Distribution and Temporal Dynamics of Metalaxyl in Potato Foliage

M. G. Milgroom, C. E. McCulloch, and W. E. Fry

First and third authors, Department of Plant Pathology; second author, Biometrics Unit, Cornell University, Ithaca, NY 14853.

Portion of a Ph.D. dissertation submitted by the first author to the Graduate School, Cornell University.

We thank Jim Sweigard and Jeff Kubecka for helping with field work and Ciba-Geigy Corp. for generously supplying metalaxyl. Supported in part by CSRS grant 85-CSRS-2-2682.

Accepted for publication 20 October 1987 (submitted for electronic processing).

ABSTRACT

Milgroom, M. G., McCulloch, C. E., and Fry, W. E. 1988. Distribution and temporal dynamics of metalaxyl in potato foliage. Phytopathology 78:555-559.

Metalaxyl was sprayed on field plots of potatoes, and leaflets were collected to monitor residues at various times after application. Residues were determined by bioassay separately for each of several thousand leaflets. Residues were highly variable within the canopy at all times. Goodness-of-fit tests showed that metalaxyl residue samples from two-thirds of the plots could have been from censored lognormal distributions. A censored distribution was used because residues determined to be below the detection limit of the bioassay inhibited lesion development in *Phytophthora infestans*. Median residues decreased exponentially from 100–200 ng/cm^2 1 hr after spraying to 5–10 ng/cm^2 30 hr later. Subsequent exponential decay rates were much slower. Overhead irrigation 5 or 30 hr after spraying reduced residues in the first day relative to nonirrigated plots. However, 3–5 days later there were no differences in residues in irrigated relative to nonirrigated plots. Time after application was the most important variable for describing the changes in the median residue. Environmental variables such as rainfall, temperature, and humidity were not significant in a regression analysis of metalaxyl residues.

Additional key words: fungicide residues, potato late blight, systemic fungicides.

Fungicide coverage and weathering have been identified in mathematical models as factors that are important to the rate of buildup of fungicide resistance in plant pathogen populations (15–17). In these models, coverage refers to the proportion of plant tissue protected by fungicide residues after spraying; this proportion is then reduced over time to represent weathering. It is important to note that coverage and weathering in these models refer only to the presence or absence of fungicide residues. Mathematically, this treatment of coverage and weathering is very similar to those of untreated areas that have been included in other models (6,10,29).

In reality, however, fungicide coverage may be more complex. For example, chlorothalonil residues on potato foliage are highly variable with skewed distributions (3,4). Models that assume presence or absence of fungicide residues (15–17) may be adequate in identifying coverage and weathering as important factors for the buildup of fungicide resistance, but more precise information may be necessary for recommending resistance management tactics for a specific system. We are interested in the coverage and temporal dynamics of metalaxyl in potato foliage to incorporate metalaxyl into a simulation model for potato late blight (2). The model may then be used for identifying management tactics that avoid or delay the occurrence of metalaxyl resistance in North American populations of *Phytophthora infestans* (Mont.) de Bary. Metalaxyl resistance has appeared in *P. infestans* in Europe (5,9,23), Israel (8), and New Zealand (13) but has not yet been documented in North America.

The specific objectives of this work were to determine the coverage and distribution of metalaxyl residues in the potato canopy and to model the weathering and temporal dynamics of metalaxyl residues in foliage of field-grown potato plants. Some preliminary results of these studies have been reported (19).

MATERIALS AND METHODS

Cultural practices. Certified potato seed pieces (*Solanum tuberosum* L.) of the cultivar Hudson were planted on 5 June 1985 and 16 May 1986. Seed pieces consisted of small whole tubers in 1985 and cut pieces dusted with captan in 1986. Pieces weighed between 50 and 75 g and were planted approximately 20 cm apart. Individual plots comprised four rows that were 10 m long and spaced 0.9 m apart. Each plot was surrounded by fallow area at least 4.6 m on all sides to allow fungicide applications to be made to single plots. Fertilizer (170 kg/ha each of N, P, and K) was applied below the tuber furrow at planting time. Insecticide (carbofuran, 3.4 kg a.i./ha) was applied in the furrow at planting time. Herbicide (linuron, 1.7 kg a.i./ha) was applied before plant emergence. In 1985 only, mancozeb (0.9 kg a.i./ha) was applied twice (16 and 23 July) before metalaxyl applications began.

Fungicide applications. All metalaxyl formulations were supplied by Ciba-Geigy Corp., Greensboro, NC. A commercial formulation of 10% metalaxyl and 48% mancozeb (Ridomil MZ58) was used in 1985 at 0.20 kg a.i. of metalaxyl per hectare. In 1986, metalaxyl was applied at 0.10, 0.14, 0.20, and 0.28 kg a.i./ha using a wettable powder formulation that was 25% active ingredient. Metalaxyl was also applied in 1986 at 0.22 kg a.i./ha using an emulsifiable concentrate formulation (Ridomil 2E). Applications were made with a tractor-mounted boom sprayer at a rate of 936 L/ha at 14.1 kg/cm^2 pressure. Spray nozzles (Empire potato spraying discs no. 2, FMC Corp., Jonesboro, AR) were mounted 30 cm apart on a 5-m-long boom, supported 15–25 cm above the canopy. Sprays were initiated 8 wk after planting when the plants had attained nearly full size and were beginning to flower. One to four plots were sprayed on any given day over a period of several weeks after sprays began.

Residue monitoring. Metalaxyl residues were monitored at various times after spray applications. In 1985, samples were collected from eight plots at 1, 6, and 30 hr after spraying to study the initial rapid decline in residues that had been observed in a greenhouse study (28); additional sampling from these same plots occurred at irregular intervals up to 14 days. In 1986, we placed more emphasis on residues that persisted after 4 days. Samples were collected at 4-day intervals from 10 plots, beginning 4–8 days after spraying and continuing until 20–26 days after spraying (up to 30 days for one plot). At each sampling time, 40 leaflets were sampled from each plot. Separate samples ($n = 40$) were collected from each of the different canopy strata in some plots in 1985: 0–15, 15–30, 30–45, and >45 cm above the ground level (3,4). In 1986, leaflets were sampled without regard to strata to concentrate our efforts on more plots and longer times after spraying.

Residues were determined using a bioassay designed for metalaxyl in small potato leaf pieces (20). Leaf disks were cut with cork borers (either 14 or 22.5 mm diameter) and soaked in methanol for 24 hr to extract the metalaxyl. Crude extracts were dried, incorporated into 1 ml of corn meal agar, autoclaved, and poured into 35- × 10-mm plastic petri dishes. Agar plugs of *Phytophthora boehmeriae* Sawada (isolate P1257, obtained from M. Coffey, UC Riverside) or *P. citrophthora* (Sm. & Sm.) Leonian (isolate P1210, obtained from W. Wilcox, New York State Agricultural Experiment Station, Geneva, NY) were placed on the edge of the plate. Radial growth measurements were made after 90–96 hr and compared with standard calibration curves to determine the total amount of metalaxyl in each leaf disk. Standard curves were generated for each set of samples by measuring radial growth of each fungus on agar amended with extracts of unsprayed leaves and known amounts of metalaxyl. Mancozeb residues do not affect the radial growth of either bioassay organism under the conditions of this assay (20).

Statistical analysis of residue data. We hypothesized that residues fit a two-parameter lognormal distribution (1). When all observations in a sample were greater than the detection limit of the bioassay, 2.5 ng/cm^2 (approximately 0.1 μg/g fresh weight) (20), parameter estimation for the lognormal distribution was done by calculating the sample mean and sample variance of the natural logarithms of metalaxyl residues. However, many of the samples contained observations that were below the detection limit. Because low levels of metalaxyl can have a large effect, inhibiting *P. infestans* (5,21), observations below the detection limit could not be considered as the absence of metalaxyl even though the bioassay could not reliably estimate these concentrations in the leaf.

Residue estimates below 2.5 ng/cm^2 were handled in two ways: Residue estimates were calculated by extrapolation of the standard calibration curve for values as low as 1.0 ng/cm^2; and residue estimates less than 1.0 ng/cm^2 were censored (1). Information from censored observations was only used to calculate the proportion of the sample that was censored, h, which was used for subsequent calculations (see below). Maximum likelihood estimation for parameters of the censored lognormal distribution was done by taking natural logarithms and using Cohen's (7) estimation method for censored normal distributions. The maximum likelihood estimates are (7):

$$\hat{\mu} = \bar{x} - \hat{\lambda}(\bar{x} - x_0) \tag{1}$$

$$\hat{\sigma}^2 = s^2 + \hat{\lambda}(\bar{x} - x_0)^2 \tag{2}$$

where $\hat{\mu}$ and $\hat{\sigma}^2$ are estimators for the two parameters of the lognormal distribution, $\bar{x}$ and s^2 are the mean and variance of the uncensored part of the sample, x_0 is the lowest possible uncensored value (in our case, $x_0 = \ln(1.0 \text{ ng/cm}^2) = 0$), and $\hat{\lambda}$ is a statistic that is a function of h, $\bar{x}$, s^2, and x_0. Values for $\hat{\lambda}$ were obtained from Cohen's Table 2 (7). When no observations were censored, $\hat{\lambda} = 0$. The rationale behind these equations is that $\bar{x}$ and s^2, calculated from the uncensored observations, must be adjusted to account for the censored observations. The sample mean, $\bar{x}$, overestimates the population mean, μ, and s^2 underestimates the population variance, σ^2, when a sample is censored because additional observations less than x_0 would reduce $\bar{x}$ and increase s^2.

A censored lognormal distribution has biological importance because residues determined to be below the detection limit are regarded as nonzero, and, therefore, may contribute to disease control. To test the assumption that residues below the detection limit are nonzero, we inoculated leaflets from field samples with *P. infestans* after leaf disks were cut for the bioassay. Twenty leaflets were inoculated from each of 10 plots on three dates in 1986: 25 and 29 July and 2 August. Forty leaflets from unsprayed plots were used for controls in the first two dates, while 20 leaflets were used as controls for the third date. Disks were cut from the control leaflets also. Each leaflet was inoculated on the abaxial surface with a 50-μl droplet containing 200 sporangia (4×10^3 sporangia per milliliter). Single inoculated leaflets were placed in inverted plastic petri dishes containing water agar and incubated at 18 C in low light (750 erg/cm^2/sec). Lesion development was scored qualitatively after 5 days on a 0–3 scale: 0 = no symptoms or hypersensitive flecks; 1 = small lesion with diameter $<$ 1.0 cm, no sporulation; 2 = intermediate lesion with diameter $>$1.0 cm but $<$2.5 cm, some sporulation but not abundant; 3 = large lesion with diameter $>$2.5 cm, usually with abundant sporulation. Most lesions could be scored unambiguously.

Leaflets were grouped into three categories according to the amount of metalaxyl residue detected by bioassay. The three categories are censored (residues less than 1.0 ng/cm^2), extrapolated (residues between 1.0 and 2.5 ng/cm^2), and detectable (residues greater than 2.5 ng/cm^2). Comparisons of lesion development (on 0–3 scale) between the censored and extrapolated categories and the control were made using chi-square tests for contingency tables.

Goodness-of-fit tests for the lognormal distribution were done on the natural logarithms of uncensored residues using Lilliefors's test for normality (18). The test statistic is a Kolmogorov-Smirnov distance statistic (D) calculated by comparing the empirical observations to the hypothetical normal distribution when the parameters are estimated from the sample. This test for normality was chosen because, with slight modifications, it can be used for censored samples.

Simulated rainfall experiments. The effects of simulated rainfall in the field were studied by applying overhead irrigation to individual plots 5 and 30 hr after metalaxyl was applied. Field plots in this experiment were paired by metalaxyl application times. One plot in each pair was randomly chosen to be irrigated. Each irrigated plot received an average of 5.2 mm of simulated rainfall (SD = 0.22) over a 30–40-min period. Each treatment (irrigation 5 or 30 hr after spraying) was conducted twice, on different days. Temperature and relative humidity data were collected throughout the field season with a hygrothermograph placed in a plot in the middle of the field. Rainfall data were collected daily from a rain gauge in the same field.

RESULTS

Distribution of metalaxyl residues. Samples of metalaxyl residues were always skewed: Most observations were at the low end of the range and only a few observations had high levels of metalaxyl (Fig. 1A). However, the natural logarithms of the residue concentrations were usually nearly symmetric (Fig. 1B). In goodness-of-fit tests, the hypothesis that samples were drawn from lognormal distributions could not be rejected at the 5% level of significance for 85 out of 131 samples (65%). Tests for an additional 15 samples could not reject the same hypothesis at the 1% level of significance ($0.01 < P < 0.05$). The parameter estimates for $\hat{\mu}$ changed with time and dose (see below); the estimates for $\hat{\sigma}$ were relatively constant with a mean of 1.0219 (SD = 0.3381, n = 131). The censored lognormal distribution appears to be an adequate model for metalaxyl residues in a potato canopy.

Lesion development on metalaxyl-treated leaflets for which metalaxyl residues were below the detection limit was significantly less than on the unsprayed control leaflets on all three sampling dates ($P < 0.01$). Lesion development was less than controls for leaflets in both the censored category (residues $<$ 1.0 ng/cm^2; χ^2 = 53.3, 2 df; χ^2 = 37.9, 2 df; χ^2 = 9.0, 1 df; for the three dates, respectively) and the extrapolated category (residues $>$ 1.0 and $<$ 2.5 ng/cm^2; χ^2 = 51.4, 2 df; χ^2 = 49.1, 3 df; χ^2 = 6.7, 1 df; for the three dates, respectively). There were no differences in lesion development between the censored and extrapolated categories at any sampling date ($P > 0.25$). Reduced lesion development on metalaxyl-treated leaflets with residues determined to be below the bioassay detection limit support the assumption that metalaxyl residues in this range are biologically active and cannot be considered as the absence of metalaxyl.

Differences in metalaxyl residues among canopy strata were analyzed by calculating the slope of the parameter estimates, $\hat{\mu}$, versus stratum (treated as equally spaced integers). Data from eight plots in 1985 show that the slopes are not significantly different from zero ($\bar{x} = -0.039$, SD = 0.374, n = 8), indicating that there was no detectable linear trend in residues from the top to the bottom stratum.

Temporal dynamics of metalaxyl residues. Metalaxyl residues decreased rapidly in the first two days after application, as shown by the decrease in the natural logarithm of the median residue, $\hat{\mu}$ (Figs. 2 and 3). Decrease in residues after 2 days was much slower, which is consistent with Ripley's results (24). For this reason, data from the first 2 days after spraying were analyzed separately from later residue data. The parameter estimates $\hat{\mu}$ were regressed on the time since spraying for each plot separately. Estimates of slopes and intercepts from regressions of $\hat{\mu}$ on time, done on separate plots, were used to estimate the mean slope and intercept for all plots in both years. This analysis was done because plots were independent experimental units; repeated samples from the same plot were not independent. The mean slope for the decrease in $\hat{\mu}$ during the first two days was -2.071 (SD $= 0.806$, $n = 8$). The mean intercept during the first 2 days after spraying was 4.691 (SD $=$ 0.332, $n = 8$). In sharp contrast to the initial rapid decline, the mean slope for $\hat{\mu}$ over time after 2 days was -0.082 (SD $= 0.091$, $n = 16$). The mean intercept for the period after 2 days was also much lower ($\bar{x} = 1.081$, SD $= 1.195$, $n = 16$).

The effect of the amount of metalaxyl applied on residues 2 or more days after spraying was analyzed by regressing the slope and intercept for $\hat{\mu}$ on time from each plot on dose (kg/ha). Intercepts from the regression of $\hat{\mu}$ on time increased as the dose increased ($0.05 < P < 0.10$, $n = 10$). In contrast, no changes in the slope of $\hat{\mu}$ on time were discernible with dose ($P < 0.10$). Intercepts and slopes from regressions of $\hat{\mu}$ on time from plots sprayed with the emulsifiable concentrate formulation of metalaxyl appeared to be similar to those for the wettable powder formulation, although no statistical analysis was done because formulation was confounded with doses.

Simulated rainfall, from overhead irrigation, reduced the residues on leaflets sampled immediately after irrigation but had no detectable effect on later residues (Fig. 3). Statistical analysis was done on the differences between pairs of irrigated and nonirrigated control plots because of the pairwise experimental design. Estimates, $\hat{\mu}$, for samples from irrigated plots immediately after irrigation were less than controls by a mean of 1.065 (SD $=$ 1.015, $n = 4$, $P = 0.065$). If irrigation had significantly reduced the residues over the long term, we would expect to find a smaller intercept for the regression of $\hat{\mu}$ after 2 days on time since spraying. The mean difference (irrigated $-$ control) in intercepts was not significantly less than zero ($P = 0.093$, $\bar{x} = -0.709$, SD $= 0.829$, $n =$ 4). Irrigation had no significant effect on slopes from the same regressions ($P > 0.10$).

No environmental factors had a measurable effect on metalaxyl residues sampled 2 or more days after spraying. Estimates, $\hat{\mu}$, were regressed on cumulative measures of average, minimum, and maximum daily temperatures, number of hours of relative humidity >90%, and rainfall accumulated from time since application or time since previous sampling. Cumulative maximum daily temperature from time of application was the only independent variable that was significant ($P < 0.05$) after time since application in a multiple regression. However, regression of $\hat{\mu}$ from each separate plot on both time and cumulative maximum temperature as independent variables resulted in larger mean squares for error than time alone for almost all the plots. We therefore concluded that environmental effects on residues are minimal compared to the time since spraying.

DISCUSSION

The coverage and distribution of metalaxyl residues in potato foliage can be characterized by the lognormal distribution. This distribution has also been assumed for some insecticide residues (25,27), but no goodness-of-fit tests were presented in support of those assumptions. Goodness-of-fit tests for the lognormal

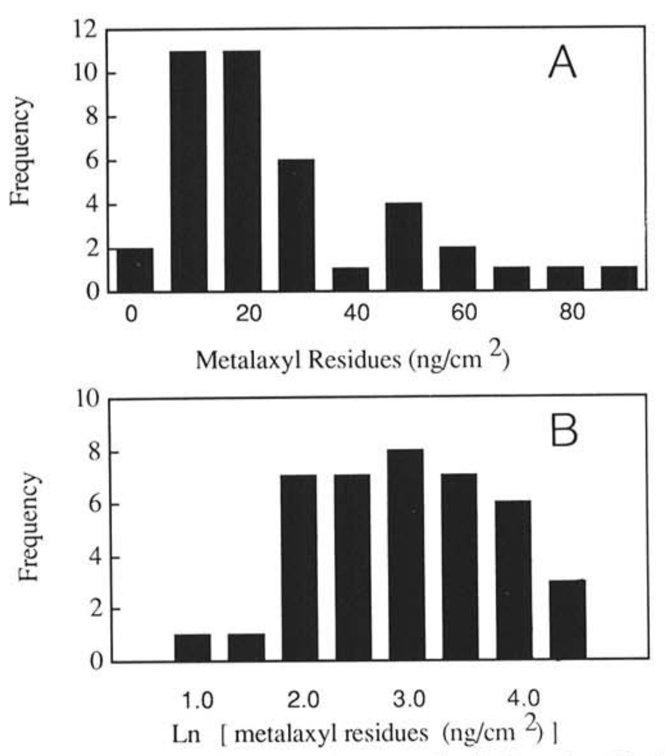

Fig. 1. A, Representative sample frequency distribution of metalaxyl residues (nanograms per square centimeter) in potato foliage, on arithmetic scale. Residues were determined separately for each potato leaflet ($n = 40$). Leaflets in this sample were collected 6 hr after metalaxyl (0.20 kg/ha) was applied to field plots. **B,** Frequency distribution of the natural logarithms of metalaxyl residues [ln(ng/cm^2)] from the same sample data shown in A.

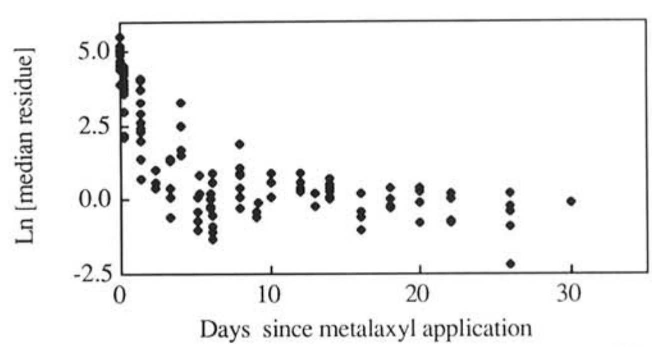

Fig. 2. The decline in the natural logarithm of the median metalaxyl residue on potato foliage over time in 18 different plots in 1985 and 1986 when metalaxyl was applied in a range of concentrations from 0.10 to 0.28 kg a.i./ha. Each datum is the maximum likelihood estimate for the median residue in a censored lognormal distribution for a random sample of 40 leaflets per plot.

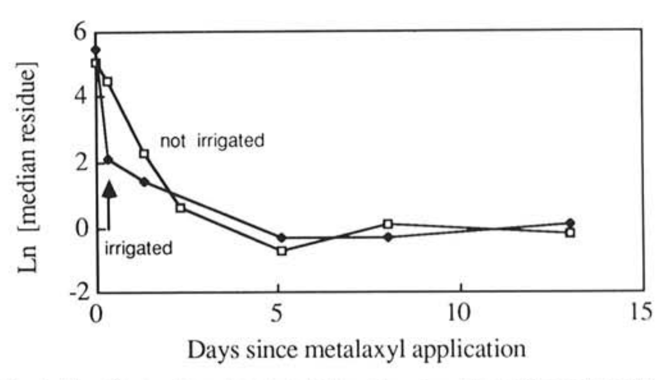

Fig. 3. The effects of simulated rainfall on the natural logarithms of median metalaxyl residues in potato foliage. These data are for two plots that were sprayed with metalaxyl on the same day (0.20 kg/ha) in 1985. One plot (solid diamonds) received 5 mm of simulated rainfall from overhead sprinkler irrigation 5 hr after metalaxyl was applied (indicated by arrow). The other plot (open squares) did not receive any simulated rainfall.

distribution of metalaxyl residues confirm our hypothesis in the majority of samples (65%). We do not rule out the possibility that metalaxyl residues may be fit by other positively skewed distributions, such as the gamma distribution. Bruhn and Fry (3,4) used the gamma distribution to model chlorothalonil residues on potatoes. However, because of the complexity of estimating parameters for the censored gamma distribution (14) and because our goal was to summarize the coverage of residues (including censored observations), we have chosen to work only with the lognormal distribution.

To fit a probability distribution to residue data, we needed to have samples with a reasonably large number of independent observations. Furthermore, for more biological relevance we sampled small leaf areas (< 4 cm^2) that were the same order of magnitude in area as late blight lesions. An alternative approach is to determine residue levels in large bulk samples of plant tissues. Although this approach would determine the mean residue for a sample, it would not reveal anything about the variability in fungicide coverage.

The bioassay for metalaxyl was an appropriate choice of methods for a large number of small samples (20). It is not as sensitive for detecting metalaxyl as are such alternative methods as gas chromatography (26). However, other analytic techniques require much larger amounts of leaf tissue (26) and are too time consuming (20) to permit measurement of a large number of samples. Consequently, with a bioassay, there were many leaflets that had residues less than the detection limit but that still had enough metalaxyl to significantly reduce lesion development when leaflets were inoculated with *P. infestans*. Therefore, a censored distribution is a necessary trade-off and is advantageous because biologically relevant information from nondetectable residues was not lost when a censored distribution was used.

Metalaxyl residues declined rapidly after application. More than 90% of the residue disappeared in the first 2 days (Figs. 2 and 3). This observation is consistent with greenhouse (28) and other field (24) studies of metalaxyl on potatoes, and a laboratory study of metalaxyl on lettuce (30). The subsequent decline in residues after 2 days was much slower (Figs. 2 and 3). Ripley (24) hypothesized that the rapid initial decrease represents volatilization of metalaxyl from the leaf surfaces, while the slower decline after a few days represents the dynamics of metalaxyl inside the leaf tissues. Although there are no direct tests of this hypothesis—because of technical limitations—it is a reasonable hypothesis in light of the volatility of metalaxyl (24). Multistage degradation from leaf surfaces has been described for insecticides as well (12,27).

We have expressed the changes in residues by using linear regression of $\hat{\mu}$ on time; this reflects an exponential decline in median residues on the arithmetic scale. Exponential decay is a good approximation for the dynamics of many pesticide residues (4,11,27). Incorporating environmental factors, such as rainfall and temperature, improved the predictions for some other pesticide residue models (4,22,27). However, these models were for nonsystemic compounds or were restricted to modeling dislodgeable residues from the leaf surfaces. Furthermore, Stanley (27) found that more complicated models predicted insecticide residues only slightly better than a simple exponential decay model. Neither temperature, humidity, nor rainfall have any large, observable effects on metalaxyl residues, and therefore, changes in metalaxyl can be modeled simply as a function of time since application.

We estimated the half-life of metalaxyl residues from data collected 2 or more days after spraying to be 8.5 days. In contrast, using similar metalaxyl residue data on potatoes published in Ripley (24), we calculated a half-life of only 2 days. It is not clear why there is so much disparity in these estimates. One possible explanation is that the bioassay and censoring techniques (e.g., assuming a lognormal distribution when a large proportion of the sampled was censored) may have resulted in a bias in which we overestimated residues when they were at low levels. An overestimate of residues would appear as slower decay and hence a longer half-life.

Rainfall apparently has no effect on the efficacy of metalaxyl for controlling disease. Simulated rainfall experiments in the field showed that initial metalaxyl residues were decreased, but there were no effects on the residues 2 or more days after application. Similar results were found in greenhouse experiments (28): Initial residues declined rapidly to an asymptote when very little artificial rainfall was applied. However, disease control by metalaxyl was not affected by rainfall in these greenhouse experiments (28). Ripley (24) also found that the only effects of rainfall, if any, occurred within the first 24 hr after metalaxyl application; rainfall occurring more than 24 hr after application had no influence on metalaxyl residues. The systemic nature of metalaxyl makes it much different than conventional protectant fungicides for which rainfall is an extremely important environmental factor (4,11).

Although we detected some differences in residue with respect to canopy strata, there was no significant linear trend among canopy strata. Residues were sometimes greater in the upper strata in the first 2 days after spraying, but the differences became smaller over time. In contrast, Bruhn and Fry (3,4) found large differences in chlorothalonil residues among canopy strata. Their findings were important for modeling the redistribution of chlorothalonil. Redistribution of protectant fungicides occurs by rain washing residues from upper strata to lower ones (4). For metalaxyl, where rainfall has no effect, this type of redistribution is apparently negligible and could not be detected in our study. However, it must be pointed out that we did not explicitly address the question of redistribution, either from leaf surfaces or through the soil.

An empirical model for metalaxyl residues in potato foliage can be summarized as follows. Residues are distributed lognormally. The parameter, μ, for the lognormal distribution can be estimated simply as a linear function of dose applied and time since application. The parameter estimates for σ in the lognormal distribution are nearly constant. By knowing the form and parameter estimates for the distribution of metalaxyl at any given time we can link this information to dose-response relationships of *P. infestans* and metalaxyl and model the effects of metalaxyl on epidemic development (21). This approach may enable us to achieve our ultimate objective of identifying specific management tactics to prevent or delay the buildup of metalaxyl resistance in North American populations of *P. infestans*.

LITERATURE CITED

1. Aitchison, J., and Brown, J. A. C. 1957. The Lognormal Distribution. Cambridge University Press, New York. 176 pp.
2. Bruhn, J. A., and Fry, W. E. 1981. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology 71:612-616.
3. Bruhn, J. A., and Fry, W. E. 1982. A statistical model of fungicide deposition on potato foliage. Phytopathology 72:1301-1305.
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. Carter, G. A., Smith, R. M., and Brent, K. J. 1982. Sensitivity to metalaxyl of *Phytophthora infestans* populations in potato crops in south-west England in 1980 and 1981. Ann. Appl. Biol. 100:433-441.
6. Chin, K. M. 1987. A simple model of selection for fungicide resistance in plant pathogen populations. Phytopathology 77:666-669.
7. Cohen, A. C., Jr. 1961. Tables for maximum likelihood estimates: Singly truncated and singly censored samples. Technometrics 4:535-541.
8. Cohen, Y., and Reuveni, M. 1983. Occurrence of metalaxyl-resistant isolates of *Phytophthora infestans* in potato fields in Israel. Phytopathology 73:925-927.
9. Davidse, L. C., Danial, D. L., and Van Westen, C. J. 1983. Resistance to metalaxyl in *Phytophthora infestans* in the Netherlands. Neth. J. Plant Pathol. 89:1-20.
10. Delp, C. J. 1980. Coping with resistance to plant disease control agents. Plant Dis. 64:652-657
11. Ebeling, W. 1963. Analysis of the basic processes involved in the deposition, degradation, persistence and effectiveness of pesticides. Residue Rev. 3:35-163.
12. Gunther, F. A., and Blinn, R. C. 1955. Analysis of Insecticides and Acaricides. Interscience, New York. 696 pp.
13. Hartill, W. F. T., Tompkins, G. R., and Kleinsman, P. J. 1983. Development in New Zealand of resistance to dicarboximide fungicide

in *Botrytis cinerea*, acylalanines in *Phytophthora infestans*, and to guazatine in *Penicillium italicum*. N.Z. J. Agric. Res. 26:261-269.
14. Johnson, N. L., and Kotz, S. 1970. Continuous Univariate Distributions. Vol. 1. John Wiley & Sons, New York. 300 pp.
15. Kable, P. F., and Jeffery, H. 1980. Selection for tolerance in organisms exposed to sprays of biocide mixtures: A theoretical model. Phytopathology 70:8-12.
16. Levy, Y., Levi, R., and Cohen, Y. 1983. Buildup of a pathogen subpopulation resistant to a systemic fungicide under various control strategies: A flexible simulation model. Phytopathology 73:1475-1480.
17. Levy, Y., and Levy, R. S. 1986. Control strategies using systemic fungicides for limiting disease development and resistance buildup: Practical implications of a simulation model. Phytoparasitica 30:303-312.
18. Lilliefors, H. W. 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J. Am. Stat. Assoc. 62:399-402.
19. Milgroom, M. G., and Fry, W. E. 1986. Spatial and temporal variation of metalaxyl residues in field-grown potato foliage. (Abstr.) Phytopathology 76:1088.
20. Milgroom, M. G., and Fry, W. E. 1987. A metalaxyl bioassay for large numbers of small foliar samples. Phytopathology 77:237-240.
21. Milgroom, M. G., and Fry, W. E. 1988. A model for the effects of metalaxyl on potato late blight epidemics. Phytopathology 78:559-565.
22. Nigg, H. N., Allen, J. C., King, R. W., Thompson, N. P., Edwards, G. J., and Brooks, R. F. 1978. Dislodgeable residues of parathion and carbophenothion in Florida citrus: A weather model. Bull. Environ. Contam. Toxicol. 19:578-588.
23. Pappas, A. C. 1985. Metalaxyl resistance in *Phytophthora infestans* on greenhouse tomatoes in Greece. Plant Pathol. 34:293-296.
24. Ripley, B. D. 1985. The behaviour and fate of metalaxyl. Ph.D. thesis. University of Guelph, Ontario, Canada.
25. Spear, R. C., Popendorf, W. J., Leffingwell, J. T., and Jenkins, D. 1975. Parathion residues on citrus foliage. Decay and decomposition as related to worker hazard. J. Agric. Food Chem. 23:808-810.
26. Speck, M., and Dirr, E. 1980. Gas chromatographic determination of metalaxyl (Ridomil) residues in tobacco. J. Chromatogr. 200:313-316.
27. Stanley, B. H. 1986. Empirical and mathematical approaches to the management of the apple magot, *Rhagoletis pomonella* (Walsh) (Diptera:Tephritidae). Ph.D. thesis. Cornell University, Ithaca, NY.
28. van Bruggen, A. H. C., Milgroom, M. G., Osmeloski, J. F., Fry, W. E., and Jacobson, J. S. 1987. Attenuation of metalaxyl on potato leaves by simulated acidic rain and residence time. Phytopathology 77:401-406.
29. Wolfe, M. S. 1982. Dynamics of the pathogen population in relation to fungicide resistance. Pages 139-149 in: Fungicide Resistance in Crop Protection. J. Dekker and S. G. Georgopoulos, eds. Center for Agricultural Publishing and Documentation, Wageningen. 265 pp.
30. Wynn, E. C., and Crute, I. R. 1981. Uptake, translocation and degradation of metalaxyl in lettuce. Pages 137-145 in: Proc. 11th Brit. Insectic. Fungic. Conf.