The Quantitative Relationship Between Late Blight of Potato and Loss in Tuber Yield

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ABSTRACT

Data for 96 disease progress curves with corresponding tuber yields, from 11 experiments representing three locations and two cultivars in eastern Canada during the period 1953-1970, were used to develop a method for estimating the loss in tuber yield caused by late blight. A multiple regression equation was derived using the increase of disease during 9 weekly periods as the independent variables and yield loss as the dependent variable. The empirical equation can be used to estimate the yield loss associated with any given progress curve. The difference between estimated loss, computed from the equation, and actual loss, derived by weighing, was less than 5% in nine cases out of 10.

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The incidence and severity of late blight of potato (*Solanum tuberosum* L.) caused by *Phytophthora infestans* (Mont.) d By. vary yearly in eastern Canada, and are governed mainly by weather conditions (3). Development of a reliable method for estimating loss in tuber yield due to late blight involves a series of field trials repeated at least 2-3 years, and using more than one cultivar at several locations. Consistent relationships between disease estimates and the loss in tuber yield can be used to develop a disease assessment method. The method can then be used to make reliable estimates of the over-all losses due to late blight in a potato-growing area. Erroneous estimates of crop loss can have serious consequences; if the estimates are too low the loss may be neglected, and if they are too high, research effort and extension advice will be misdirected.

A disease assessment method for estimating loss in total tuber yield was developed in England (5, 8). However, when this method was used for data from eastern Canada, the actual losses were not in agreement with the estimated losses (7). The objectives of the experiments presented in this paper were to generate data to determine actual losses in tuber yield associated with various levels of disease, to explore different methods of deriving estimates of the quantitative relationship between the development of late blight and loss in tuber yield, and to propose a method which could give more reliable estimates of loss in tuber yield for the potato crop in eastern Canada.

MATERIALS AND METHODS.–*Experimental methods.*–Epidemics of late blight were initiated in six field trials at Fredericton, Charlottetown, and Ottawa in 1969 and 1970, by varying the fungicide spray schedules for each treatment (7). A randomized block design was used for each experiment, but the number of treatments, type of fungicide, and potato cultivar differed for some of the experiments. Dithane M-45 (coordination product of zinc ion and maneb 80% WP) was used in some trials at the rate of 2.24 kg in 1,348 liters of water per hectare (2.0 lb. in 120 gal/acre). The epidemics were started by inoculating the buffer rows between the four-row plots with a water suspension of sporangia of *P. infestans*. Disease assessments based on the British Mycological Society Key (2) were recorded at 3- to 7-day intervals. The crops were topkilled ca. 120 days after planting, and yields were determined for marketable, small, and blighted tubers in the center two rows of a four-row plot.

Additional data were obtained from five other experiments carried out at Charlottetown from 1953 to 1969 (4). In these trials, the efficacy of different fungicides was tested, the progress of late blight recorded, and yield of tubers determined for sprayed and unsprayed plots. The experiments were conducted as described above.

The data represent 96 blight progress curves and corresponding tuber yields from 11 experiments. Two cultivars, Green Mountain and Katahdin, and three locations, Charlottetown, Fredericton, and Ottawa, are represented.

Analysis of data.–Various methods have been used to relate disease development to time and to relate yield losses to disease severity. Van der Plank (11) presented several S-shaped curves for potato late blight using the logit transformation $\log_{10} \frac{x}{1-x}$ for describing the linear relationship between increase of disease and time. However, the 96 progress curves examined deviated considerably from the typical S-shaped curve. Therefore, they could not be

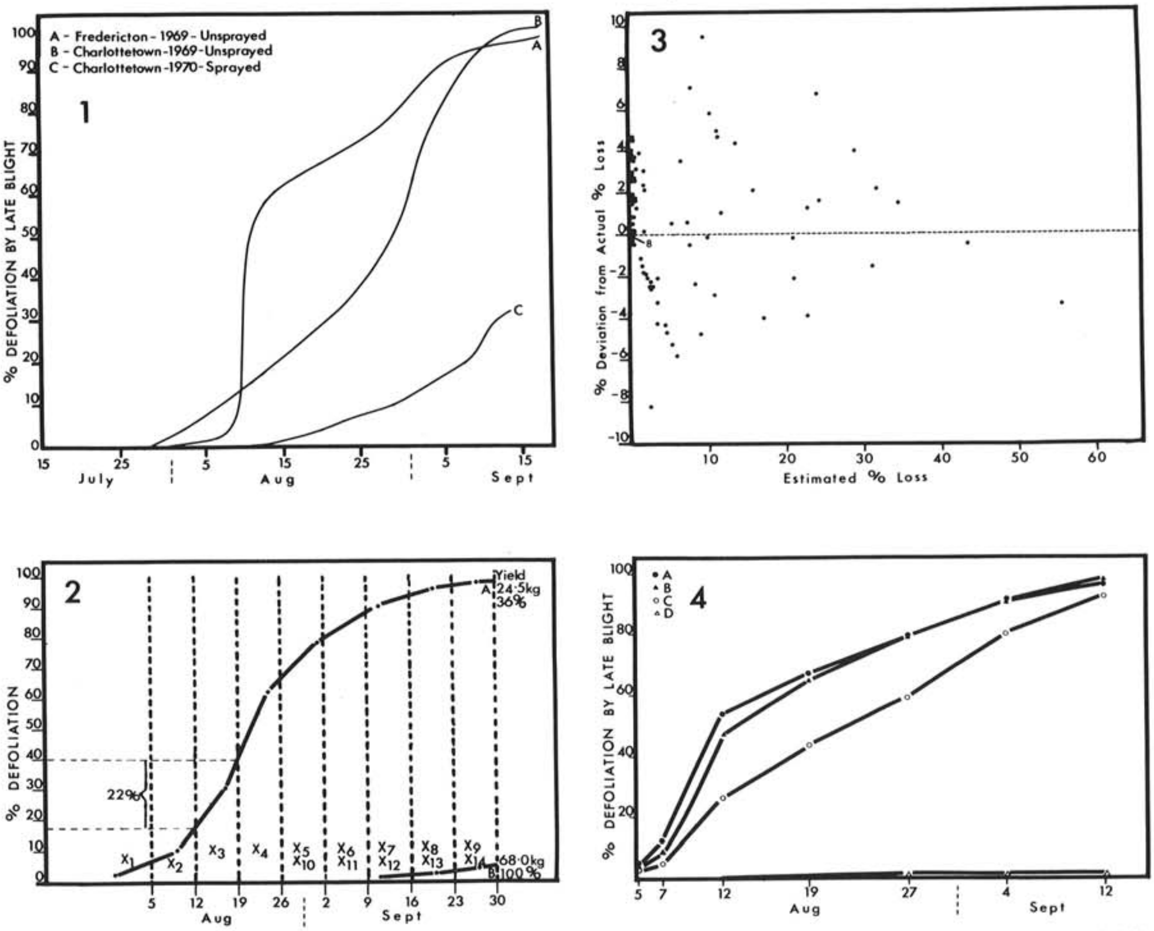

Fig. 1-4. 1) Disease progress curves of potato late blight. **2)** Calculation of disease increment and per cent tuber yield loss from a hypothetical potato late blight progress curve. **3)** Deviations between estimated and actual per cent yield loss for 85 potato late blight disease-progress curves. **4)** Potato late blight disease-progress curves for four fungicide spray schedules for the cultivar Katahdin at Fredericton in 1969.

adequately described by a linear regression after the data were transformed (7). Figure 1 illustrates the variability in the shape of some of the progress curves.

We explored four methods to relate tuber yield loss to disease severity. The first was based on the critical point theory that yield was correlated with disease severity at one point in time. This method has been used successfully to predict losses in yield when leaf diseases affect cereals (6, 10). However, we compared the progress curves and tuber yields and found no relationship.

The second method (8) related the loss of potato tuber yield to the date when the disease reached a particular level (75% defoliation). James et al. (7) reported that the method underestimated yield loss in the 1969 and 1970 experiments. Lower disease levels were substituted for the 75% level to test whether the method (8) worked under Canadian conditions with a lower critical level. The results showed that the estimates of yield loss lacked correlation with the actual losses.

The third method employed van der Plank's suggestion (11) that the area under the disease progress curve may be related to yield loss. This method was not successful because it did not distinguish between early low infections and late severe infections which occupied the same area under the disease progress curve. The yield loss attributable to the former was much greater than that recorded for the latter.

The fourth method developed and presented in this paper used multiple regression analyses to develop an empirical equation to relate yield losses directly to the epidemic. The growth season was divided into nine periods: (i) up to 5 August; (ii) 5-12 August; (iii) 12-19 August; (iv) 19-26 August; (v) 26 August–2 September; (vi) 2-9 September; (vii) 9-16 September; (viii) 16-23 September; and (ix) 23-30 September.

Values of disease increments during the nine periods were used as independent variables in regression analyses. To calculate disease increments, we joined two successive disease assessments by a straight line and read the disease increment from the graph (22% for the third period in Fig. 2). Smooth curves may provide a better representation of the epidemic than the present method, but the straight line method has the advantage of being simple and reproducible, and differences between the two methods are likely to be small.

Yield loss was the dependent variable in the analyses. Yield data were originally recorded in pounds per plot. The yield associated with each progress curve was the mean yield of four to six plots. The mean yields were then converted into percentages as follows: From each experiment, a base treatment was selected which was either free of disease or was infected very late in the season with very low disease severity at the time of topkilling. The yield of the base treatment, B (68 kg, Fig. 2), was equated to 100%, and the yield of other treatments from the same experiment was expressed as the percentages of the yield of the base treatment (treatment A = 24.5/68.0 = 0.36 = 36%, Fig. 2). Yield loss, which will be called actual loss, was then equal to 100% – yield (%) (100 - 36 = 64% for A in Fig. 2).

Over 100 regression equations were fitted to the data. In addition to using the disease increments defined above, many of these equations also used independent variables derived from the increments, such as the squares of the increments, products of the increments from two periods (to account for interaction effect), and others. Instead of employing commonly used techniques such as the step-wise regression method, subjective criteria were used to screen the equations fitted. There were three major criteria. Firstly, the residual mean square associated with the final equation should be reasonably small. Secondly, the disease increment of any one period should not have a net effect of increasing estimated tuber yield, as it would (for example) when the partial regression coefficient for a period is negative. Finally, no single period should have so large a net effect on the estimated yield loss that a very small change (ca. 1%) in the disease increment for that period would change the estimated loss greatly. It was also evident that if good agreement were to be obtained between actual and estimated yield losses, early and late infections would require different treatment. Different definitions of early and late infection were tried. The definition finally adopted was that an early infection had occurred when the total disease increment for the first five periods was greater than 10%; otherwise it was termed a late infection. The general form of regression equation used is $y = b_1X_1 + b_2X_2 + \cdots b_{14}X_{14}$, where y is per cent yield loss and X_1 to X_9 are the disease increments for the first to the ninth period, respectively. For early infection, X_{10} to X_{14} are taken as zero. For late infection, $X_{10} = X_5$, $X_{11} = X_6$, etc. The partial regression coefficients b_1 to b_{14} are multiplied by the corresponding increments X_1 to X_{14} to calculate yield loss. The final equation obtained is as follows:

$$y = 1.867X_1 + 0.446X_2 + 1.144X_3 + 0.628X_4 + 0.193X_5 + 0.180X_6 - 0.012X_7 + 0.343X_8 + 0.829X_9 + 0.170X_{10} + 0.067X_{11} + 0.044X_{12} - 0.155X_{13} - 0.829X_{14}.$$

The equation passes through the origin with a multiple correlation coefficient of 0.976 and with a residual mean square of 10.2 (82 degrees of freedom). In practice, the equation can be reduced to a simpler form. For early infection, the equation can be written as (since $X_{10} = X_{11} \cdots = X_{14} = 0.$)

$$y = b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7 + b_8X_8 + b_9X_9$$
$$= 1.867X_1 + 0.446X_2 + 1.144X_3 + 0.628X_4 + 0.193X_5 + 0.180X_6 + 0.343X_8 + 0.829X_9.$$

Note that the term b_7X_7 has also been deleted because b_7, a very small negative number, has virtually no effect on the value of y. For late infection, since $X_5 = X_{10}$, $X_6 = X_{11}$, etc., the equation can be written as

$$y = b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + (b_5 + b_{10})X_5 + (b_6 + b_{11})X_6 + (b_7 + b_{12})X_7 + (b_8 + b_{13})X_8 + (b_9 + b_{14})X_9$$
$$= 1.867X_1 + 0.446X_2 + 1.144X_3 + 0.628X_4 + 0.363X_5 + 0.113X_6 + 0.032X_7 + 0.188X_8.$$

Ordinarily, in a regression analysis, the estimated values calculated from the equation can be compared with the observed values to examine the goodness of fit of the equation. In this paper, a modified procedure was used for comparison. The progress curves in Fig. 2 will be used to illustrate the procedure. For each experiment, the following were calculated:

1) The estimated loss for each progress curve:
   Treatment A, early infection:

$$y = 1.867X_1 + 0.446X_2 + 1.144X_3 + 0.628X_4 + 0.193X_5 + 0.180X_6 + 0.343X_8 + 0.829X_9$$
$$= 1.867 \times 7 + 0.446 \times 11 + 1.144 \times 22 + 0.628 \times 27 + 0.193 \times 13 + 0.180 \times 9 + 0.343 \times 3 + 0.829 \times 2$$
$$= 66.92\ (\%).$$

   Treatment B, late infection:

$$y = 1.867X_1 + 0.446X_2 + 1.144X_3 + 0.628X_4 + 0.363X_5 + 0.113X_6 + 0.032X_7 + 0.188X_8$$
$$= 1.867 \times 0 + 0.446 \times 0 + 1.144 \times 0 + 0.628 \times 0 + 0.363 \times 0 + 0.113 \times 0 + 0.032 \times 2 + 0.188 \times 1$$
$$= 0.25\ (\%).$$

2) The estimated yield for each progress curve: estimated yield for A = 100 – 66.92 = 33.08%; estimated yield for B = 100 – 0.25 = 99.75%.
3) Estimated yield of A as the percentage of the estimated yield for the base treatment (B):
$$\frac{33.08}{99.75} \times 100 = 33.17\%$$
4) Estimated loss in A relative to the estimated yield of B: 100 – 33.17 = 66.83%, which is then compared with the actual loss (64%).

It should be noted that the procedure above provides a method for comparing the estimated losses to actual losses even when a base treatment cannot be found. It is for this reason that the procedure was chosen. The loss calculated in step 4 above will hereafter be termed estimated loss.

RESULTS.–The estimated losses in yield associated with the 96 progress curves were calculated, and the results in Fig. 3 show that in only seven out of the 85 disease progress curves (deviations for the 11 base treatments were zero) was the

TABLE I. Actual and estimated losses (%) in potato tuber yield caused by late blight, using data obtained from experiments in eastern Canada from 1953 to 1970

Estimated[a]	Actual	Estimated[b] (equation method)
16	52	55
23	42	44
8	36	35
2	34	32
10	33	35
5	33	30
0	31	25
0	26	24
4	24	23

[a] Based on the assumption that tuber production stops when 75% of the foliage is affected by late blight.

[b] Using equation based on multiple regression of yield loss (%) on weekly disease increments.

difference between the estimated and actual loss in yield greater than 5%, and in no case did it exceed 10%.

The results in Table 1 show how the estimated yield losses computed from our equation compare with actual yield losses and also the corresponding estimated loss using the method based on the assumption that tuber production stops when 75% of the foliage is affected by late blight (8). Treatments with actual losses exceeding 20% are listed in Table 1.

The equation was tested further by using it to estimate the yield losses associated with the progress curves in Fig. 4 and comparing the result with actual losses in tuber yield obtaining by weighing. The data from this experiment were not used to derive the equation, and therefore could serve as an independent test. The results in Table 2 show that the estimated loss using the equation was in close agreement with the actual losses.

DISCUSSION.–Late blight causes several types of loss in the potato crop, but it is only practical to estimate the decrease in total tuber production. Estimation of loss due to blighted tubers is not possible because it is affected by soil type, rainfall, cultivar susceptibility, and amount of soil covering tubers (3). Accordingly, Large (8) and Olofsson (9) ignored losses due to blighted tubers.

Olofsson (9) reported that significant relationships were obtained for yield and length of blight-free period. The data from the current experiments

TABLE 2. Actual and estimated losses (%) in potato tuber yield caused by late blight. Estimates based on multiple regression equation of yield loss (%) on weekly disease increments. Data obtained from an experiment at Fredericton in 1969, using three fungicide spray schedules on the cultivar Katahdin

Fungicide schedule	Actual loss	Estimated loss
A	52	55.9 ± 4.5[a]
B	53	56.6 ± 4.2
C	45	48.4 ± 3.9

[a] Standard deviation.

showed that this was not a reliable estimate because epidemics with the same starting date could have completely different characteristics and consequently different yield losses. However, it was noted that early infection was more important than late infection in relation to yield loss.

For leaf diseases of cereals, the critical point theory (6, 10) is applicable; i.e., one disease assessment at a particular growth stage, during a relatively short period when dry matter is accumulated, can be used to estimate yield loss. In potatoes, however, the theory is difficult to apply because there are no obvious morphological changes occurring during the period which can be used as a critical stage. Furthermore, tuberization starts about halfway through the growing season, and can continue until the end. It follows that a change in disease level at any point in the season may affect yield, and variables such as fungicide sprays and weather can profoundly modify the characteristics of the epidemic, and consequently the effect of the disease on yield; it is therefore necessary to obtain assessments throughout the season.

The specifications of a flexible method for estimating losses in tuber yield due to late blight are very demanding. To develop an empirical equation which estimated yield loss within ca. 5% of the actual loss, we had to allow for the diverse shapes represented by disease progress curves. In practice, our technique can be used to distinguish two curves which reached 75% defoliation at the same time (8), but which have different characteristics before and after that date. The equation should estimate the loss from any given curve irrespective of whether the disease reached the 75% level, since any prediction method will eventually be used on sprayed commercial crops, where blight usually does not reach 75%. A final requirement was that the equation would allow comparison of losses from any two progress curves, and also estimate the yield loss in relation to a healthy crop.

The proposed equation for estimating loss in yield of tubers caused by late blight satisfies all the above requirements. The relationship between the shape of the progress curve and loss in yield was tested under varying conditions, and the difference between actual and estimated loss is less than 5% in over 90% of the cases. When the estimated loss is small, the difference between the estimated and the actual loss can be large relative to the actual loss; e.g., estimated = 5%; actual = 1%; difference = 4%. If the difference (4%) is expressed as the per cent of the estimated (5%), the apparent error is large (80%). However, biologically and economically it is more meaningful to measure the error in terms of the absolute difference (4%) between actual and estimated loss, because this represents a real tuber yield which has an economic value. Although the test was based on the data used to obtain the equation, the wide range of conditions under which the data were collected attests to the general applicability of the equation.

The cultivars, Sebago, Kennebec, and Netted Gem, also grown extensively in eastern Canada, were not subjected to analysis because suitable data are lacking. Tuberization curves for Sebago and Kennebec are similar to those for Green Mountain and Katahdin (1); thus, there is a good possibility that the relationship between disease and yield loss will be similar. The method has been tested in the Maritime provinces, and should also apply to the potato-growing area in Maine, which is ca. 97 km (60 miles) from Fredericton. The particular equation reported in this paper will probably not be applicable in other countries such as Great Britain, where the growing season is 160 days, 40 days longer than in North America. However, the method used to derive the equation could be used to develop similar equations for other potato-growing regions.

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