Forecasting Incidence Thresholds of Cercospora Blight in Carrots to Initiate Fungicide Application

A. C. KUSHALAPPA, Macdonald College of McGill University, Ste. Anne de Bellevue, PQ, H9X 1C0; G. BOIVIN, Agriculture Canada Research Station, P.O. Box 457, St.-Jean-sur-Richelieu, PQ, J3B 6Z8; and L. BRODEUR, Service de depistage, 539 Blvd. Edward 7, St. Jacques le Mineur, PQ, G0G 1Z0, Canada

ABSTRACT

Kushalappa, A. C., Boivin, G., and Brodeur, L. 1989. Forecasting incidence thresholds of Cercospora blight in carrots to initiate fungicide application. Plant Disease 73:979-983.

Observations of Cercospora blight, caused by *Cercospora carotae*, in carrots (*Daucus carota* var. *sativa*) during 1984–1987 were analyzed to formulate alternative methods for predicting the disease incidence threshold recommended to initiate fungicide application. Regression equations with days after cotyledon stage (DAY), plant growth stage (GS), and degree-day with a base of 7 C (DD_7), each as an independent variable, explained 83, 86, and 85%, respectively, of the variation in the rate of blight development; the disease incidence threshold of 50% was reached at 48 DAY, GS 8.6, and 557 DD_7. These alternative action thresholds could be used to time the first fungicide treatment for late carrots (those reaching cotyledon stage after the third week of May). The mean time after disease detection (TADD) until the threshold was reached was 21 days, but no regression equation was established. Predictive equations were not developed for early carrots because the disease developed late and few or no fungicide applications were needed. However, the mean observed values of DAY and TADD for a disease incidence threshold of 100% were 89 and 42 days, respectively, and these may be considered as alternative action thresholds to initiate fungicide applications on early carrots.

Additional keywords: expert system

Carrot (*Daucus carota* L. var. *sativa* DC.) is an important vegetable crop in Quebec, with 4,430 ha in production and an annual value of $15 million (Canadian) (13). Blights caused by *Cercospora carotae* (Pass.) Solh. and *Alternaria dauci* (Kühn) Groves & Skolko are the most important foliar diseases of carrots and require regular applications of fungicides to minimize losses, in both Canada and the United States (3,5,6,14). In Quebec, Cercospora blight is generally observed early in the season and Alternaria blight later (3). Fungicide applications to control Cercospora blight probably also control Alternaria blight. Both blights weaken the leaves and petioles, reducing the amount of intact foliage required for mechanical harvesters to pull carrots and thus increasing losses at harvest (5). In some years, Cercospora blight appears to be more severe than Alternaria blight in southwestern Quebec (1).

For the control of carrot blights in Ontario, the first fungicide application is recommended when the blight severity reaches 1–2% on the middle leaves (25% of plants with middle leaf blighted) and rain is forecast or the minimum temperature on the previous night was ≥16 C (15). A blight monitoring program initiated in Quebec in 1982 in which fungicides were first applied at a disease incidence threshold of 100% for early and 50% for late carrots has resulted in reduction of fungicide use from an average of 10 kg to 4 kg a.i./ha (2). A growers organization for southwest Quebec offers a scouting service for a fee, but not all growers participate in this program.

The objective of this study was to formulate alternative methods to time the first fungicide application to control Cercospora blight of carrots. A preliminary report has been published (7).

MATERIALS AND METHODS

Data collection. From 1984 to 1987, data were collected each year from approximately 350 fields managed by 35 growers who participated in an IPM scouting program for the muck soil region in southwest Quebec. Each year, these fields represented a total area of approximately 1,000 ha. After seeding, each field was visited biweekly until 1 wk after fungicide application. On each sampling date, scouts walked diagonally across the fields and arbitrarily selected 50 plants from each. On each plant, the tallest leaf, which generally corresponded to the middle nonsenescent leaf, was examined, and a plant was considered blighted when one or more Cercospora lesions were present on this leaf. Plants sampled 1 wk after the first fungicide application were not included.

Daily maximum and minimum temperature readings were obtained from a thermograph placed 1 m above the ground within a shelter at the meteorological station in Sainte-Clotilde. Farms included in this program were located within a 10-km radius of the meteorological station.

Sowing dates and growth stages. Sowing dates varied, and the data for fields were grouped into classes of 5-day intervals based on the day of year that carrot plants reached the cotyledon stage (DOYCS). Carrots that reached the cotyledon stage before day 139 (third week of May) were designated as early and those that reached the cotyledon stage on days 140–184 were designated as late.

Plant growth stage (GS), recorded twice a week, was based on a 0–10 scale, where 0 = cotyledon stage, 1–8 = one to eight true leaves, 9 = more than eight true leaves but space between rows not covered by canopy, and 10 = space between rows covered by canopy.

Average daily temperatures and degree-days. The average daily temperature for intervals of 20 days was calculated, starting from day 120. The degree-days with a base of 7 C (DD_7) and 15 C (DD_{15}) also were calculated for different DOYCS as (equation 1): $DD_{BT} = \Sigma^{n}_{i=1} (((T_{max} + T_{min})/2) - BT)$, where DD_{BT} is degree-day with a base of minimum temperature (BT) for growth (7 C for carrot growth [10] and 15 C for germination of *C. carotae* conidia [O. Carisse and A. C. Kushalappa, *unpublished*]), T_{max} is the maximum daily temperature, and T_{min} is the minimum daily temperature.

Disease and host parameters and regression analysis. The mean proportion of plants diseased (PPD) was calculated as an average for all the fields included in each class of DOYCS. The time at which the disease was detected and the time at which the disease incidence threshold (100% for early and 50% for late carrots) was reached were determined, on the basis of PPD, for three parameters: the day of year (DOY), time after cotyledon stage (DAY), and growth stage (GS). The time after disease detection until the disease incidence threshold was reached (TADD) was also determined. The *Y* axis intercept (b_0 = initial disease level) and the rate of disease

This research was funded by the Conseil des recherches en pêche et en agro-alimentaire du Québec and the Natural Sciences and Engineering Research Council of Canada.

Accepted for publication 24 June 1989.

increase ($b_1 = k$) were calculated using nonlinear regression (9,12) for the logistic, Gompertz, monomolecular, and exponential models, with DAY, GS, DD_7, or DD_{15} as the independent variable and the disease incidence as the dependent variable. For nonlinear regression, the Marquardt convergence was used in most cases and the DUD (does not use derivatives) method was used when the convergence criterion was not met for the Marquardt method. Growth models were evaluated on the basis of values for the coefficient of determination and residual mean square. For the development of prediction equations, data from only four cotyledon stage classes were considered, whereas data from seven cotyledon stage classes were included in the calculation of mean observed values.

The equations formulated for late carrots were used to predict the disease incidence from DAY, GS, DD_7, and DD_{15}. The action thresholds to initiate fungicide treatments were derived by substituting a disease incidence threshold (PPD = 0.5) in the respective equations. The upper and lower bounds of approximate 95% confidence intervals for individual predictions were provided to indicate the variation in the predicted values, which includes the variance of the error as well as the variance of the parameter estimates. Because the convergence criterion was not met in the nonlinear regression models, linear regression analysis was used to develop equations to predict plant growth stages from DAY and DD_7. Significance ($P \geq 0.05$) of a quadratic term was tested by means of a partial F test.

Prediction equations were not developed for early carrots, and only the mean observed values were calculated for various potential forecast parameters. For late carrots, most of the parameters were used to develop equations and, in addition, the mean observed values for all parameters were calculated.

RESULTS

Disease detection. The time (DOY) of initial detection of blight varied with sowing date and had a mean value of day 172 for early carrots and day 187 for late carrots (Table 1). Disease was first detected 45–49 days (mean 47 DAY) and 20–38 days (mean 27 DAY) after the cotyledon stage in early and late carrots, respectively. Blight was first detected at GS 7.6–8.3 (mean 8.0) and 4.7–6.8 (mean 5.5) for early and late carrots, respectively.

Disease progress. The Gompertz model was the best (highest R^2 and lowest residual mean square) in predicting disease incidence from DAY in late carrots (Table 2). The equations for fields with sowing dates grouped into cotyledon stage classes (DOYCS) 120, 140, 160, and 180 were: (equation 2) PPD = exp(−189.24 * exp(−0.08664 * DAY)) (R^2 = 0.85); (equation 3) PPD = exp(−24.693 * exp(−0.06648 * DAY)) (R^2 = 0.89); (equation 4) PPD = exp(−14.186 * exp(−0.06648 * DAY)) (R^2 = 0.86); and (equation 5) PPD = exp(−9.9884 * exp(−0.06452 * DAY)) (R^2 = 0.80).

Initial disease (b_0) and the rate of disease increase ($b_1 = k$) varied among the four classes of DOYCS. The onset of disease was later in early carrots than in late carrots (Fig. 1); for example, a disease incidence of PPD = 0.5 was reached in 41–54 days (equations 3 and 5) at different cotyledon stage classes of late carrots and in 65 days (equation 2) in early carrots. This delay is due to a lower initial disease in late carrots (b_0 = −189 [equation 2]) than in early carrots (b_0 = −25 to −10 [equations 3–5]). The initial delay in disease in early carrots was also associated with low temperature. The average daily mean temperatures were 11, 16, 17, 20, and 20 C for the intervals of 120–139, 140–159, 160–179, 180–199, and 200–219 DOY, respectively. The rate of disease increase was relatively higher in early carrots than in late carrots.

Table 1. Day of year (DOY), days after cotyledon stage (DAY), and growth stage (GS) of carrots on which Cercospora blight was detected and reached the disease incidence threshold[a] and the time after disease detection until the disease incidence threshold was reached (TADD) for various fields in each of seven day of year at cotyledon stage (DOYCS) classes from 1984 to 1987 at Sainte-Clotilde, Quebec

	Time or growth stages when:						
	Disease detected			Threshold reached			
DOYCS	DOY	DAY	GS	DOY	DAY	GS	TADD
Early carrots (threshold = 100% plants diseased)							
120	169	49	8.3	206	86	10	37
130	175	45	7.6	222	92	9.9	47
Mean	172	47	8.0	214	89	10	42
Late carrots (threshold = 50% plants diseased)							
140	178	38	6.8	199	59	9.1	21
150	183	33	6.0	204	54	9.0	21
160	185	25	4.9	204	44	8.2	19
170	190	20	4.7	212	42	8.6	22
180	200	20	5.2	221	41	8.9	21
Mean	187	27	5.5	208	48	8.8	21

[a]Thresholds were 100 and 50% of plants diseased for early and late carrots, respectively. Sowing dates were grouped into DOYCS classes according to when cotyledon stage was reached.

Table 2. Coefficients of determination (% R^2) and residual mean squares (RMS) for disease incidence predicted by three independent variables and four growth models for Cercospora blight in late carrots

		Independent variable		
Growth model[a]	Selection parameter	DAY	GS	DD
Logistic	$\%R^2$	81.9	85.5	84.4
	RMS	0.0203	0.0160	0.0176
Gompertz	$\%R^2$	82.8	84.8	85.4
	RMS	0.0191	0.0167	0.0161
Monomolecular	$\%R^2$	71.2	61.0	74.0
	RMS	0.0330	0.0434	0.0291
Exponential	$\%R^2$	70.4	84.4	71.7
	RMS	0.0345	0.0174	0.0332

[a]Logistic: $Y = 1/(1 + b_0 * \exp(-b_1 * X))$; Gompertz: $Y = \exp(-b_0 * \exp(-b_1 * X))$; monomolecular: $Y = 1 - b_0 * \exp(-b_1 * X)$; exponential: $Y = b_0 * \exp(b_1 * X)$. Y is proportion of plants diseased; X is days after cotyledon stage (DAY), plant growth stage (GS), or degree-day with a base of 7 C after cotyledon stage (DD_7); b_0 is the Y axis intercept; and b_1 is the rate of disease increase = k (units per DAY, GS, or DD_7 [9,16]).

Alternative methods to predict disease incidence thresholds to initiate fungicide application. *Day of year (DOY).* The DOY when the disease incidence threshold was reached varied with the sowing dates (Table 1) and averaged 214 DOY for early carrots and 208 DOY for late carrots. The range of DOY on which the thresholds were reached was wide, and thus DOY is not appropriate for timing the initial fungicide spray.

Days after cotyledon stage (DAY). The disease incidence threshold was reached sooner in late carrots than in early carrots. The mean time period for the 4 yr between the cotyledon stage and the specified disease threshold was 89 days for early carrots and 48 days for late carrots. The parameter DAY decreased gradually from 59 to 41 days with the increase in time of cotyledon stage from 140 to 180 DOYCS (Table 1).

Regression equations were developed

to predict disease threshold from DAY for late carrots (Fig. 2). The maximum R^2 and the minimum residual mean square values were observed for the Gompertz model (Table 2). Equation 6 was: PPD = exp[−10.13918 * exp(−0.05553 * DAY)] (R^2 = 0.83). Based on this equation, the disease incidence threshold of PPD = 0.5 (±0.27) for late carrots was reached 48 days after the DOYCS. The predicted value given here is the same as the mean observed value (Table 1).

Plant growth stages (GS). The mean growth stage at which the disease threshold was reached was quite stable among classes of cotyledon stage. The mean for 4 yr was 10.0 for early carrots and 8.8 for late carrots, the latter ranging from 8.2 to 9.1 (Table 1).

Equations were developed for late carrots to estimate the 0.5 disease incidence threshold from the parameter GS. The logistic model had the highest R^2 and the lowest residual mean square values (Table 2). Equation 7 was (Fig. 3): PPD = 1/(1 + 4892.876 * exp(−0.9948 * GS)) (R^2 = 0.86). On the basis of this equation, the disease incidence threshold of PPD = 0.5 (±0.25) for late carrots was reached at GS 8.6, which is close to the mean GS value observed (Table 1).

Time after disease detection (TADD). The time interval between disease detection and the proportion of diseased plants reaching the thresholds varied from 37 to 47 days after cotyledon stage (mean TADD = 42) for early carrots and from 19 to 22 days after cotyledon stage (mean TADD = 21) for late carrots (Table 1).

Degree-days with a base of 7 C (DD_7). The maximum R^2 and the minimum residual mean squares were observed for the Gompertz model (Table 2). Equation 8, to predict disease incidence in late carrots from DD_7, was (Fig. 4): PPD = exp(−11.00412 * exp(−0.00497 * DD_7)) (R^2 = 0.85). Based on this equation, the disease incidence threshold of PPD = 0.5 (±0.25) was reached at 557 DD_7. The equations for degree-days with a base 15 C gave low R^2 values.

Equations to predict plant growth. The R^2 values were higher for a quadratic function of DD_7 (Fig. 5) than for DAY. Equation 9 was: GS = 0.582 + 0.022 DD_7 − 0.000013 DD_7^2 (R^2 = 0.97). Equation 10 was: GS = 0.335 + 0.229 DAY − 0.0013 DAY^2 (R^2 = 0.93).

DISCUSSION

The delay in development of Cercospora blight in early carrots may be due to low levels of initial inoculum as well as to temperatures below (11 C) the minimum (15 C) required for the germination of spores of *C. carotae*. Blight developed sooner in late carrots because of warmer temperatures and higher inoculum levels resulting from disease buildup on early carrots. Among late carrots, those that reached the cotyledon stage earlier took longer to reach the disease incidence threshold level.

Although observations were made on a per-field basis, average values were derived for all fields in each cotyledon stage class to allow growers to apply fungicides on the same day to many fields. Fractional values may be rounded off to the nearest integer, depending on the chosen risk level.

The proportion of plants diseased was calculated on the basis of the middle leaf that changed as the plants grew. Current disease proportion would be diluted if disease progress was slower than the rate of host growth (9), and this would explain in part the high variation in PPD with time.

Indirect assessment of initial inoculum, based on mean daily and monthly

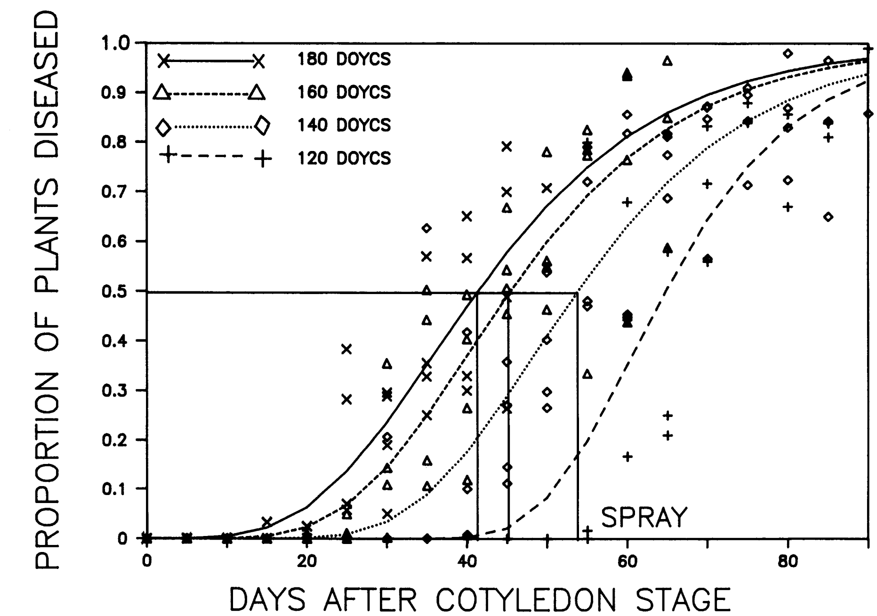

Fig. 1. Disease progress curves for Cercospora blight in commercial carrot fields. Symbols represent the observed average values (total = 221, many values aggregated) of proportion of plants diseased for fields in each of four cotyledon stage classes—120 (early carrots), 140, 160, and 180 (late carrots) day of year at cotyledon stage (DOYCS)—for 4 yr. Curves represent predicted values from the nonlinear regression equations using the Gompertz model.

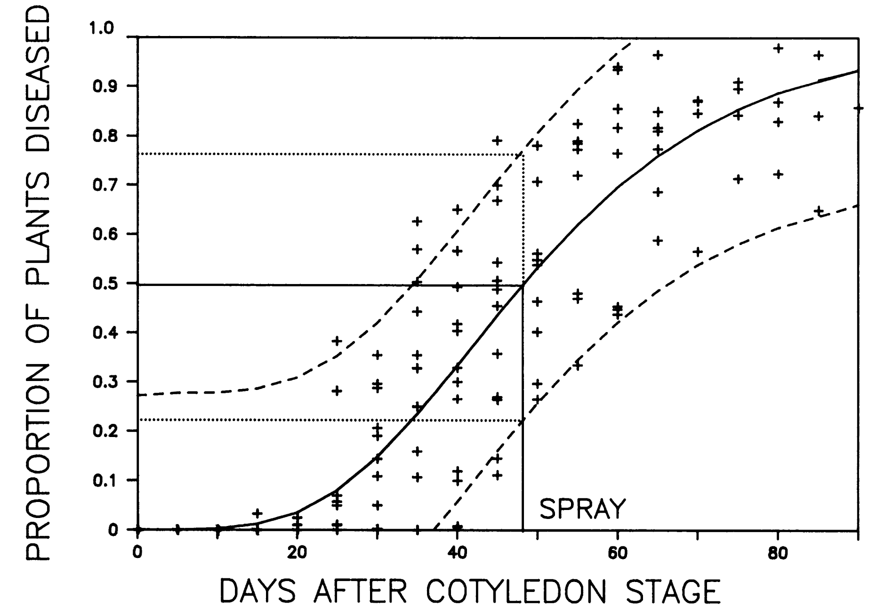

Fig. 2. Regression model to predict carrot blight incidence from number of days after cotyledon stage (DAY). Symbols represent observed average values (total = 168, many values aggregated) of proportion of plants diseased for fields in each of three cotyledon stage classes—140, 160, and 180 DOYCS—for 4 yr. Solid curve represents predicted values based on the Gompertz model. Solid vertical line intercepting prediction curve at the 0.5 threshold indicates time after cotyledon stage (mean DAY = 48) to apply fungicide. Two broken curves are the 95% upper and lower confidence limits (SD = 0.3), and two horizontal dotted lines are 95% confidence intervals at the 0.5 ± 0.27 threshold.

temperatures, has been used in the past to initiate pesticide application against fire blight of pear and insect vectors of Stewart's wilt of corn (4). Plant growth stages have been used to time fungicide application to control lettuce drop (11). Seasonal periodicity in weather, i.e., seasonal rainfall, has been used to time fungicide application to control coffee rust (8). We attempted to identify and quantify significant forecast parameters by relating some factors known to influence plant disease to the incidence of carrot blight. Because of its relation with seasonal variation in climate, DOY was considered as a parameter to investigate its indirect association with disease initiation and buildup. Disease was detected at various DOYs, implying varying levels of residual inoculum, seasonal variation in temperature, and availability of host for infection that was associated with sowing dates. After detection, rapid development of disease was associated with an increase in temperature. The DD_7 explained significant variation in both plant growth and disease progress, resulting in a high correlation between the latter two parameters. At GS = 9, when fungicide application is recommended, canopy cover is extensive and a long period of leaf wetness, required for infection by *C. carotae*, can be expected. GS is simple and easy to determine under commercial field conditions. Among parameters for which no equations were developed, the range of TADD was sufficiently narrow for use in timing the first fungicide treatment.

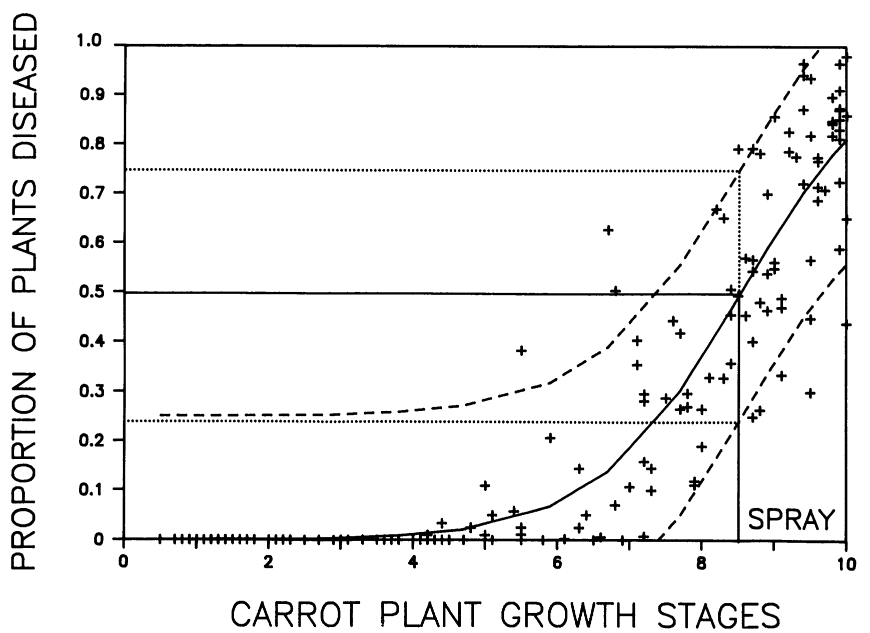

Fig. 3. Regression model to predict carrot blight incidence from plant growth stages (GS). Symbols represent observed average values of proportion of plants diseased for fields of each of three cotyledon stage classes—140, 160, and 180 DOYCS. Solid curve is prediction value based on the logistic model. Solid vertical line intercepting prediction curve at the 0.5 threshold indicates growth stage (mean GS = 8.6) at which to apply fungicide. Two broken curves are the 95% upper and lower confidence limits (SD = 0.31), and two horizontal dotted lines are 95% confidence intervals at the 0.5 ± 0.25 threshold.

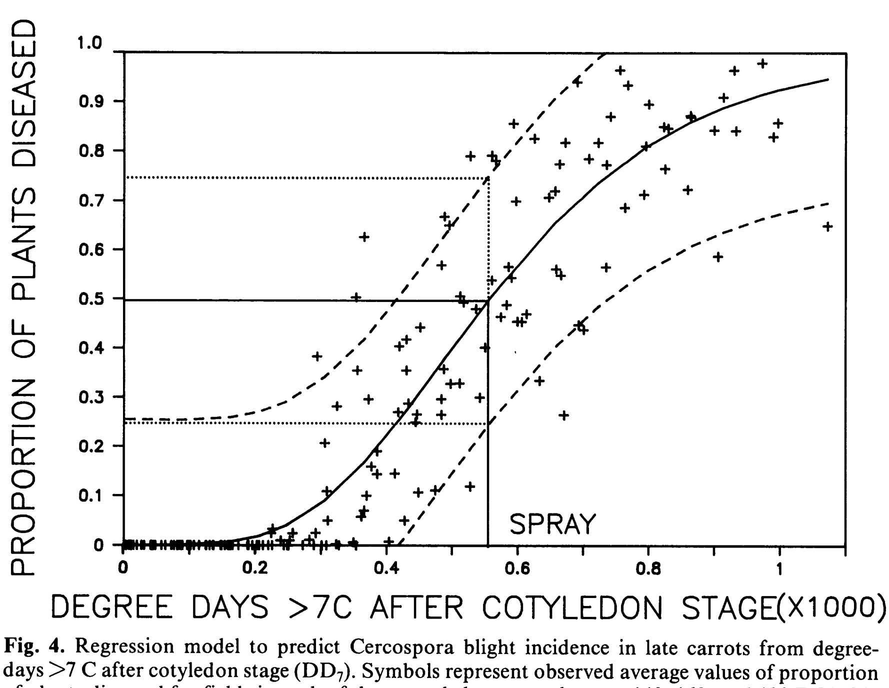

Fig. 4. Regression model to predict Cercospora blight incidence in late carrots from degree-days >7 C after cotyledon stage (DD_7). Symbols represent observed average values of proportion of plants diseased for fields in each of three cotyledon stage classes—140, 160, and 180 DOYCS. Solid curve represents values based on Gompertz model. Solid vertical line intercepting prediction curve at 0.5 threshold indicates degree-days (mean DD_7 = 557) at which to apply fungicide. Two broken curves are the 95% upper and lower confidence limits (SD = 0.31), and two horizontal dotted lines are 95% confidence intervals at 0.5 ± 0.25 threshold.

For late carrots, a PPD of 0.5 is a conservative disease incidence threshold for initiation of fungicide application. However, the disease incidence predicted from the alternative action thresholds recommended here would not be exactly 50% and could vary from 25 to 75%. For a higher level of precision, the grower should either sample at regular intervals, as in a scout program, or sample once when the alternative action threshold is reached. If the disease incidence is closer to the upper limit (75%), a higher dose of the recommended fungicide may be needed. If the incidence is closer to the lower limit (25%), the spray may be recommended after a forecast of rain or after a night when the temperature was >15 C; this recommendation is similar to that for Alternaria blight (5,15).

Growers desiring a lower risk level may choose a lower disease incidence threshold derived from the equations or graphs presented here. For example, the alternative action thresholds for a 40% disease incidence threshold would be 43 DAY, GS 8.1, and 500 DD_7 and the predicted disease incidence would be about 15–65%. A more precise forecasting method could include various environmental, plant, and pathogen parameters explaining the pathway of biological action, as well as other factors related to the economics of yield loss and fungicide application.

A more precise alternative forecasting method for early carrots could not be devised from the data available. The 100% disease incidence threshold was often reached near harvest, so that either no fungicide or, rarely, one or two applications were required. For both early and late carrots, the GS parameter is not sufficiently precise. A scale that is more sensitive after GS = 8 is necessary to improve the forecasting system.

The alternative action thresholds recommended here should be useful to scouts in the disease monitoring program, since scouting can be postponed until a certain disease incidence threshold is reached. Scouts may choose a lower disease incidence threshold (e.g., 40%

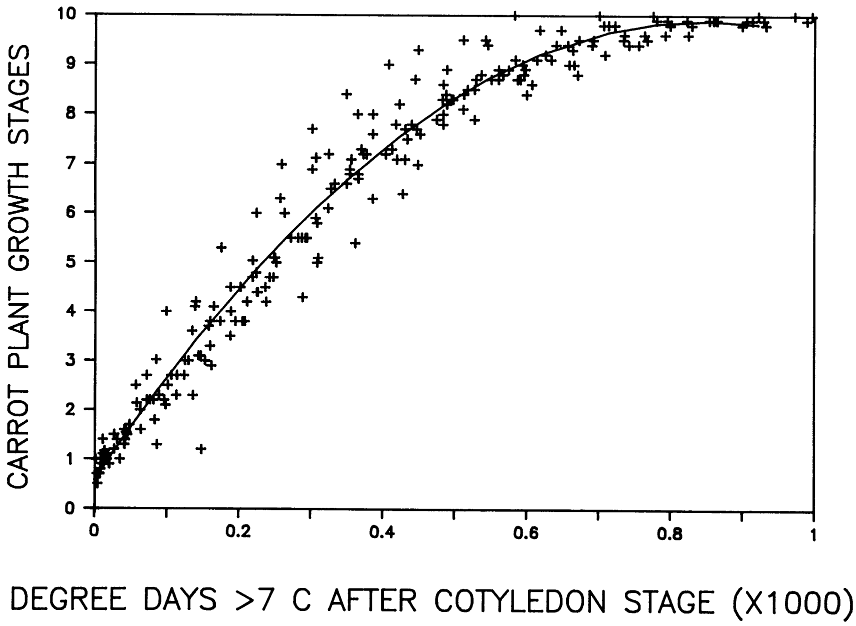

Fig. 5. Regression model to predict carrot growth stages from degree-days >7 C after cotyledon stage (DD_7). Symbols represent observed average values of growth stages (total observations = 221) for fields in each of four cotyledon stage classes—120, 140, 160, and 180 DOYCS. Curve is derived from a quadratic equation.

plants diseased) to arrive at an alternative action threshold, in this case to determine when to initiate sampling.

The alternative forecasting methods presented here could be used by growers after brief training in estimating the various parameters. Because the data used in this study were obtained from commercial fields, these alternative forecasting methods may be recommended to carrot growers in Quebec and nearby areas in the United States (with a warning), although validation would be helpful. To implement the recommendations, the grower should group all the fields that reached cotyledon stage within each 5-day period into separate cotyledon stage classes (DOYCS). The grower could then use any action threshold to initiate fungicide application. The grower should determine the selected forecasting parameter and calculate the mean value of the parameter for all the fields grouped in one class of DOYCS. Fungicide application is initiated when the alternative action threshold is reached; the mean values for late carrots are 48 DAY, GS 9, and 557 DD_7. Because the forecasts based on monitoring disease incidence thresholds have saved substantial amounts of fungicide (>50% [2]), we believe the forecasts recommended here should result in a net saving of >25% of the fungicides used observing conventional methods.

LITERATURE CITED

1. Arcelin, R., Kushalappa, A. C., and Brodeur, L. 1989. Evaluation des maladies de la carotte dans le sud-ouest de Montreal. Annu. Meet. Quebec Soc. Prot. Plants.
2. Boivin, G., and Sauriol, P. 1984. Rentabilité du depistage. Prod. Agric. 7:46-47.
3. Crête, R. 1981. Diseases of carrots in Canada. Agric. Can. Publ. 1615. 26 pp.
4. Fry, W. E. 1982. Principles of Plant Disease Management. Academic Press, New York. 378 pp.
5. Gillespie, T. J., and Sutton, J. C. 1979. A predictive scheme for timing fungicide applications to control Alternaria leaf blight in carrots. Can. J. Plant Pathol. 1:95-99.
6. Hooker, W. J. 1944. Comparative studies of two carrot leaf diseases. Phytopathology 34:606-612.
7. Kushalappa, A. C., Boivin, G., and Brodeur, L. 1988. Alternative methods to forecast the time of first fungicide application against Cercospora blight of carrot. (Abstr.) Can. J. Plant Pathol. 9:367.
8. Kushalappa, A. C., and Eskes, A. B. 1989. Advances in coffee rust research. Annu. Rev. Phytopathol. 27:503-531.
9. Kushalappa, A. C., and Ludwig, A. 1982. Calculation of apparent infection rate in plant diseases: Development of a method to correct for host growth. Phytopathology 72:1373-1377.
10. Lorenz, O. A., and Maynard, D. N. 1980. Knott's Handbook for Vegetable Growers. 2nd ed. John Wiley & Sons, New York. 390 pp.
11. Patterson, C. L., and Grogan, R. G. 1985. Differences in epidemiology and control of lettuce drop caused by *Sclerotinia minor* and *S. sclerotiorum*. Plant Dis. 69:766-770.
12. SAS Institute Inc. 1987. SAS/STAT Guide for Personal Computers. 6th ed. SAS Institute Inc., Cary, NC. 1,028 pp.
13. Statistics Canada. 1988. Fruit and vegetable production, Dec. 1987. Cat. 22-003.
14. Strandberg, J. O. 1977. Spore production and dispersal of *Alternaria dauci*. Phytopathology 67:1262-1266.
15. Sutton, J. C., and Gillespie, T. J. 1979. Weather-timed sprays for carrot blight control. Ont. Minist. Agric. Food AGDEX 258/635.
16. Vanderplank, J. E. 1963. Plant Diseases: Epidemics and Control. Academic Press, New York. 349 pp.