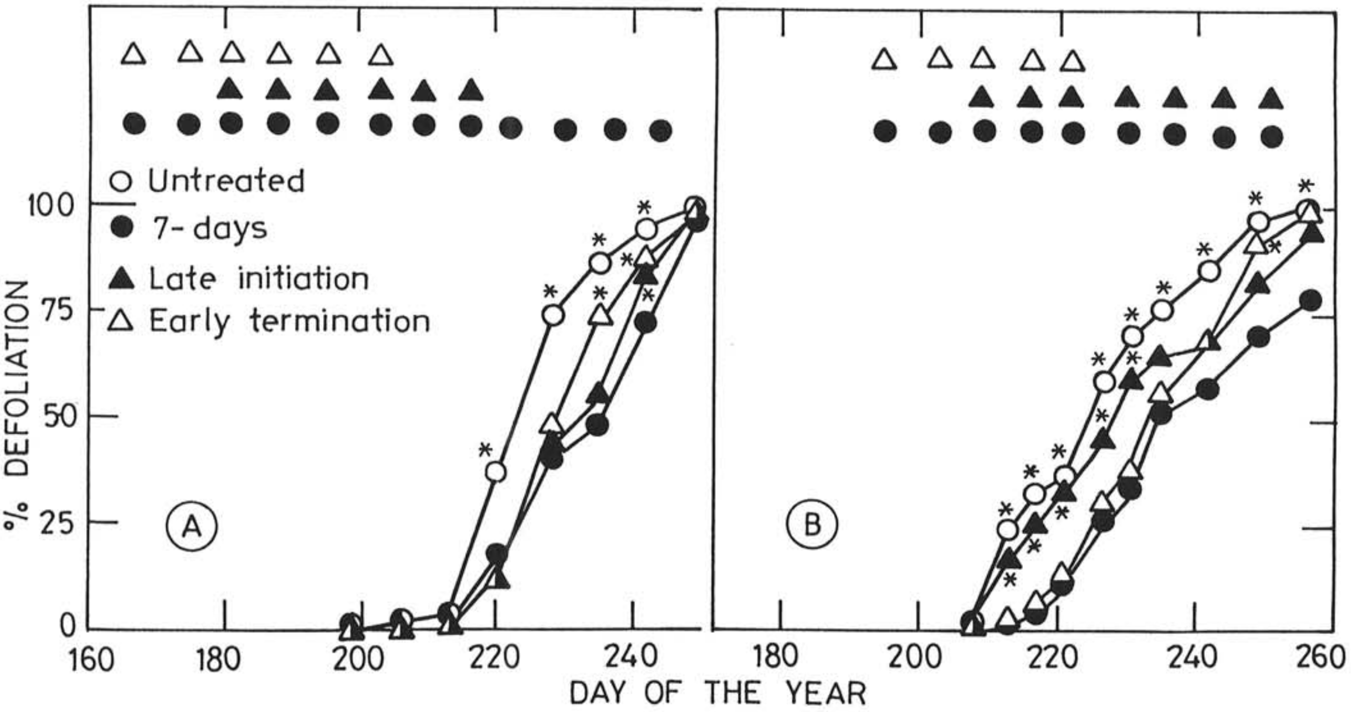

Fig. 1. Effect of spraying schedules on percent defoliation in plots infected by early blight (A) or late blight (B) in 1988. Symbols indicate the dates of corresponding fungicide applications (e.g., △ for early termination). Asterisks indicate a significant difference ($P = 0.05$) between a treatment and the 7-day schedule for that date. Results are means of three replications.

Simulation forecast. The simulation forecast is a forecast system for late blight developed in the northeastern United States, which schedules sprays according to the effect of weather on the pathogen and on fungicide weathering (8). Since this system does not determine the initiation of sprays, they were initiated in our simulation experiments according to Blitecast. Subsequent applications were timed according to the accumulation of blight and fungicide units (8).

Unsprayed. No fungicides were applied throughout the season.

The efficiency of fungicide use was a criterion used for comparing scheduling methods. Efficiency (E) was defined as the percent control per application and was calculated as follows:

$$E = \{[1 - (Am - Au)/Au]/N\}100$$

in which Am = simulated AUDPC for a spray-scheduling method, Au = simulated AUDPC of untreated crop, and N = number of applications scheduled by the method.

RESULTS

Field evaluation of the reduced-sprays strategy. Omission of the first two sprays in the EB experiments did not result in increased percent defoliation due to early blight relative to the conventional weekly schedule (Fig. 1A). In contrast, omission of the first two sprays for late-blight suppression resulted in a significant increase in disease relative to the weekly schedule (Fig. 1B). The importance of late sprays for both early and late blight was evaluated by terminating sprays before the end of the season. Defoliation levels in plots with either disease did not differ significantly ($P > 0.05$) from sprayed plots until at least 3 wk after termination of the applications (Fig. 1, Table 2).

In the EBLB experiment, 18 severity values of Blitecast were accumulated on 25 June 1989. Sprays were initiated for the reduced-sprays strategy 4 days later. Since plants were approximately 20 cm in height at that time, sprays were also initiated for the conventional treatment. The initial appearance of late blight was observed on 1 July. Favorable weather conditions for late blight resulted in rapid development of the disease in the untreated plots. In plots treated according to the reduced-sprays strategy, sprays were terminated about 3 wk before the end of the season. However, defoliation levels, AUDPC, yield, and percent blighted tubers in these plots did not differ significantly ($P = 0.05$) from those in plots sprayed until the end of the season (Fig. 2, Table 3).

TABLE 2. Effect of various fungicide schedules on defoliation caused by potato early blight (EB) and potato late blight (LB) in field experiments in 1988

Experiment	Fungicide treatment[w]	Percent defoliation[x]	AUDPC[y]	Yield[z] (ton/ha)	Percent tubers blighted (by wt)
EB	Untreated	73.4 a	6.0 a	29.2 a	···
	Late initiation	42.8 b	2.6 b	33.2 a	···
	Early termination	47.1 b	2.8 b	33.2 a	···
	7 days	38.8 b	2.3 b	33.6 a	···
LB	Untreated	84.9 a	16.2 a	26.3 b	3.8 a
	Late initiation	67.6 b	13.4 b	27.4 b	0.3 a
	Early termination	67.3 b	9.1 c	31.2 a	2.6 a
	7 days	56.1 b	7.9 c	31.9 a	2.3 a

[w] Chlorothalonil (Bravo 720) was applied at the rate of 0.84 kg a.i./ha.

[x] Defoliation levels as were recorded 3 wk after the last spray was applied in the "early termination" treatment. Numbers within a column (for each experiment) followed by the same letter are not significantly different ($P = 0.05$), as determined by Fisher's protected LSD test.

[y] Area under the defoliation progress curve in proportion days, 3 wk after the last spray was applied in the "early termination" treatment.

[z] Plots were harvested at the end of the season.

Comparison of spray-scheduling methods via simulation analysis. On average, all six spray-scheduling methods suppressed early blight and late blight significantly ($P < 0.05$) on the susceptible cultivar, with slight fluctuation in control efficacy among methods (Table 4). While there were a few years with significant differences among methods for disease suppression, there were no significant differences among methods when compared over the 6 yr of simulations. In each year, the reduced-sprays strategy suppressed early blight and late blight as well as the conventional schedule. PDM/EB was as effective as

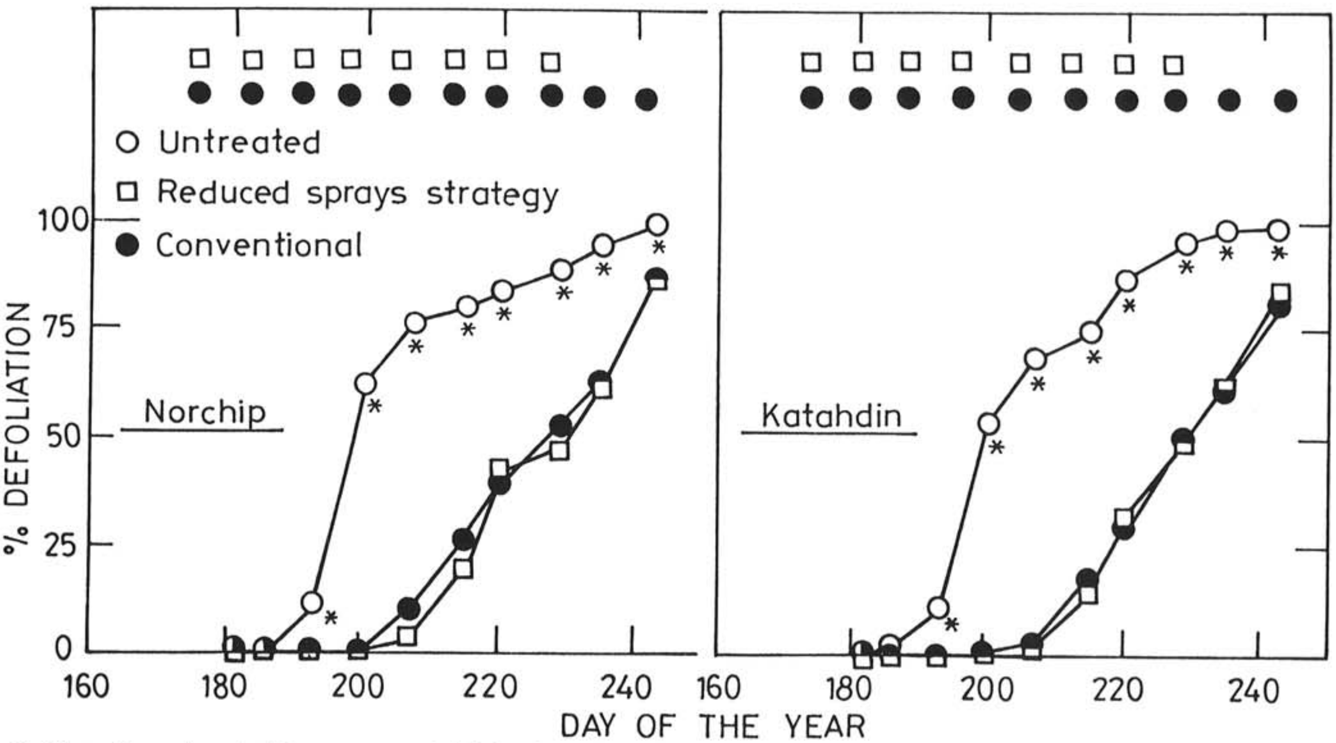

Fig. 2. Effect of spraying schedules on percent defoliation in cultivars Norchip and Katahdin infected by early and late blight in 1989. Symbols indicate the dates of corresponding fungicide applications (e.g., ● for the conventional method). Asterisks indicate a significant difference ($P = 0.05$) between a treatment and the conventional treatment for that date. Results are the means of four replications.

TABLE 3. Effect of fungicide schedules on defoliation caused by potato early and late blight in field experiments in 1989

Cultivar[v]	Fungicide treatment[x]	Percent defoliation[y]	AUDPC[z]	Yield (ton/ha)	Percent tubers blighted (by wt)
Norchip	Untreated	100.0 a	39.6 a	14.7 a	1.77 a
	Reduced-sprays strategy	88.1 b	16.2 b	32.1 b	0.02 b
	Conventional	88.1 b	17.9 b	31.9 b	0.22 b
Katahdin	Untreated	100.0 a	39.4 a	15.2 a	0.05 a
	Reduced-sprays strategy	85.0 b	15.3 b	35.0 b	0.65 a
	Conventional	81.6 b	15.2 b	38.7 b	0.00 a

[v] Norchip is susceptible to early blight and late blight, whereas Katahdin is moderately susceptible to each disease.

[x] Chlorothalonil (Bravo 720) was applied at the rate of 0.84 kg a.i./ha.

[y] Defoliation levels as were recorded 3 wk after the last spray was applied in the reduced-sprays strategy treatment. Numbers within a column (for each cultivar) followed by the same letter are not significantly different ($P = 0.05$), as determined by Fisher's protected LSD test.

[z] Area under the defoliation progress curve in proportion days, 3 wk after the last spray was applied in the reduced-sprays strategy treatment.

Blitecast and PDM (with one exception) in suppressing early blight, but it failed to suppress late blight as effectively as other methods when there was high potential for late-blight epidemics (data of 1978 and 1981, Table 4). The simulation forecast system suppressed early blight as well as, and late blight better than (in the severe epidemics), the conventional method (Table 4). The number of fungicide applications scheduled by the different methods varied among years. However, intervals between sprays on the average did not fluctuate much (5.9–7.0 days).

Simulations were also done with moderately resistant cultivars, and similar trends among scheduling methods were observed. Results are not shown because the only important difference from results with susceptible cultivars was uniformly less disease on moderately resistant cultivars than on susceptible ones.

The average efficiency (E) of a fungicide application (percent control per application) varied significantly among spray-scheduling methods. In most combinations of disease and cultivar characteristics, sprays scheduled according to the reduced-sprays strategy had a significantly higher ($P < 0.05$) efficiency than all the other methods (Table 5). PDM, PDM/EB, and the simulation forecast system did not vary in most cases among themselves, but were significantly more efficient ($P < 0.05$) than the conventional method (Table 5).

DISCUSSION

This study corroborated previous predictions (18) concerning approaches for enhancing the efficiency of fungicide used to suppress potato early blight and potato late blight. Initial sprays were not important for early-blight suppression, but essential for late-blight control; sprays applied 1 or 2 wk before the end of the season did not contribute substantially to efficient disease suppression (Figs. 1 and 2, Tables 2 and 3). These conclusions rest not only on 2 yr of field data but on simulation experiments done with 6 yr of weather data. These weather data were not used for developing the reduced-sprays strategy.

In our simulation analysis, all examined spray-scheduling methods suppressed early blight and/or late blight effectively (Table 4). The early-blight-specific method (PDM/EB) suppressed early blight well, but failed to suppress late blight well under conditions which favored severe epidemics (Table 4). On the other hand, late-blight-specific forecast systems (Blitecast, simulation forecast) and the general methods (reduced-sprays strategy, PDM) suppressed both diseases as well and as efficiently as the conventional method (Table 4). This suggests that under northeastern United States conditions, higher risks are involved in using early-blight-specific spray-scheduling methods than in using late-blight-specific methods.

The efficacy of individual sprays in disease suppression varies according to the disease, date of inoculation, and date of application (18). However, overall efficiency (percent control per fungicide application) may be used for overall comparison of fungicide-scheduling methods since it expresses an average figure for each spray's efficiency. The return (in percent control terms)

TABLE 4. Influence of several spray-scheduling methods on early blight or late blight as identified by simulation experiments[w]

Spray-scheduling method[x]	AUDPC													
	Early blight							Late blight						
	1977	1978	1979	1980	1981	1983	Mean	1977	1978	1979	1980	1981	1983	Mean
Conventional	9.3 ab[y] (10)[z]	19.6 a (10)	15.2 b (10)	5.1 b (10)	25.0 a (10)	12.3 c (10)	14.4 a (10)	0.08 a (10)	10.5 b (10)	0.05 a (10)	0.14 a (10)	12.4 b (10)	0.07 a (10)	4.0 a (10)
Reduced-sprays strategy	10.3 b (6)	20.9 a (8)	15.0 b (6)	4.7 b (6)	24.8 a (8)	11.7 bc (6)	14.6 a (6.7)	0.09 a (6)	10.2 b (8)	0.08 a (6)	0.25 a (6)	12.1 b (8)	0.08 a (6)	3.9 a (6.7)
PDM	12.4 c (7)	19.7 a (13)	13.1 a (9)	3.4 a (8)	24.4 a (13)	11.1 ab (8)	14.0 a (9.7)	0.12 a (7)	7.8 a (13)	0.04 a (9)	0.08 a (8)	9.7 a (13)	0.05 a (8)	3.0 a (9.7)
Blitecast	12.4 c (7)	19.7 a (13)	15.3 b (8)	3.4 a (8)	24.2 a (13)	10.3 a (8)	14.2 a (9.5)	0.12 ac (7)	7.8 a (13)	0.05 a (8)	0.08 a (8)	9.7 a (13)	0.04 a (8)	3.0 a (9.5)
PDM/EB	11.5 bc (7)	20.9 a (8)	13.1 a (8)	4.3 ab (6)	24.5 a (10)	11.1 ab (6)	14.1 a (7.5)	0.09 a (7)	13.2 c (8)	0.04 a (8)	0.08 a (6)	15.4 c (10)	0.06 a (6)	4.9 a (7.5)
Simulation forecast	8.5 a (8)	18.5 a (13)	14.5 b (7)	3.4 a (8)	25.1 a (12)	12.4 c (8)	13.7 a (9.3)	0.05 a (8)	7.4 a (13)	0.05 a (7)	0.09 a (8)	9.9 a (12)	0.05 a (8)	3.0 a (9.3)
Untreated	19.5 d (0)	26.4 b (0)	27.9 c (0)	14.4 c (0)	31.9 b (0)	20.2 d (0)	23.4 b (0)	5.10 b (0)	24.9 d (0)	3.00 b (0)	5.10 b (0)	27.1 d (0)	2.10 b (0)	11.2 b (0)
LSD ($P = 0.05$)	1.7	2.7	0.9	1.1	0.9	1.0	1.5	1.3	1.0	2.0	1.4	1.5	0.6	2.9

[w] Results are presented as area under the defoliation progress curve (AUDPC, in proportion days). Epidemics were simulated for a susceptible cultivar using 6 yr of weather data, as described in the text.

[x] Spray scheduling methods are described in the text.

[y] Numbers are means of five runs differing in the dates of appearance of the initial disease. Numbers within a column followed by the same letter are not significantly different ($P = 0.05$), as determined by Fisher's protected LSD test.

[z] Numbers in parentheses indicate the number of fungicide applications scheduled by the spray-scheduling method in the given year.

TABLE 5. Percent control per fungicide application[w] achieved in simulation experiments by several spray-scheduling methods while suppressing early blight (EB) and late blight (LB)

Spray-scheduling method[x]	Early blight		Late blight	
	EB-S[y]	EB-MR	LB-S	LB-MR
Conventional	4.1 a[z]	5.6 a	7.8 a	9.0 a
Reduced-sprays strategy	6.6 c	8.7 c	12.3 c	13.8 c
PDM	4.6 ab	6.8 ab	9.5 b	10.4 ab
Blitecast	4.5 ab	7.0 b	9.7 b	10.7 b
PDM/EB	5.5 bc	7.9 bc	10.5 b	11.6 b
Simulation forecast	6.3 c	7.1 b	9.7 b	10.7 b
LSD ($P = 0.05$)	1.2	1.2	1.6	1.4

[w] Percent control per fungicide application was calculated as described in the text.

[x] Spray-scheduling methods are described in the text.

[y] Cultivar characteristics: S = susceptible; MR = moderately resistant.

[z] Numbers are means of 5 replicates (different dates of initial disease occurrence) in each of 6 yrs. Numbers within a column followed by the same letter are not significantly different ($P = 0.05$), as determined by Fisher's protected LSD test.

of sprays scheduled according to the reduced-sprays strategy was significantly higher ($P < 0.05$) than that for the conventional method, and, in most cases, than for other examined methods (Table 5). This result was independent of the disease and cultivar susceptibility. On average, most other examined methods used fungicides more efficiently than the conventional method, but did not vary much among themselves (Table 5).

The most feared aspect of late blight in northeastern United States is probably infections of tubers (10). Infection of tubers by the early-blight pathogen can also be important on some cultivars and in some parts of the U.S. Before abandoning sprays at the end of the growing season, growers need to be aware of the potential risk of tuber infections. However, early termination of sprays did not increase tuber infections in field experiments done over 2 yr (Tables 2 and 3). A carefully timed application of metalaxyl may effectively suppress tuber infections. General guidelines for optimal timing are in development (4), and incorporation of metalaxyl use into the reduced-sprays strategy needs to be evaluated before implementing this strategy. Use of IPM scouting programs to monitor the presence or absence of late blight may also help to modify late-season spray programs and further reduce the risk of tuber infections.

Several advantages of the reduced-sprays strategy, relative to the other examined spray-scheduling methods, may promote implementation by growers. The strategy deals with both early blight and late blight. Weather monitoring is required just in a short period. Sprays are scheduled in weekly intervals after wk 7. Two to four fewer sprays are applied in a growing season. And, most important, both diseases are suppressed as well by this method as by the other spray-scheduling methods.

The highly reliable predictions of the simulation models concerning the effectiveness of the various treatments deserves additional comment. The models were initiated in the mid-1970s and have been modified and expanded at various times during the interim. The models predict disease development in small plots of potatoes, and all tests of predictions have been done in small plots. During evaluation of the models, predictions from iterations have been compared to observed epidemics in small plots many times. At this point, comparisons used in model construction and in model validation number more than 100. Thus, the models have developed into useful tools to obtain additional data concerning the effects of treatments applied in small plots. However, restrictions concerning conclusions from small-plot experiments apply equally to conclusions from the simulation models.

LITERATURE CITED

1. Bruhn, J. A., and Fry, W. E. 1981. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology 71:612-616.
2. Bruhn, J. A., and Fry, W. E. 1982. A mathematical model of spatial and temporal dynamics of chlorothalonil residues in a potato canopy. Phytopathology 72:1306-1312.
3. Bruhn, J. A., and Fry, W. E. 1982. A statistical model of fungicide deposition on potato foliage. Phytopathology 72:1301-1305.
4. Doster, M. A., and Fry, W. E. 1988. Toward optimal timing of metalaxyl application for control of potato late blight via computer simulations and field experimentation. (Abstr.) Phytopathology 78:1532.
5. Doster, M. A., Sweigard, J. A., and Fry, W. E. 1989. The influence of host resistance and climate on the initial appearance of foliar late

blight of potato from infected seed tubers. Am. Potato J. 66:227-233.

6. Fohner, G. R., Fry, W. E., and White G. B. 1984. Computer simulation raises questions about timing protectant fungicide application frequency according to late blight forecast. Phytopathology 74:1145-1147.
7. Fry, W. E. 1975. Integrated effects of polygenic resistance and a protective fungicide on development of potato late blight. Phytopathology 65:908-911.
8. Fry, W. E., Apple, A. E., and Bruhn, J. A. 1983. Evaluation of potato late blight forecast modified to incorporate host resistance and fungicide weathering. Phytopathology 73:1054-1059.
9. Fry, W. E., Bruck, P. I., and Mundt, C. C. 1979. Retardation of potato late blight epidemics by fungicides with eradicant and protectant properties. Plant Dis. Rep. 63:970-974.
10. Fry, W. E., and Fohner, G. R. 1985. Construction of predictive models. I. Forecasting disease development. Pages 161-178 in: Advances in Plant Pathology, Vol. 3. C. A. Gilligan, ed. Academic Press Inc., London.
11. Halseth, D. E., Sieczka, J. B., Tingey, W. M., and Zitter, T. A. 1987. Cornell Recommendations for Commercial Potato Production. Cornell Extension Service, Ithaca, NY. 16 pp.
12. Krause, R. A., Massie, L. B., and Hyre, R. A. 1975. Blitecast: A computerized forecast to potato late blight. Plant Dis. Rep. 59:95-98.
13. Madden, L., Pennypacker, S. P., and MacNab, A. A. 1978. FAST, a forecast system for *Alternaria solani* on tomato. Phytopathology 68:1354-1358.
14. Nutter, Jr., F. W., and MacHardy, W. E. 1981. Timing of additional sprays for control of potato early blight (*Alternaria solani*) when following a late blight forecasting spray schedule in New Hampshire. Prot. Ecol. 3:47-54.
15. Pelletier, J. R. 1987. Computer simulation of cultivar resistance and fungicide effects on epidemics of potato early blight. Ph.D. thesis. Cornell University, Ithaca, NY. 127 pp.
16. Pscheidt, J. W., and Stevenson, W. R. 1986. Comparison of forecasting methods for control of potato early blight in Wisconsin. Plant Dis. 70:915-920.
17. Shaner, G., and Finney, R. E. 1977. The effect of nitrogen fertilization on the expression of slow-mildewing resistance in Knox wheat. Phytopathology 67:1051-1056.
18. Shtienberg, D., Doster, M. A., Pelletier, J. R., and Fry, W. E. 1989. Use of simulation models to develop a low risk strategy to suppress early and late blight in potato foliage. Phytopathology 79:590-595.
19. Stevenson, W. R. 1983. An integrated program for managing potato late blight. Plant Dis. 67:1047-1048.
20. Stevenson, W. R., Pscheidt, J. W., Thielman, D. G., and Shields, E. J. 1986. PDM (Potato Disease Management): A computer tool for potato disease management. University of Wisconsin-Madison. Version 1.1, April 1986. IPM Program. 39 pp.