Evaluation of Potato Late Blight Forecasts Modified to Incorporate Host Resistance and Fungicide Weathering

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ABSTRACT

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Host resistance was incorporated into two potato late blight forecasts, Blitecast and a computer simulation model-generated forecast. Each forecasting system recommended that less frequent fungicide sprays be applied to resistant than to susceptible cultivars. Modifications of Blitecast were based on field estimates of fungicide weathering and cultivar resistance and were conservative; adjustments in fungicide dosage were insufficient to compensate for differences between moderately resistant and susceptible cultivars. The simulation forecast was derived from analysis of two simulation models. One model described weather effects on fungicide distribution and amount. The second model described weather and host resistance effects on development of the pathogen, *Phytophthora infestans*. The simulation forecast accurately incorporated host resistance and fungicide effects — late blight was suppressed similarly on susceptible and resistant cultivars. During the course of these experiments, differences in host resistance caused greater differences in disease development than did variation in weather.

Potato late blight forecasts in North America and in Europe are based on the assumption that cultivars are susceptible (9,11,12). However, some potato cultivars have measurable levels of apparently durable (sensu Johnson [7]), rate-reducing resistance (6). Late blight can be suppressed on moderately resistant cultivars with less fungicide than is required on susceptible cultivars. If fungicide dosage is adjusted to complement cultivar resistance, and if applications are timed according to a forecast technique, fungicide can be used more efficiently than in nonadjusted fixed interval sprays (5). Adjustment of fungicide application frequency to complement cultivar resistance requires less fuel and labor, and therefore may be preferred by some growers relative to adjustment of fungicide dosage at each application.

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The purpose of the research reported here was to identify a way to incorporate host resistance into forecasting systems by adjusting fungicide frequency, rather than by altering fungicide concentration. Two approaches were used. In the first approach, an existing potato late blight forecasting technique, Blitecast (8), was modified to include the effects of host resistance. The second approach was to evaluate a new potato late blight forecasting technique developed from simulation analysis (1,2) in which host resistance had been included. No attempt was made to determine the timing of the initial fungicide spray.

MATERIALS AND METHODS

Cultural procedures. Foundation or certified potato (*Solanum tuberosum* L.) seed pieces were planted at approximately a 23-cm spacing during the last 10 days in May 1979, 1980, and 1981. Seed pieces were small whole tubers or tuber pieces each weighing about 50 g. Tuber pieces were treated with a mancozeb dust prior to planting. Herbicide (linuron 50 WP, 1.7 kg [a.i.]/ha) was applied after planting, but prior to plant emergence each year. Fertilizer (168 kg N, 74 kg P, 139 kg K/ha) and insecticide, aldicarb (3.3 kg [a.i.]/ha), were applied at planting. The insecticide methamidophos (0.77–1.1 kg [a.i.]/ha) was applied as needed—usually once or twice in August. Fungicides were applied hydraulically (beginning in mid-July) in spray volumes equivalent to 935 L/ha with a tractor-mounted boom at 19.4 kg/cm^2. A vine killer (dinoseb [4.7 L/ha] or ametryn [1.8 kg (a.i.)/ha] followed by dinoseb) was applied during the second week of September each year.

Experimental plots were four rows wide (0.9 m between rows) and 3.6 m long. Treatments were randomized in complete blocks and there were either three or four complete blocks depending on the experiment. Plots were separated from each other by fallowed areas 4.6 m wide.

Conditions favorable to disease increase were maintained in some of the experiments by sprinkler irrigation from ~0730 to 0800 hours and from ~1930 to 2000 hours daily (1 hr/day, total) at 0.23 cm/hr. Disease was estimated visually as described previously (5). Assessments were made every 2–7 days from inoculation until application of vine killer, or until plants died. The area under the disease progress curve (AUDPC) (6,10) has units of proportion-days (= proportion × time [days]) and was subjected to statistical analysis without transformation. Analyses using proportions were done on arcsin transformed data. The final proportion of disease was that determined from measurement made at the end of the assessment period.

The impact of fungicide application interval on disease development was evaluated in each of 2 yr. This information was necessary to determine how Blitecast should be modified to incorporate host resistance effects. Fungicide weathering and the production and expansion of new leaves limit the extent to which application intervals can be expanded. Experiments were done with three protectant fungicides used extensively to suppress late blight and a systemic fungicide potentially important in late blight suppression. Protectant fungicides were applied to small plots of cultivar Hudson potatoes every 5, 7, 10, or 14 days; the systemic fungicide was applied every 7, 10, 14, and 21 days. For each fungicide, the dosage per application was adjusted so that each plot received the same average dosage per day. For example, the fungicide concentration in the 5-day treatment was 50% that in the 10-day treatment. In 1979, fungicides were captafol (Difolatan, 4F, 0.037 kg [a.i.]/ha/day), mancozeb (Manzate 200, 80 W, 0.080 kg [a.i.]/ha/day), and metalaxyl (Ridomil, 2 EC, 0.01 kg [a.i.]/ha/day). These amounts are about 20–40% of recommended dosages. Plots were inoculated by applying *P. infestans* race 1, 2, 3, 4 (8,000 sporangia in 20 ml of water) to a portion of the center plant in each plot on 23 and 24 July 1979.

The impact of application interval was determined for chlorothalonil in 1980. A low concentration of chlorothalonil (Bravo 500, 0.050 kg [a.i.]/ha/day) was applied every 5, 7, 10, or 14 days to one set of plots, and a higher concentration (0.100 kg [a.i.]/ha/day) was applied every 5, 7, or 10 days to a different set of plots. These amounts are about 25 and 50%, respectively, of the maximum recommended dosages. Experimental error prevented us from assessing the effect of the 14-day interval at the higher concentration. Plots were inoculated on 28 and 29 July 1980 by applying *P. infestans* race 0 (125,000 sporangia in 25 ml) to a portion of a plant in the center of each plot.

Host resistance and Blitecast. We modified Blitecast to incorporate some effects of plant resistance. Recommendations for timing the frequency of fungicide applications to moderately resistant cultivars were added. These recommendations were developed from results of previous field experiments with cultivars Hudson (susceptible) and Cornell breeding line NY59 (moderately resistant). These studies identified the difference in resistance between these two clones as equivalent to weekly applications of at least 0.56 kg (a.i.) mancozeb per hectare made to Hudson. Thus, NY59 should require only 60–70% as much fungicide as that normally applied to susceptible cultivars (1.34–1.79 kg [a.i.]/ha/wk). Blitecast recommendations for timing the initial spray, or for the frequency of fungicide application to susceptible cultivars were not changed.

Recommendations for timing fungicide applications to moderately resistant cultivars were evaluated in field experiments in 1979 and 1980. Fungicide was applied at a low dosage (0.9 kg [a.i.] mancozeb per hectare) to ensure disease development. The moderately susceptible cultivar, NY59, received fungicide every 7 days or every 9 days in weather that was favorable or moderately favorable, respectively, to disease development. In contrast, recommendations from Blitecast (8) derived from Wallin's work (13) recommended sprays every 5 days or every 7 days in weather favorable or moderately favorable, respectively, to disease development. Consequently, in weather favorable to late blight development, moderately resistant cultivars received about 0.9 kg (a.i.) mancozeb per hectare per week, and susceptible cultivars received 1.25 kg (a.i.) mancozeb per hectare per week. In moderately favorable weather, moderately resistant cultivars

TABLE 1. Blight units for the simulation forecast as determined by temperature and periods of high relative humidity[a]

Average temperature (C)	Cultivar resistance	Consecutive hours of relative humidity ≥90% that should result in Blight units of: 0	1	2	3	4	5	6	7
>27	S[b]	24	...	...	...	...	...	...	...
	MS[c]	24	...	...	...	...	...	...	...
	MR[d]	24	...	...	...	...	...	...	...
23–27	S	6	7–9	10–12	13–15	16–18	19–24	...	...
	MS	9	10–18	19–24	...	...	...	...	...
	MR	15	16–24	...	...	...	...	...	...
13–22	S	6	...	...	...	...	7–9	10–12	13–24
	MS	6	7	8	9	10	11–12	13–24	...
	MR	6	7	8	9	10–12	13–24	...	...
8–12	S	6	7	8–9	10	11–12	13–15	16–24	...
	MS	6	7–9	10–12	13–15	16–18	19–24	...	...
	MR	9	10–12	13–15	16–24	...	...	...	...
3–7	S	9	10–12	13–15	16–18	19–24	...	...	...
	MS	12	13–24	...	...	...	...	...	...
	MR	18	19–24	...	...	...	...	...	...
<3	S	24	...	...	...	...	...	...	...
	MS	24	...	...	...	...	...	...	...
	MR	24	...	...	...	...	...	...	...

[a] High relative humidity ≥90%. Blight unit estimation period is 24 hr (1200 hours to 1200 hours).
[b] S = susceptible cultivars.
[c] MS = moderately susceptible cultivars.
[d] MR = moderately resistant cultivars.

received 0.7 kg (a.i.) mancozeb per hectare per week, but susceptible cultivars received 0.9 kg (a.i.) mancozeb per hectare per week. The differences in fungicide were conservative in that the differences of 0.35 and 0.20 kg (a.i.) mancozeb per hectare per week were considerably less than the 0.56 kg/wk difference calculated previously. Conservative differences were chosen because the impact of fungicide application interval on disease suppression was not known precisely.

In 1980, the recommendations for timing fungicide applications to moderately resistant cultivars were adjusted to include estimates of the impact of fungicide application interval on disease development. We estimated that each day's extension of the spray interval allowed an increase in disease of about 10% (see results). Consequently, applications of mancozeb (0.9 kg [a.i.]/ha) to moderately resistant cultivars were made every 7–8 days or every 11 days in weather favorable or moderately favorable to late blight, respectively. Recommendations for susceptible cultivars remained as described by Blitecast—every 5 days or every 7 days, respectively, in weather favorable or moderately favorable to late blight. Consequently, in weather favorable or moderately favorable to late blight, susceptible cultivars received more mancozeb (0.42 or 0.33 kg [a.i.] mancozeb per hectare, respectively), than did moderately resistant cultivars.

Late blight was favored each year. Plots were sprinkler-irrigated at 0730–0800 and 1930–2000 hours daily at 0.23 cm/hr. Inoculum (*P. infestans* race 1, 2, 3, 4—800 sporangia in 20 ml) was applied on 30 July 1979 to a portion of a plant in the center of each plot. In 1980, inoculum was provided from diseased plants in nearby experiments during late July.

Simulation forecasts. A preliminary forecast derived from analysis of two computer simulation models was evaluated in 1980, and a revised version was evaluated in 1981. Descriptions of the simulation models are given elsewhere (1,3,4). The simulation forecasts include host resistance and fungicide (chlorothalonil) effects as well as weather (rainfall, temperature, and relative humidity) effects. Fungicide effect is identified from knowledge of efficacy, initial distribution, subsequent redistribution, and weathering. These were determined from studies with chlorothalonil; therefore, the simulation forecast was tested with chlorothalonil (0.95 kg/ha). The degree to which the weather favors late blight development is described by blight units. The calculation of blight units depends on the resistance of a cultivar (Table 1). Blight units in the simulation forecasts quantify weather effects on disease development; thus, they are similar to severity values in Blitecast. In the simulation forecast, sprays are recommended less frequently for resistant than for susceptible cultivars in the same environment. Sprays may also be recommended if fungicide (chlorothalonil) residues on foliage decline to low levels. Fungicide removal is monitored as fungicide units (Table 2), and residue levels are permitted to decline more on resistant than on susceptible cultivars before another fungicide application is recommended (Table 3). The derivation of the decision rules is to be described subsequently (J. A. Bruhn and W. E. Fry, *unpublished*).

The simulation forecast was evaluated in field experiments. Resistant cultivars in the experiments were Rosa or Sebago, and the susceptible cultivar was Hudson. Weather data for Blitecast and the simulation forecast were obtained from hygrothermographs located in weather shelters within the canopy. Floors of the shelters were about 25 cm above the soil surface.

Two of the three tests of the simulation-generated forecasts were stress tests: inoculum was available from infected plants in adjacent plots, and plots in the experiment were sprinkler-irrigated as described previously. The third test (done in 1981) was a nonstress test. Plots were not sprinkler irrigated and were 150 m upwind from the nearest infected potato plants. The nonstress test was located 500 m north of the stress test and on the far side of a line of tall trees. The prevailing wind was from the west. Disease symptoms were first detected in unsprayed plots 15 days after initial inoculation at the site of the stress test. Unsprayed plots at the site of the nonstress test were eliminated as source of inoculum by treatment with metalaxyl (Ridomil 2 EC, 0.11 kg [a.i.]/ha per application) immediately after disease symptoms were detected and again 1 wk later.

RESULTS

Environment and disease. The 1979, 1980, and 1981 growing seasons were favorable to late blight, and total Blitecast severity values in regularly irrigated plots were 63, 59, and 128, respectively. In each of the 3 yr, disease developed rapidly in plots of Hudson potatoes that received no fungicide. The time of 75% defoliation (= 75% disease) occurred at 34, 24, and 22 days after inoculation in 1979, 1980, and 1981, respectively. AUDPCs were 16.5, 16.5, and

TABLE 2. Fungicide units (for chlorothalonil) for the potato late blight simulation forecast as determined by rainfall and the number of days since the last fungicide application

Time (days) since fungicide application	Daily rainfall amounts (mm) that result in fungicide units of						
	1	2	3	4	5	6	7
1	<1	···	···	1	2–3	4–6	>6
2	<1	···	1	2–4	5–8	>8	···
3	<1	···	1–2	3–5	>5	···	···
4–5	<1	···	1–3	3–8	>8	···	···
6–9	<1	···	1–4	>4	···	···	···
10–14	<1	1	2–8	>8	···	···	···
>14	<1	1–8	>8	···	···	···	···

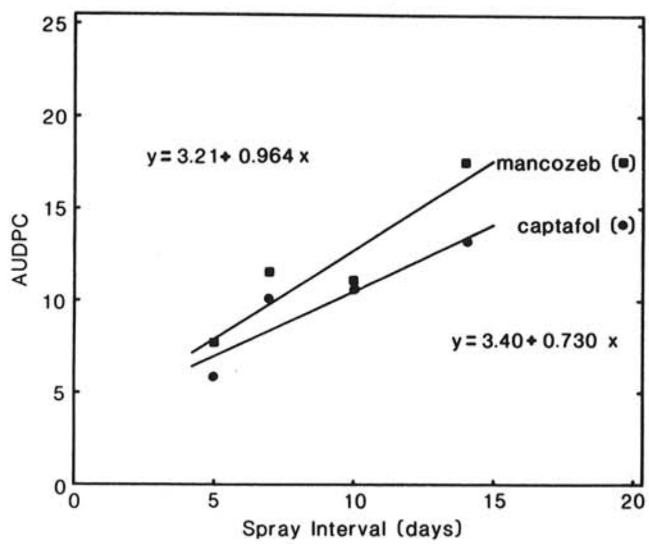

Fig. 1. Influence of spray interval on the efficacy of mancozeb and captafol to suppress potato late blight epidemics induced by *Phytophthora infestans*. Disease severity is indicated by area under the disease progress curve (AUDPC). Fungicide dosages were adjusted so that all mancozeb- or captafol-treated plots received the same total amount of mancozeb (0.08 kg/ha/day) or captafol (0.037 kg/ha/day), respectively. The R-squared was 64% for mancozeb and 60% for captafol.

TABLE 3. Decision rules for the simulation forecast

Logic statements	Cultivar resistance: Susceptible	Moderately susceptible	Moderately resistant
Fungicide should be applied if fungicide has not been applied within 5 days			
AND cumulative blight units since last spray exceed:	30	35	40
OR cumulative fungicide units since last spray exceed:	15	20	25

30.0 and epidemic lengths were 52, 45, and 50 days in 1979, 1980, and 1981, respectively.

In 1981, three unirrigated plots of Hudson potatoes were unprotected by fungicide. These were inoculated by sporangia produced in other plots, and 75% disease occurred at 40 days after plots in other experiments that were inoculated. The average area under the disease progress curve was 14.8, and 109 Blitecast severity values were recorded during the season.

Impact of fungicide application frequency. The nonsystemic fungicides suppressed potato late blight epidemics more effectively if smaller doses were applied more frequently than if higher dosages were applied less frequently. A measure of this effect was obtained by regressing the area under the disease progress curve against the interval between fungicide applications (Fig. 1). The area under the disease progress curve nearly doubled as the application interval was extended from 5 to 14 days (Figs. 1 and 2).

The greater efficacy of frequent application compared to infrequent application was more pronounced at a higher dosage than at lower dosage, although the slopes of the lines were not significantly different (Fig. 2). In contrast, application of a systemic fungicide, metalaxyl, within the intervals of 7–21 days had no detectable influence on the efficacy of the fungicide.

The effects of fungicide application frequency on fungicide efficacy were similar for the three protectant fungicides. Different dosages and different years prevent precise comparison of chlorothalonil with mancozeb and captafol.

Host resistance and Blitecast. Two experiments were designed to evaluate methods of incorporating host resistance into Blitecast. In the first experiment (1979), late blight developed so slowly in all plots that the original fungicide rate (0.9 kg/ha per application) was reduced to 0.67 kg/ha per application part way through the season. Consequently, the average dosage to the susceptible cultivar was 7.41 kg/45 days (= 0.17 kg mancozeb per hectare per day) and that applied to the moderately resistant cultivars was 0.13 kg/ha/day. The resistance of NY59 had a greater disease suppression effect than did the additional fungicide applied to the susceptible cultivar Hudson (Table 4).

In the second experiment (1980), the resistance of cultivar NY59 again suppressed disease more effectively than did modifications of fungicide dosages (Table 5). The resistant cultivar received four applications for an average dosage of 0.083 kg mancozeb per hectare per day. The susceptible cultivar (Hudson) received five applications for an average of 0.104 kg mancozeb per hectare per day. The difference (0.02 kg/ha/day) is only one-fourth as large as the predicted difference between Hudson and NY59 (7).

Simulation forecasts. The simulation forecast was evaluated in three experiments. The first experiment evaluated a preliminary form of the forecast in 1980. The revision (1981 experiments) was based on knowledge that fungicide residues were described by a gamma probability distribution (3). Thus, the arithmetic mean of fungicide residues, used to derive the preliminary simulation forecast, had overestimated the effect of fungicide.

The preliminary simulation forecast was used to indicate frequency of fungicide sprays applied to a moderately resistant cultivar (Rosa) and Blitecast was used to indicate frequency of fungicide sprays to a susceptible cultivar (Hudson). Plots were irrigated and were located near other plots, which produced inoculum. The preliminary simulation forecast recommended three fungicide applications to Rosa, but Blitecast recommended five applications to Hudson. Late blight developed similarly in all plots.

The revised simulation forecast accurately incorporated host resistance, fungicide, and weather effects, as measured in two experiments in 1981. In the stress test, plots were inoculated initially on 20 July, inoculum was consistently available from diseased plants in nearby small plots, and disease developed in all plots. Blitecast recommended eight applications to both susceptible (Hudson) and moderately resistant (Rosa) cultivars. Weekly fungicide applications resulted in seven sprays and slightly higher disease levels relative to those plots of the same cultivar to which fungicide applications were timed according to Blitecast (Table 6). When applications were made either weekly or according to Blitecast, the susceptible cultivar was more severely diseased than the moderately resistant one (Table 6). The simulation forecast technique recommended that nine applications be made to the susceptible cultivar (Hudson) and that six be made to the moderately resistant cultivar (Rosa). These combinations of fungicide and host resistance resulted in similar levels of disease suppression (Table 6).

The simulation forecast also accurately incorporated host resistance as determined by a nonstress test. The moderately resistant cultivar Sebago was compared to Hudson. Although the

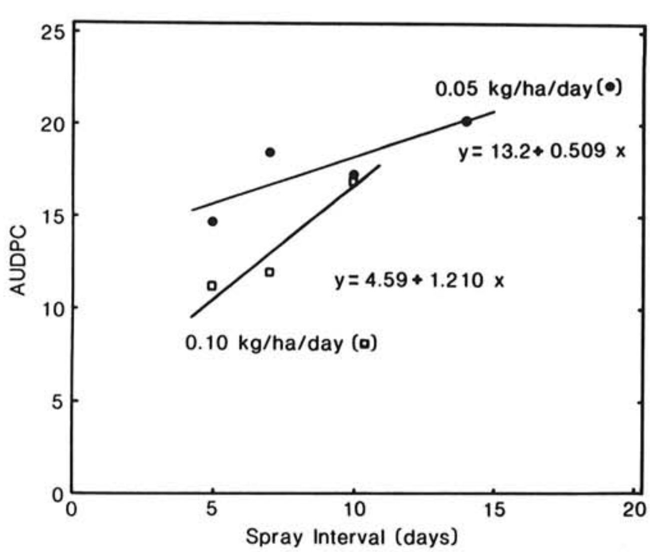

Fig. 2. Influence of spray interval on the effect of two different concentrations of chlorothalonil on epidemics of potato late blight induced by *Phytophthora infestans*. Chlorothalonil dosages were adjusted so that one series of plots received an average of 0.10 kg/ha/day, and another series of plots received 0.05 kg/ha/day. Disease severity was indicated by area under the disease progress curve (AUDPC). Slopes of the two lines were not significantly different ($P = 0.05$), as indicated by a pooled t test. Significance was attained at $P > 0.28$. The R-squared was 30% for the 0.05 kg/ha rate and 62% for the 0.10 kg/ha rate.

TABLE 4. Effects of host resistance and various fungicide[v] timing techniques on potato late blight (induced by *Phytophthora infestans*) in 1979

Cultivar	Timing technique[w]	Final disease rating (%)	AUDPC[x]	Fungicide Applications (no.)	Fungicide Total amount (kg [a.i.]/ha)
Treated					
Hudson[y]	7-day	30.2 ab[z]	1.5 ab	8	6.74
	Blitecast	18.1 b	0.9 b	9	7.41
	modification	32.3 a	1.8 a	7	5.84
NY59	7-day	2.8 c	0.2 c	8	6.74
	Blitecast	1.5 c	0.1 c	9	7.41
	modification	3.4 c	0.2 c	7	5.84
Untreated					
Hudson		98.3	16.5	...	...
NY59		52.1	5.8	...	...

[v] The fungicide dosage per application was 0.9 kg mancozeb per hectare until 20 August 1979, after which it was 0.7 kg/ha. For the weekly spray, regular Blitecast and modified Blitecast treatments, there were six, six, and five applications, respectively, at the 0.9-kg/ha dosage.

[w] Mancozeb was applied every 7 days, or at intervals indicated by Blitecast (8) or by a modification of Blitecast, which was developed for moderately resistant cultivars.

[x] Area under the disease progress curve in proportion-days. Duration of the epidemic was 45 days.

[y] Cultivar Hudson is susceptible and cultivar NY59 is moderately resistant to late blight.

[z] Numbers followed by the same letter are not significantly different ($P = 0.05$), as indicated by Duncan's new multiple range test. Analyses using percentages were done on arcsin transformations.

TABLE 5. Effects of host resistance and various fungicide[u] timing techniques[v] on potato late blight (induced by *Phytophthora infestans*) in 1980

Treatment		Final disease rating		Fungicide		Yield	
Cultivar	Timing technique	(%)	AUDPC[w]	Number of applications	Total amount (kg [a.i.]/ha)	Total kg/ha	Percent (by wt) blighted
Hudson[x]	7-day	87 b[y]	9.5 a	7	6.3	36,884 b	0.8 bc
	Blitecast[v]	91 a	10.5 a	5	4.5	45,274 ab	0.0 c
NY59	7-day	22 d	1.3 b	7	6.3	50,023 a	9.3 a
	Blitecast[v]	44 c	2.5 b	5	4.5	49,390 a	1.1 bc
	Modification[v]	30 d	1.5 b	4	3.6	51,606 a	5.5 ab
Hudson[z]	None	>99	16.5	0	0	19,471	0.5
NY59[z]	None	67	6.6	0	0	28,019	16.6

[u] Fungicide was mancozeb (Manzate 200, 80W) applied at 0.9 kg (a.i.)/ha.
[v] Blitecast recommended sprays every 5 or 7 days when weather was favorable or moderately favorable, respectively, to disease development. Modified Blitecast recommended sprays every 7–8 or 11 days in weather favorable or moderately favorable to disease development, respectively.
[w] Area under the disease progress curve in proportion-days. Duration of the epidemic was 37 days.
[x] Hudson is susceptible and NY59 is moderately resistant to late blight.
[y] Numbers within a column followed by the same letter are not significantly different ($P = 0.05$) as indicated by Duncan's new multiple range test. Analyses using percentages were done on arcsin transformations.
[z] Plots of Hudson and NY59, unprotected by fungicide, were located 200 m away from the forecasting experiment, and were inoculated 6 days after plots in the forecasting experiment. Environmental conditions were the same, but disease developed over a shorter time in the unprotected plots. Thus, the values reported here are low and not precisely comparable to treatments in the forecasting experiment. They are reported here for general comparison.

TABLE 6. Evaluation of simulation forecast[u] and Blitecast[v] 1981

Treatment		Final disease rating		Fungicide[x]		Yield	
Cultivar	Timing technique	(%)	AUDPC[w]	No. of applications	Total amount (kg [a.i.]/ha)	Total (kg/ha)	Percent (by wt) blighted
Hudson[y]	7-day	92 a[z]	12.3 a	7	6.15	40,050	4.5 a
	Simulation	74 c	7.0 b	9	7.90	46,857	2.0 a
	Blitecast	79 bc	9.6 ab	8	7.02	44,799	3.4 a
Rosa	7-day	44 d	2.3 c	7	6.15	58,571	0.6 b
	Simulation	84 ab	10.6 ab	6	5.27	52,239	2.1 a
	Blitecast	30 e	1.3 c	8	7.02	59,679	0.2 b
Hudson	None	100	30.0	...	0	10,923	0.5
Rosa	None	100	25.1	...	0	27,386	0

[u] Simulation forecast is described in Tables 1–3.
[v] Blitecast is described by Krause et al (8).
[w] Area under the disease progress curve in proportion-days. Duration of the epidemic was 51 days.
[x] Fungicide was chlorothalonil (Bravo 500) at 0.9 kg (a.i.)/ha at each application.
[y] Hudson is susceptible and Rosa is moderately resistant to late blight.
[z] Numbers within a column followed by the same letter are not significantly different ($P = 0.05$), as determined by Duncan's new multiple range test. Analyses using percentages were done on arcsin transformations.

TABLE 7. Nonstress test[s] of simulation forecast[t] and Blitecast[u] in 1981

		Final disease rating		Fungicide[w]		Yield	
Cultivar	Timing technique	(%)	AUDPC[v]	No. of applications	Total amount (kg [a.i.]/ha)	Total (kg/ha)	Percent (by wt) blighted
Hudson[x]	7-day	2.1 ab[y]	0.09 a	7	6.15	50,656	0.7 a
Hudson	Simulation forecast	4.6 a	0.12 a	8	7.02	56,038	0.1 a
Hudson	Blitecast	2.2 ab	0.06 a	9	7.90	56,671	0.0 a
Rosa	Simulation forecast	4.9 ab	0.12 a	5	4.39	54,297	0.0 a
Sebago	7-day	0.5 b	0.01 a	7	6.15	41,158	0.2 a
Sebago	Simulation forecast	4.1 ab	0.22 a	5	4.39	43,374	0.0 a
Sebago	Blitecast	0.2 b	0.01 a	9	7.90	41,791	0.0 a
Hudson[z]	none	99.5	14.78	0	0	27,386	5.5
Rosa[z]	none	92.5	8.15	0	0	43,691	6.6
Sebago[z]	none	82.7	6.42	0	0	31,027	0.3

[s] Plots were not sprinkler irrigated and were separated by 500 m from other plots with late blight.
[t] Computer-generated forecast is described in Tables 1–3.
[u] Blitecast is described by Krause et al (8).
[v] Area under the disease progress curve in proportion-days. Duration of the epidemic was 35 days.
[w] Fungicide was chlorothalonil (Bravo 500) at 0.9 kg (a.i.)/ha at each application.
[x] Hudson is susceptible and Rosa and Sebago are moderately resistant to late blight.
[y] Numbers followed by the same letter are not significantly different ($P = 0.05$), as determined by Duncan's new multiple range test. Analyses using percentage were done on arcsin transformed data.
[z] Unsprayed plots of potatoes were located ca 150 m downwind from the site of the sprayed plots.

test was termed nonstress, the environment was still favorable to late blight. Several plots of unsprayed potatoes located 150 m downwind from the site of the nonstress test were severely affected by late blight (Table 7). Fungicide applied according to each timing technique suppressed late blight to less than 5% total final disease. When applications were made weekly (seven applications) or according to Blitecast (nine applications), the moderately resistant cultivar Sebago tended (nonsignificantly, at $P = 0.05$) to develop less disease than did the susceptible cultivar Hudson. However, when application frequencies were recommended according to the simulation forecast, the moderately resistant cultivars Rosa and Sebago, which received five applications, had levels of disease similar to that in the susceptible cultivar, Hudson, which received eight applications. Thus, the simulation-generated forecast accurately incorporated the effects of host resistance and provided a means to adjust fungicide to complement cultivar resistance via a weather-dependent forecast.

In general, yields of potato tubers and the proportion of tubers that were blighted were not noticeably affected by any forecast technique (Tables 5–7). We were unable to discern simple relations between foliar blight and tuber blight or between yield suppression and tuber blight (Tables 5–7).

DISCUSSION

The adjustment of fungicide application frequencies to complement moderate host resistance always permitted a reduction in numbers of fungicide sprays, but adjustment of application frequencies because of variation in weather did not always permit as great a reduction. The effect of resistance on disease development was greater than the effect of weather variability during the course of these studies. Thus, for efficiency of fungicide use, host resistance needs to be considered.

When Blitecast was modified to incorporate host resistance, the modifications underestimated host resistance effects, and caused more than the necessary number of sprays to be applied. Three factors contributed to the development of conservative estimates of host resistance effects. First, in 1979, fungicide concentration was reduced from 0.9 to 0.7 kg/ha per application midway through the season. Thus, the fewer applications made to the moderately resistant cultivar caused a smaller difference in fungicide dosage than that planned. Second, the modification of Blitecast created situations that we interpreted conservatively. For example, if weather was just favorable enough that Blitecast recommended a 5-day application interval, we applied fungicide to the moderately resistant cultivar on a 7-day interval whether the interim two days were favorable or not. Third, fungicide-weathering effects in the second experiment (1980), although real and large, were probably overestimated. We expect that Blitecast can be modified more accurately than was done by our modifications. The more accurate modifications will recommend fewer applications on moderately resistant cultivars than did either of our modifications.

The computer simulation models incorporated weather variability, host resistance, and fungicide effects into an accurate forecast technique. In the nonstress test, the simulation forecast recommended a total application of 7.0 kg chlorothalonil per hectare to the susceptible cultivar (Hudson) and 4.4 kg chlorothalonil per hectare to the resistant cultivar (Sebago). The difference is equivalent to 0.05 kg chlorothalonil per hectare per day for a 50-day season. This value compares favorably to an estimate of 0.06–0.08 kg chlorothalonil per hectare per day as the fungicide equivalent for the difference in resistance between Sebago and Hudson (6). The simulation forecast was easy to use, presumably because it was constructed to incorporate host resistance and fungicide effects into a disease forecast. The simulation forecast and Blitecast recommended similar frequencies of fungicide applications to susceptible cultivars.

The simulation forecast is restricted to use with chlorothalonil because this fungicide was used to construct the forecast. Generalization of the simulation forecast for use with other fungicides is currently being done.

We did not attempt to modify that part of Blitecast, which attempts to identify the interval between emergence of potato plants and the first fungicide application. Recommendations of this type could be improved with accurate estimates of initial pathogen populations. These estimates are not available with present knowledge and technology. In the simulation forecast, the timing of the first application is left to the discretion of the disease management specialist.

The successful construction of a disease forecast from analysis of accurate computer simulation models illustrates the benefit of developing such models as tools for further research. Similar models for other diseases should lead to techniques that enhance their control.

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