Effects of Simulated Acidic Rain on Wash-off of Fungicides and Control of Late Blight on Potato Leaves

Ariena H. C. van Bruggen, J. F. Osmeloski, and J. S. Jacobson

Postdoctoral associate, research technician, and plant physiologist, respectively, Boyce Thompson Institute for Plant Research, Ithaca, NY 14853-1801.
Present address of first author: Department of Plant Pathology, University of California, Davis 95616.
Supported by the J. J. McDonald Foundation, Inc., Cortland, NY.
Accepted for publication 11 February 1986.

ABSTRACT

van Bruggen, A. H. C., Osmeloski, J. F., and Jacobson, J. S. 1986. Effects of simulated acidic rain on wash-off of fungicides and control of late blight on potato leaves. Phytopathology 76:800-804.

The effects of simulated acidic rain at two pH levels (2.8 and 4.6) on removal of five fungicides in each of two formulations (wettable powders and flowables) on three potato cultivars (Norchip, Monona, and Katahdin) were investigated in a series of factorial experiments. Residual fungicide on leaf disks was determined by atomic absorption spectroscopy for maneb, mancozeb, and copper hydroxide, by gas chromatography with electron capture detection for chlorothalonil, and by yeast bioassay for triphenyltin hydroxide (TPTH). Wash-off of TPTH and copper hydroxide from potato leaves was significantly increased by simulated rain at pH 2.8 compared with rain at pH 4.6 regardless of fungicide formulation and potato cultivar. Removal of maneb, mancozeb, and chlorothalonil was not affected by acidity of simulated rain. Regardless of acidity of simulated rain, wettable powders were removed more effectively than flowables. Despite 13–83% removal of fungicides from foliage by simulated acidic rain, late blight control was still significant compared with plants not treated with fungicide. *Phytophthora infestans* infection of potato leaves sprayed with TPTH was higher after an acid rain treatment at pH 2.8 than at pH 4.6, but the increased infection was ascribed to enhanced susceptibility of foliage to late blight caused by rain at pH 2.8 rather than to increased removal of the fungicide per se.

Additional key words: fungicide retention, *Solanum tuberosum*.

Although elevated levels of acidity are common in ambient rain in the eastern United States (5), and despite nearly 10 yr of research, there has been no clear evidence of reductions in growth and yield of crop plants attributable to direct effects of acid precipitation on foliage (1,8,11,12). However, indirect effects via disease development and control may be important (17,21).

The most commonly used disease control strategy for potato is to maintain an effective dose of protectant fungicide on the plant surface before and during the infection process. However, retention of applied fungicides depends on physical and chemical characteristics of the leaf surface (10), on formulation of the fungicide, and on environmental factors, of which rainfall is most important (7). Wash-off of fungicides by rain depends on the duration of exposure and on the interval between application of a fungicide and onset of rain (4,18).

Deionized or tap water has commonly been used in experiments to assess weathering of fungicides by simulated rainfall (4,18), but Troiano and Butterfield (21) demonstrated that increased acidity of simulated rain accelerated removal of triphenyltin hydroxide (TPTH) and copper hydroxide from leaf surfaces. Acidity of simulated rain did not affect wash-off of chlorothalonil on potato cultivar Norchip (21). However, Bruhn and Fry (4) showed that wash-off of chlorothalonil by ambient rain was highly cultivar-dependent. Effects of cultivar or fungicide formulation on wash-off of fungicides by acidic rain have not been studied thus far.

Because of the frequent use of fungicides on potatoes to control late blight in the northeastern United States (9), we selected potatoes to study the effect of acidic rain on wash-off of five fungicides (each in two formulations) from foliage and on subsequent late blight control. The fungicides were selected on the basis of their commercial use on potato in New York State (9). TPTH and copper hydroxide were included because of their demonstrated sensitivity to acidic rain.

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. § 1734 solely to indicate this fact.

The objectives of this research were to determine whether removal of fungicides from potato foliage is affected by simulated acidic rain, fungicide formulation, and potato cultivar and whether alterations in fungicide persistence affect the level of late blight control.

MATERIALS AND METHODS

Plant culture. Single-leaf cuttings were taken from mature potato (*Solanum tuberosum* L.) plants in a greenhouse to produce small plants with mature leaves. The cultivars used were Norchip, Monona, and Katahdin. The cuttings were selected for uniformity in size and age and were taken from mother plants that were 2–4 mo old. The cut surfaces were dipped in a mixture of auxin and thiram (Rootone F, Union Carbide Agricultural Products, Ambler, PA), and placed in moist perlite (Terra-lite, W. R. Grace & Co., Cambridge, MA) on a tap water mist bench in a greenhouse. After 1 wk, rooted cuttings were transplanted to 7-cm-diameter pots containing Cornell peat-lite mix A (3) and placed in a greenhouse with a 16-hr photoperiod and day/night temperatures of about 25/18 C and relative humidity of at least 50%. Supplementary lighting was provided by multivapor lamps (MV400/U, General Electric, Bridgeport, CT).

Treatment application. Fungicide suspensions or emulsions were prepared in deionized water and sprayed onto upper leaf surfaces with a paint spray gun (T6A series 502, DeVilbiss Co., Toledo, OH) to the point of runoff. The wettable powders had been finely ground with a Talboys grinder (model 104, Talboys Instrument Corp., Emerson, NJ), and the suspensions were stirred constantly during their application to ensure homogeneous deposition. The concentrations of the fungicides used were 1,500 mg a.i./L for maneb (Manzate D and Manzate F) and mancozeb (Manzate 200 and Manzate 200F), 750 mg a.i./L for chlorothalonil (Bravo W-75 and Bravo 500 F), 250 mg a.i./L for TPTH (Duter 47.5WP and Duter F30), and 1,200 mg a.i./L for copper hydroxide (Kocide 101 and cupric hydroxide flowable). The fungicide concentrations were within the range of those recommended to growers (14).

Two days after fungicide application, simulated rain was applied for 20 min. To prepare simulated rain solutions, background ions were added to deionized water in concentrations similar to those measured in ambient rain (5). The simulated rain solutions were acidified to pH 2.8 and 4.6 with a mixture of sulfuric and nitric acids in a 2:1 (w/w) ratio of sulfate and nitrate, a ratio common to ambient rain in New York State (23). The concentrations of all ions added to deionized water are given in Table 1. Rain was simulated by hydraulic nozzles (RA2, Delevan Corp., West Des Moines, IA) situated about 3 m above rotating turntables. Each nozzle, operated at a water pressure of 1.2 $kg \cdot cm^{-2}$, produced droplets with a median diameter of 1 mm. The deposition rate, measured by collecting rain in plastic cups, averaged 11.2 ($\pm$0.9) mm/hr for all experiments. This rate corresponds to a moderately heavy rain.

Leaf samples were taken to evaluate treatment effects, and subsequently, the terminal leaflets of plants treated with fungicides and acid rain or with acid rain alone were inoculated with 50 μl of a sporangial suspension of *Phytophthora infestans* de Bary (6.6 ($\pm$2.4) $\times 10^4$/ml) and incubated in a mist chamber at 18 C. The mist consisted of a solution at pH 4.0 prepared as described above and produced by a humidifer (DeVilbiss Co., Somerset, PA). Sporangial suspensions of *P. infestans* were prepared in simulated rain solutions of pH 4.0 from 16-day-old cultures on V-8/$CaCO_3$ agar (18) or V-8/lima bean agar (lima bean broth from 80 g of lima beans in 200 ml of deionized water added to 100 ml of clarified V-8/$CaCO_3$ and 15 g of Bacto agar).

Evaluation of treatment effects. Effects of treatments on removal of fungicide were evaluated by determining residues on leaves before and after application of simulated acidic rain. Four leaf disks (0.33 cm^2) were cut out of four lateral leaflets before simulated rain application and eight leaf disks after rain application. The four or eight disks were pooled to form one sample of each cutting.

Residues of maneb, mancozeb, and copper hydroxide were determined by atomic absorption spectroscopy. Four (or eight) leaf disks were placed in 2 ml of 5.8 N hydrochloric acid when treated with maneb or mancozeb and in 2 ml of 0.1 N nitric acid when treated with copper hydroxide (6) and extracted for 1 hr on a rotary shaker at 150 rpm (model 5917, New Brunswick Scientific, New Brunswick, NJ). The concentration of manganese and copper ions in the extract was measured directly with an atomic absorption spectrophotometer (Perkin-Elmer 305A, Norwalk, CT) at 279 nm for manganese and 325 nm for copper. Certified Atomic Absorption Standard Manganese and Copper (Fisher Scientific, Fairlawn, NJ) were used to make standard series (0.32, 0.63, 1.25, 2.5, 5.0, and 10.0 mg/L) in 5.8 N hydrochloric acid or 0.1 N nitric acid.

Residues of chlorothalonil were determined by gas chromatography with an electron capture detector (4). Four leaf disks (before and after application of simulated rain) were placed in 10 ml of acetone and extracted for 1 hr on a rotary shaker at 150 rpm. The chlorothalonil concentration in the extract was determined with a gas chromatograph (Varian series 3700, Varian Associates Inc., Palo Alto, CA) equipped with an Ni63 electron capture detector and 3390A Hewlett-Packard peak integrator (Hewlett-Packard, Cupertino, CA). The column was 0.4 $\times$ 1.0 cm with a packing of 1.5% SP-2250 and 1.95% SP-2401 on a 100/120 Supelcoport (Supelco Inc., Bellefonte, PA). The flow of the carrier gas (5% argon-methane) was 50 ml/min, and the temperatures were 250 C for the injector, 220 C for the column, and 300 C for the detector. Technical chlorothalonil in acetone (0.35, 0.7, 1.5, 3.0, 6.0, and 12.0 mg/L) was used for the standard curve.

Residues of TPTH were estimated using a yeast bioassay as described by Spadafora et al (18). Four (or eight) leaf disks per plant were frozen at -10 C for 24 hr, then placed into scintillation vials with 9 ml of sterile potato-dextrose broth (Difco, Detroit, MI) amended with streptomycin sulfate (0.05 g/L) and chloramphenicol (0.05 g/L). The broth was inoculated with a 1-ml suspension of 24-hr-old yeast cells (3×10^6 cells per milliliter of *Saccharomyces cerevisiae* Myen ex Hansen, isolate D273.10B of the American Type Culture Collection). The vials were incubated on a rotary shaker (150 rpm) at ambient temperature (20–22 C) for 24 hr. The optical density of each culture was then determined with a Spectronic 20 spectrophotometer (Bausch & Lomb, Rochester, NY) at 625 nm. The optical density was converted to concentration of TPTH via a standard dose-response curve (0, 0.125, 0.25, 0.5, 1.0, and 2.0 mg/L). The standard curve was not significantly affected by number of leaf disks or formulation of TPTH, so the same conversion equation could be used for all treatments per experiment. The concentrations of all fungicides were expressed as micrograms of active ingredient per square centimeter of leaf area.

Effects of treatments on infection by *P. infestans* were evaluated by counting the late blight lesions per leaflet 4–5 days after inoculation and calculating the percentage of leaflets infected by dividing the number of leaflets with lesions by the number of plants per treatment.

Experimental design. Factorial experiments were performed for each fungicide separately. The experimental factors were two pH levels in simulated rain, two fungicide formulations, and three potato cultivars (two cultivars for copper hydroxide). Timing and duration of acid rain applications were kept constant. The experiments had split-plot designs, with pH in the main plots (one simulated rain table as experimental unit) and cultivars and formulations in subplots (one plant as experimental unit). pH levels were assigned randomly to the simulated rain tables, and cultivars and formulations were completely randomized on each rain table. There were four or five plants per treatment, and each experiment was repeated at least three times (considered as blocks in the statistical analysis). Each sample for fungicide residue analysis consisted of four or eight disks cut out of four lateral leaflets of each plant.

Data analysis. The effects of pH, cultivar, and formulation and their interactions were analyzed in analyses of variance with the Statistical Analysis System (15). After each analysis of variance, the residual values were tested for normality by the Kolomogorov D statistic for sample sizes larger than 50 and by the Shapiro-Wilk statistic for sample sizes smaller than 51 (15). When individual plants were considered as experimental units, the residual values were not normally distributed. Therefore, the data of four or five plants of each treatment level were averaged, and the means were used in an analysis of variance so that residual values became normally distributed. In the experiments with maneb, mancozeb, and chlorothalonil, residual values for the means of disease observations were still not normally distributed, but logarithmic transformations of the means resulted in normally distributed residual values. Initially, fungicide removal was evaluated on the basis of statistical analysis of the reductions in fungicide concentration by acidic rain. Because fungicide removal appeared to be related to initial deposit, the reductions in fungicide concentration were expressed as a percentage of the initial deposit for the final analysis.

RESULTS

Fungicide retention. Wash-off of TPTH and copper hydroxide was affected by pH of simulated rain, regardless of fungicide formulation and potato cultivar (Table 2). Wash-off of maneb, mancozeb, and chlorothalonil was not affected by acidity of rain, again regardless of fungicide formulation and potato cultivar. TPTH and copper hydroxide concentrations decreased

TABLE 1. Concentrations of ions in simulated acidic rain solutions in milligrams per liter

Ions	pH 2.8	pH 4.6
NH_4^+	0.369	0.369
Ca^{+2}	0.112	0.112
K^+	0.055	0.055
Na^+	0.028	0.028
Mg^{+2}	0.019	0.019
H^+	1.585	0.025
Cl^-	0.124	0.124
SO_4^{-2}	55.814	1.690
NO_3^-	27.753	0.837

TABLE 2. Analysis of variance table for percent wash-off of five fungicides from potato leaves by simulated acidic rain (in percentage of the concentration before application of simulated rain)

	Maneb		Mancozeb		Chlorothalonil		TPTH		Copper hydroxide	
Source	df[a]	SS[b]	df	SS	df	SS	df	SS	df	SS
Block (B)	2	327.3	2	62.6	2	299.0	4	2,891	3	82.9
pH[c]	1	0.6	1	1.2	1	1.2	1	3,947*[d]	1	14,029.5**
B × pH (error a)	2	19.4	2	22.3	2	33.2	4	1,359	3	960.6
Cultivar (C)[e]	2	100.8	2	119.3	2	154.7	2	198	1	174.4
Formulation (F)[f]	1	122.3*	1	447.5**	1	3,147.9**	1	1,279**	1	721.7*
C × F	2	11.1	2	55.9	2	8.9	2	30	1	1.5
pH × C	2	19.8	2	57.4	2	649.6	2	707	1	117.2
pH × F	1	53.4	1	28.3	1	226.5	1	30	1	49.3
pH × C × F	2	84.5	2	16.8	2	11.2	2	490	1	0.7
Residual (error b)	20	608.7	20	1,111.1	20	1,482.4	24	3,827	18	1,871.6
R^2 (%)		55		42		75		74		90
C.V. (%)		7		9		38		18		21
Mean		81		81		23		68		48

[a] Degrees of freedom.
[b] Sequential sums of squares.
[c] pH of simulated rain: 2.8 and 4.6.
[d] Significance level: * = $P \leq 0.05$ and ** = $P \leq 0.01$.
[e] Potato cultivars: Norchip, Monona, and Katahdin.
[f] Formulation: wettable powder and flowable.

significantly more at pH 2.8 than at pH 4.6 (Table 3). Wash-off of all fungicides was significantly higher when they were applied as wettable powder than as flowable (Tables 2 and 4). However, this formulation effect was mainly due to higher initial deposits of the wettable powders (Table 4).

Late blight control. The percentage of potato leaflets infected by *P. infestans* was affected by fungicide treatment and cultivar (or their interaction) (Table 5). Analysis of the same data sets, excluding the controls (acid rain treatment only, no fungicide treatment), showed that the fungicide treatment effects were not due to effects of different formulations but solely to reductions in infection by the fungicide treatments compared to the controls (Table 6). These fungicide effects were highly significant, despite the fact that the fungicide concentrations were drastically reduced as a result of the simulated rain treatment. In most experiments, Norchip was more susceptible to late blight than Monona or Katahdin, except for the last series (with copper hydroxide), when Monona plants were more senescent and more susceptible to late blight (Table 6). Only in the case of TPTH was there a significant effect of pH of rain on late blight infection (Table 5). The percentage of leaflets infected was higher at pH 2.8 than at pH 4.6, both on plants sprayed with TPTH and on unsprayed plants (Table 7). However, the differences were only significant for the unsprayed plants (no significant pH effect in an analysis excluding these plants).

Effect of pH on infection. To investigate whether acidity of rain had a direct effect on late blight development, the observations for the unsprayed plants of all experiments were pooled and analyzed separately. The experiments were considered as blocks in a split-plot design, with pH in the main plot and cultivar in the subplot. There were significant effects of pH ($P = 0.04$) and cultivar ($P = 0.02$) on the number of lesions per leaflet, and there was no significant interaction between pH and cultivar. Infection by *P. infestans* was significantly enhanced by a preinoculation treatment with acid rain at pH 2.8 compared with pH 4.6 (Table 8). Norchip was most susceptible to late blight, followed by Monona, and Katahdin was least susceptible.

TABLE 3. Effect of pH of simulated acid rain on the decrease in fungicide concentration (micrograms of active ingredient per square centimeter of leaf surface) and percent wash-off caused by simulated acid rain

	Decrease in fungicide concentration		Percent wash-off	
Fungicide	pH 2.8	pH 4.6	pH 2.8	pH 4.6
Maneb	6.2 (2.0)[a]	6.0 (2.4)	81 (6)	82 (7)
Mancozeb	6.8 (2.0)	6.8 (2.4)	81 (7)	81 (8)
Chlorothalonil	1.3 (1.0)	1.4 (1.1)	23 (15)	23 (12)
TPTH	3.7 (1.7)	2.5 (2.0)	77 (17)	58 (15)
Copper hydroxide	3.9 (1.6)	1.8 (1.4)	69 (11)	27 (12)

[a] Standard error of the mean in parentheses.

DISCUSSION

Fungicide retention. The results presented in this paper confirm the results previously obtained by Troiano and Butterfield (21), viz., that removal of TPTH and copper hydroxide from potato leaves is enhanced by increased acidity of simulated rain. Removal of chlorothalonil, maneb, and mancozeb from potato leaves was not affected by acidity of simulated rain. Troiano and Butterfield

TABLE 4. Effect of fungicide formulation on the mean concentrations of fungicides (micrograms of active ingredient per square centimeter of leaf surface) before and after application of simulated acidic rain and the decrease in concentration and percent wash-off caused by simulated acid rain

	Concentration before rain		Concentration after rain		Decrease in concentration		Percent wash-off	
Fungicide	WP[a]	FL[a]	WP	FL	WP	FL	WP	FL
Maneb	8.7 (2.6)[b]	6.1 (1.4)	1.5 (0.6)	1.3 (0.5)	7.3 (2.3)	4.8 (1.1)	83 (6)	80 (6)
Mancozeb	9.6 (2.2)	7.1 (1.8)	1.4 (0.5)	1.6 (0.6)	8.2 (2.0)	5.5 (1.5)	85 (6)	78 (7)
Chlorothalonil	5.9 (1.9)	5.0 (1.8)	4.0 (1.2)	4.6 (1.5)	2.0 (1.0)	0.7 (0.5)	32 (11)	13 (8)
TPTH	5.1 (3.0)	3.9 (3.1)	1.4 (1.3)	1.5 (1.7)	3.7 (2.0)	2.4 (1.7)	73 (16)	62 (19)
Copper hydroxide	7.0 (1.5)	4.1 (1.0)	3.2 (1.9)	2.3 (1.0)	3.8 (1.7)	1.8 (1.3)	53 (23)	43 (25)

[a] WP = wettable powder and FL = flowable.
[b] Standard error of the mean in parentheses.

TABLE 5. Analysis of variance table for percent potato leaflets infected with late blight after application of fungicide and simulated acidic rain

Source	Maneb[a]		Mancozeb[a]		Chlorothalonil[a]		TPTH		Copper hydroxide	
	df[b]	SS[c]	df	SS	df	SS	df	SS	df	SS
Block (B)	2	10.890	2	12.56	2	4.52	7	15,411**[d]	3	8,906
pH[e]	1	0.002	1	0.08	1	1.03	1	570*	1	1,302
B × pH (error a)	2	1.250	2	4.19	2	2.60	7	676	3	990
Cultivar (C)[f]	2	4.320	2	12.45*	2	3.29	2	1,369	1	5,208**
Fungicide (F)[g]	2	60.470**[d]	2	41.91**	2	19.10**	2	88,367**	2	48,229**
C × F	4	15.240*	4	22.75*	4	2.76	4	10,646**	2	104
pH × C	2	0.110	2	1.76	2	4.31	2	1,249	1	0
pH × F	2	2.410	2	0.84	2	2.07	2	70	2	104
pH × C × F	4	3.090	4	3.65	4	12.89	4	2,023	2	1,250
Residual (error b)	32	46.900	32	57.59	32	54.59	82	39,911	30	7,604
R^2 (%)		68		63		49		75		90
C. V. (%)		121		108		226		65		37
Mean (%)		16.4		17.8		32.0		34.0		42.7

[a] Analysis of log-transformed data.
[b] Degrees of freedom.
[c] Sequential sum of squares.
[d] Significance level: * = $P \leqslant 0.05$, ** = $P \leqslant 0.01$.
[e] PH of simulated rain: 2.8 and 4.6.
[f] Potato cultivars: Norchip, Monona, and Katahdin.
[g] Fungicide treatment: wettable powder, flowable, and none (control).

TABLE 6. Percentage of potato leaflets infected with late blight as affected by fungicide treatment and potato cultivar

Series of experiments	Treatment	Cultivar		
		Norchip	Monona	Katahdin
1	Maneb	1.7 (1.7)[a]	0.0 (0.0)	3.8 (2.5)
	Mancozeb	6.1 (3.3)	6.1 (3.3)	1.7 (1.7)
	Control	45.3 (12.9)	30.8 (12.2)	16.5 (11.3)
2	Chlorothalonil	1.7 (1.7)	1.7 (1.7)	0.0 (0.0)
	Control	33.3 (17.2)	22.2 (16.5)	16.7 (16.7)
3	TPTH	12.6 (3.0)	14.1 (3.3)	20.0 (4.9)
	Control	91.7 (4.8)	66.7 (9.0)	41.7 (20.1)
4	Copper hydroxide	10.9 (3.2)	29.7 (7.6)	...
	Control	75.0 (8.2)	100.0 (0.0)	...

[a] Standard error of the mean in parentheses.

TABLE 7. Percentage of potato leaflets infected with late blight and number of late blight lesions per leaflet as affected by residual levels of TPTH (after wash-off by acidic rain) and pH of simulated rain

Dependent variable	Treatment	pH 2.8	pH 4.6
Leaflets infected (%)	TPTH	16.2 (3.0)[a]	12.5 (2.8)
	Control	76.3 (7.8)	70.2 (9.1)
Lesions/leaflet (no.)	TPTH	0.3 (0.1)	0.2 (0.06)
	Control	11.1 (2.5)	4.2 (1.1)

[a] Standard error of the mean in parentheses.

TABLE 8. Number of late blight lesions per leaflet as affected by pH of simulated rain and potato cultivar

pH	Cultivar			Together
	Norchip	Monona	Katahdin	
2.8	9.1 (2.9)[a]	4.8 (1.9)	1.8 (1.5)	5.9 (1.5)
4.6	3.9 (1.2)	3.2 (1.2)	0.5 (0.4)	2.9 (0.7)
Together	6.5 (1.6)	4.0 (1.1)	1.2 (0.7)	

[a] Standard error of the mean in parentheses.

(21) also reported the absence of any effect of acidity on wash-off rates of chlorothalonil. They used only one formulation of each fungicide and one potato (or bean) cultivar. We tested both wettable powders and flowables on three potato cultivars, but the effect of acidity of rain on fungicide retention was independent of fungicide formulation and potato cultivar.

Removal of chlorothalonil and copper hydroxide was less than that of maneb, mancozeb, and TPTH after exposure to simulated rain at pH 4.6. This order is similar to that found by Troiano and Butterfield (21), except chlorothalonil was washed off more easily in their experiments. A possible explanation is increased attachment of this fungicide to the leaves during the 2-day period between application of the fungicide and simulated rain compared with the 1-day period used by Troiano and Butterfield. Bruhn and Fry (4) found that the wash-off rate of chlorothalonil was reduced after longer periods between spraying of the fungicide and onset of rain.

Removal of maneb and mancozeb was higher than that of the other fungicides. This was probably partly due to higher initial concentrations. On the other hand, relatively more manganese ions (assumed to be proportional to the fungicide concentrations) might have been washed off than dithiocarbamate ions. Therefore, more caution needs to be exercised in the use of atomic absorption spectroscopy than was suggested recently (20). Nevertheless, when residues of maneb were determined by acid hydrolysis combined with colorimetry, assaying the dithiocarbamate itself, 50–60% of the maneb was washed off by simulated acidic rain under field conditions (*unpublished*).

The decrease in fungicide concentration was dependent on the concentration present before the rain treatment. Degradation of pesticides from leaf surfaces over time and by rain is generally related to pesticide concentration present at any moment (19). Despite our efforts to prevent settling out of the wettable powders so that the initial concentration would be similar for the different formulations of the same fungicide, the concentrations on the leaf surface measured before application of simulated rain were always higher for the wettable powders than for the flowables. Yet, the concentrations in the spray suspensions/emulsions were the same (checked for maneb and mancozeb). Possible explanations for the differences in initial concentration are 1) the wettable powders settled to the bottom of the container where the spray tube was located, or 2) the flowables degraded more during the 2-day period between fungicide application and the rain treatment.

Disease development. Inoculation of the plants with *P. infestans* after fungicide and rain treatments showed that all fungicide treatments resulted in significant control of late blight, even when most of the fungicide had been washed off. Except for the experiments with TPTH, infection by *P. infestans* was independent of pH of simulated rain. The increased levels of disease on plants treated with rain of pH 2.8 compared with pH 4.6 (plants treated with TPTH and control plants) was ascribed to increased susceptibility of potato leaves to late blight after exposure to rain with pH 2.8 and not to higher wash-off rates. Increased susceptibility of plants resulting from preinoculation treatment with acidic rain has been reported for other host-pathogen combinations (17) but not for potato late blight.

Conclusions. Of the five fungicides tested, only two were washed off more easily by acidic rain of a lower pH level. Both are hydroxides and could be expected to dissolve better in acidic solutions. Both TPTH and copper hydroxide are less widely used than the other fungicides tested (9), so the economic impact of the effect of acid rain on fungicide retention on potato may be of minor importance. Recently, the fungicide metalaxyl has been registered (as Ridomil MZ-58) for late blight control on potato (13). In separate experiments, we tested the effect of acidity of simulated rain on removal of this fungicide, but its wash-off rate was not affected by pH of rain (22). Although TPTH is not widely used by growers in upstate New York (9), it is recommended on Long Island for the additional benefit of Colorado Potato Beetle control (14). If this fungicide were to be used on a large scale on Long Island, surface and ground water contamination might become a problem, especially under conditions of acidic rain. Long Island has sandy soils in which adsorption of TPTH would be relatively low (2). Moreover, TPTH is a fungicide that is relatively toxic to human beings and aquatic flora and fauna (2,16).

Although the experiments under discussion were not set up to investigate direct effects of acidic rain on late blight development, they did demonstrate that high acidity of simulated rain (pH 2.8) enhanced susceptibility of unsprayed potato plants to late blight when rain was applied before inoculation with *P. infestans*. However, in separate experiments, application of simulated acidic mist (pH 2.8) during and after inoculation with *P. infestans* decreased late blight development on potato leaves (*unpublished*). A similar distinction between effects of preinoculation and postinoculation application of simulated acidic precipitation had to be made for the development of halo blight on bean plants (17). Therefore, increased infection after a preinoculation acid rain treatment does not imply that epidemic development of late blight would be enhanced by acidic rain.

LITERATURE CITED

1. Arny, C. J., Pell, E. J., Evans, L. S., and Lewin, K. F. 1983. Impact of simulated acid rain treatments on yield of potato. (Abstr.) Phytopathology 73:361.
2. Bock, R. 1981. Triphenyltin compounds and their degradation products. Residue Rev. 79:1-230.
3. Boodley, J. W., and Sheldrake, R. J. 1973. Cornell peat-lite mixes for commercial growing. Cornell Inf. Bull. 43. 8 pp.
4. Bruhn, J. A., and Fry, W. E. 1982. A mathematical model of the spatial and temporal dynamics of chlorothalonil residues on potato foliage. Phytopathology 72:1306-1312.
5. Dana, M. T., and Rothert, J. E. 1979-1982. The MAP3S precipitation chemistry network: Third, fourth, fifth and sixth periodic summary reports. PNL-4599, Pacific Northwest Laboratory, Richland, WA. 235 pp.
6. Dubin, H. J., and English, H. 1974. Factors affecting control of European apple canker by Difolatan and copper sulfate. Phytopathology 64:300-306.
7. Ebeling, W. 1963. Analysis of the basic processes involved in the deposition, degradation, persistence and effectiveness of pesticides. Residue Rev. 3:35-163.
8. Environmental Protection Agency. 1984. The acidic deposition phenomenon and its effects: Critical assessment review papers. Office of Research and Development, Washington, DC.
9. Fohner, G. R., and White, G. B. 1981. Pesticide use on potatoes in upstate New York. Agric. Econ. Res. 81-7, Dep. Agric. Econ., Cornell Univ. 25 pp.
10. Furmidge, C. G. L. 1962. Physico-chemical studies on agricultural spray. IV. The retention of spray liquids on leaf surfaces. J. Sci. Food Agric. 13:127-140.
11. Jacobson, J. S. 1984. Effects of acidic aerosol, fog, mist and rain on crops and trees. Philos. Trans. R. Soc. Lond. Ser. B:305:327-338.
12. Pell, E. J., Arny, C. J., and Pearson, N. S. 1984. Yield and quality of field grown potato plants exposed to acid rain. (Abstr.) Phytopathology 74:842.
13. Rowe, R. C. 1984. Fungicide testing for early and late blight control in potatoes. Plant Dis. 68:742.
14. Sandsted, R. F., Ellerbrock, L., Halseth, D. E., Kelly, W. C., Kline, R. A., Minotti, P. L., Muka, A. A., Sieczka, J. B., Sweet, R. D., Tingey, W., Topoleski, L., Warholic, D. T., Wien, H. C., and Zitter, T. A. 1984. Cornell recommendations for commercial vegetable production. N. Y. State Coll. Agric. Life Sci. N.Y. Agric. Exp. Stn. Ithaca. 78 pp.
15. SAS Institute. 1982. SAS User's Guide: Statistics. SAS Institute, Cary, NC.
16. Schaefer, C. H., Miura, T., Dupras, E. F., Jr., and Wilder, W. H. 1981. Environmental impact of the fungicide triphenyltin hydroxide after application to rice fields. J. Econ. Entomol. 74:597-600.
17. Shriner, D. S. 1978. Effects of simulated acidic rain on host-parasite interactions in plant diseases. Phytopathology 68:213-218.
18. Spadafora, V. J., Bruhn, J. A., and Fry, W. E. 1984. Influence of selected protectant fungicides and host resistance on simple and complex potato late blight forecasts. Phytopathology 74:519-523.
19. Stanley, B. H., Reissig, W. H., and Seem, R. C. 1986. A comparison of models describing azinphosmethyl loss from treated McIntosh apple foliage and fruit. In: Proc. Conf. Appl. Agric. Chem. Tree Fruits Ground Equip. K. D. Hickey, ed. Harpers Ferry, WV. In press.
20. Travis, J. W., Sutton, T. B., and Skroch, W. A. 1985. A technique for determining the deposition of heavy metals in pesticides and foliar nutrient materials on apple leaves. Phytopathology 75:783-785.
21. Troiano, J., and Butterfield, E. J. 1984. Effects of simulated acidic rain on retention of pesticides on leaf surfaces. Phytopathology 74:1377-1380.
22. van Bruggen, A. H. C., Milgroom, M., Osmeloski, J., Fry, W. E., and Jacobson, J. 1985. Attenuation of metalaxyl on/in potato leaves over time and by acidic rain. (Abstr.) Phytopathology 75:1329.
23. Wilson, J. W., and Mohnen, V. A. 1982. An analysis of spatial variability of the dominant ions in precipitation in the eastern United States. Water Air Soil Pollut. 18:199-213.