A Simulation Model to Describe Epidemics of Rust of Phaseolus Beans II. Validation

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ABSTRACT

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The FERRUGEM simulation model of bean rust epidemics, based on infections of *Uromyces appendiculatus* that occur on daily cohorts of bean leaf growth, was validated with data from 35 bean rust epidemics monitored in the southeastern region of Brazil. Subjective and goodness-of-fit tests of data were used. Good agreement was obtained between model output and real data in the majority of epidemics. Linear regression lines of Gompertz-transformed proportions of pustular area predicted by the model did not differ for both slope and intercept from regression lines of observed pustular areas in 60.0% of the epidemics. In 71.4% of the epidemics, there was no significant difference in intercepts. Lack of agreement between model-predicted outcomes and observed epidemics occurred in two situations: when the initial proportion of pustular area observed in the field was very low (<0.000005) and when there were long periods of weather very favorable for infection. In the first situation, it may be possible to improve the fit of the model by more rigorous sampling to obtain accurate estimates of initial pustular area, because solitary pustules and small foci are easily missed by chance. In the second situation, the model overestimated the final pustular area, possibly because long periods of leaf wetness may have had a negative influence on dispersal of the urediniospores. This latter factor was not considered in the model routines. Specific experiments to evaluate the effect of weather variables on the dispersion of *U. appendiculatus* should be conducted before the model is implemented.

After the development, calibration, and verification of a simulation model, the final version of the model should be evaluated by validation techniques (5,22). The final version of the model, however, is rarely complete and never perfect (14). Since the simulator is a simplification of reality, the model would always be incapable of mimicking all the complex nuances of the real world. The most important characteristics of a disease simulator are the capacity to reproduce the relevant features of epidemics (4) and not to describe the epidemic in all its details. Since the 1960s, with the pioneering work of Waggoner and Horsfall (25), Waggoner et al. (26), and Zadoks (29), simulation models have been developed for a wide variety of pathosystems (4,10,11,23). Although many simulators have been published without a strict validation process, there are cases in which forecasts made by a model managed to describe real epidemics satisfactorily (23).

Validation is considered the last step in simulation modeling. In validation, the degree of agreement between the behavior of the real system and the behavior simulated by the model are quantified. For validation, sets of driving variables are used that were not used in the development of the model (22). The approach selected to test a simulation model depends on the objectives of the model. Models developed to understand a system should be validated against theories, whereas models developed for forecasting should be validated with goodness-of-fit tests (5). The validation process for predictive models basically involves two types of tests: the first, which is subjective, is based on the visual comparison of real data with data predicted by the model. The second analysis, which is objective, uses statistical methods (e.g., regression analyses, correlation, and analysis of variance) to compare quantitatively the output of the simulator with reality. Validation is an essential process in simulation modeling since without it the usefulness of the simulator remains subject to question (22,27). The rigor of the validation test, however, should not be exaggerated, as "too often models have been underutilized because of excessive demands for validity" (23). The objective of this paper was to validate the simulation model FERRUGEM (Portuguese for rust) (3) for epidemics of bean rust based on infections that occur on daily cohorts of leaf growth.

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MATERIALS AND METHODS

Crop culture and disease estimation. Crops of beans (*Phaseolus vulgaris* L.) were monitored for rust (*Uromyces appendiculatus* (Pers.) Unger) at various times since 1986 at Piracicaba (22°S 47°W, 540 m) and Viçosa (20°S 42°W, 649 m) in southeastern Brazil, under different climatic conditions. Thirty-five curves for the increase in pustular area were used. Fourteen curves were obtained from crops grown in Piracicaba (1,17) with cvs. Carioca and Rosinha during seven seasons (sown during July and September 1986, June and October 1989, and July 1990, 1991, and 1992). Twenty-one curves were obtained from crops grown in Viçosa (21) with cvs. Carioca, Rosinha, and Milionário during seven seasons (sown during November 1988, March, June, and November 1989, and March, August, and November 1990).

Data obtained from Rosinha during July 1990 in Piracicaba were the only data utilized in calibration and verification of the simulator. None of the experiments were designed specifically for the validation process. In most cases, each experimental plot contained 20 rows, was 10 m long, and occupied an area of 100 m^2. The sample unit was one plant, with five replications on each sampling date, and destructive sampling was used to determine leaf and pustular areas. Tracings of leaves were made on paper, and the areas of the leaves were determined by planimetry. The pustular area was always estimated in the same way as $[\Sigma(n_i \times s_i)]/L$, where n_i was the number of pustules in each of eight size classes, s_i was the sporulating area of each pustule, and L was the total leaf area. Evaluations were conducted every 3 to 4 days from plant emergence to senescence. Daily maximum and minimum temperatures and hours of leaf wetness were obtained from instruments located in the experimental plots.

Initialization of the model. The relative rates of latent period duration (3) for each day in each season were calculated as a function of daily mean temperature (T) with the equation

$$1/p(T) = -0.19966 + 0.04888T - 0.00392T^2 + 0.00019T^3 - 0.0000035T^4$$

These latent periods were entered into the appropriate statement in the model. Five inputs were necessary to initialize the model: choice of cultivar, number of days in the season, data file with weather favorability values, day of first infection, and proportion of tissue to be infected on the first day.

In the choice of cultivar, two possibilities were offered: a susceptible cultivar (Rosinha) with a final leaf area of 2,500 cm^2 per plant and with a fast basic infection rate (R_{max} = 12), or a more resistant cultivar (Carioca or Milionário) with a leaf area of 1,950 cm^2 per plant and a slower basic infection rate (R_{max} = 6). This characterization of values of R_{max} for Carioca and Milionário was based on the rates of disease progress compared to Rosinha observed in previous experiments. Host and pustular areas from Carioca and Milionário had not been used in calibration and verification of the model.

The number of days to be simulated was equal to the duration of each epidemic. Daily environmental favorability values (F) were calculated with the equation

$$F = ([0.0058(T_{min} - 8)^{1.481}]\,[(29 - T_{min})^{2.93}]\{[1 - \exp(-0.2095W)]^{5.509}\})\ 0.004423$$

where T_{min} was the daily minimum temperature and W was the number of hours of leaf wetness (3). The favorability values were stocked in ASCII files for each season. To begin a simulated epidemic, the initial amount of infected area was adjusted in value to achieve the pustular area observed on the first date of assessment in the field. The day chosen for first infection in the model was one latent period before the first date of assessment. The length of this latent period varied and depended on the observed daily mean temperatures (as described above).

Validation analysis. Subjective and objective analyses were performed to validate the FERRUGEM simulator. The first step was the subjective analysis by a visual comparison of the plotted curves of the nontransformed proportions of pustular area for observed and simulated epidemics. The second step was the comparison of linear regressions of Gompertz-transformed proportions of pustular area $\{-\ln[-\ln(y)]\}$ (16) over time for observed versus simulated epidemics. The comparison of the regression slopes was based on a t test, as $t_{0.05} = (b_1 - b_2)/\sqrt{\text{var } b_1 + \text{var } b_2}$, where b_1 was the slope of the regression line for observed values, b_2 was the slope of the regression line for simulated values, var b_1 was the variance from b_1 (the square of the standard error of the slope), and var b_2 was the variance of b_2. The comparison of intercepts from the regressions also was done with a t test as $t_{0.05} = (a_1 - a_2)\sqrt{\text{var } a_1 + a_2}$, where a_1 was the intercept for observed values and a_2 was the intercept for simulated values. The variances for a_1 and a_2 (var a_1 and var a_2, respectively) were calculated as, e.g., a_1, var $a_1 = [(SEa_1)^2/n] + \bar{x}^2$ var b_1, where SEa_1 was the standard error of a_1, n was the number of observations, and $\bar{x}$ was the mean of the sample.

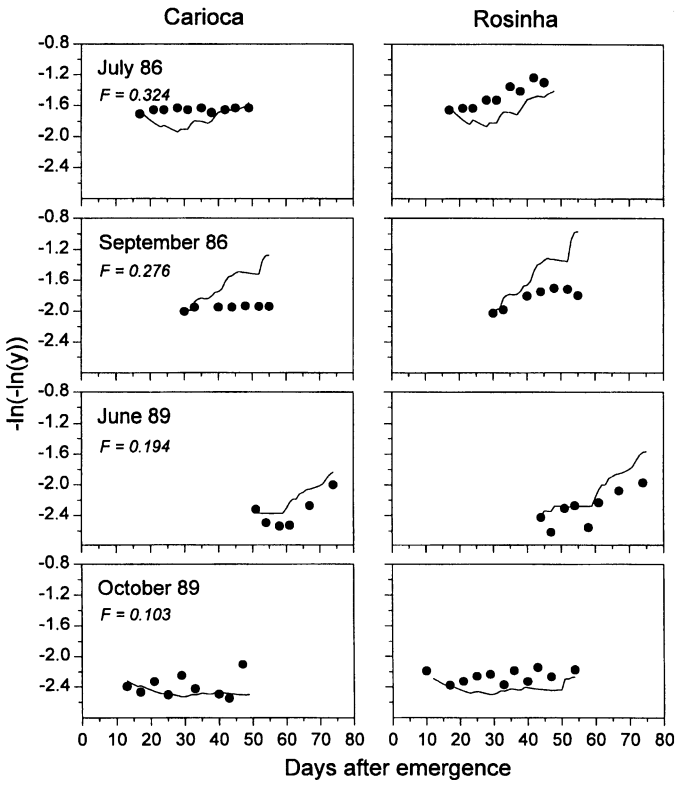

Fig. 1. Observed (dots) and simulated (solid lines) curves of Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, in Piracicaba, Brazil, during July and September 1986 and June and October 1989 on cvs. Carioca and Rosinha.

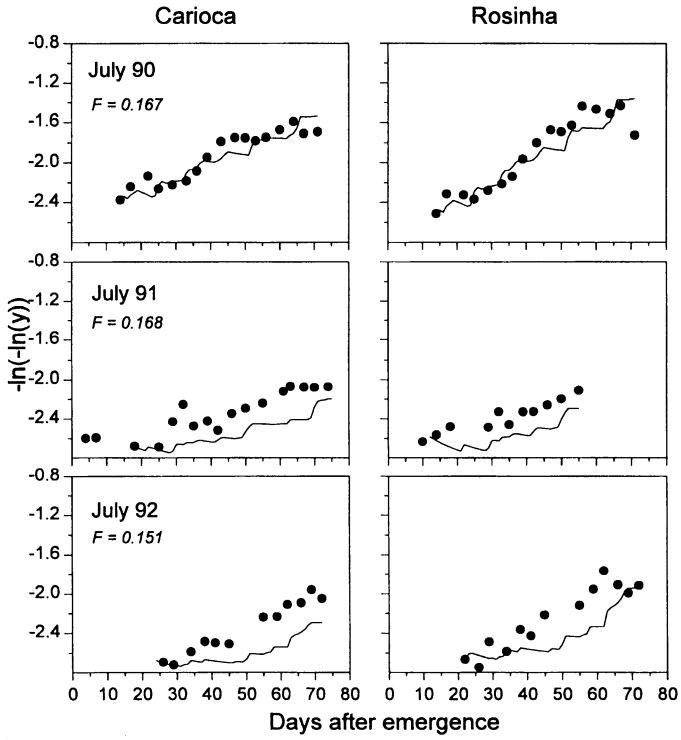

Fig. 2. Observed (dots) and simulated (solid lines) curves of Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, in Piracicaba, Brazil, during July 1990, 1991, and 1992 on cvs. Carioca and Rosinha.

RESULTS

The curves of the Gompertz-transformed proportions of pustular area over time for the observed epidemics had various shapes (Figs. 1, 2, 3, and 4). Several curves reached a plateau or even a decrease in pustular area during the final week(s) of the season. Usually, the observed proportion of pustular area on the first assessment date averaged about 0.00002 $\{-\ln[-\ln(y)] \approx -2.4\}$; consequently, the infected areas used to initialize the model were also very low. This initial proportion of infected area varied from 1.0×10^{-7} for Milionário during March 1990 (Fig. 4) to 0.074 for Rosinha during July 1986 (Fig. 1). The final pustular areas in the field seldom exceeded 0.5%, with a maximum of 3.3% observed for Rosinha during July 1986 (Fig. 1). The day symptoms first were observed varied considerably among crops; the earliest was 4 days after emergence for Carioca during July 1991 (Fig. 2), and the latest was 51 days after emergence for Carioca during July 1989 (Fig. 1).

In general, the average epidemic rates (slopes of the regression lines) increased as the average environmental favorability (F) increased. A notable exception was for the season during July 1986 at Piracicaba (Fig. 1). Despite the relatively high, average daily favorability (F = 0.324), only mild epidemics occurred on both Carioca and Rosinha. The high average favorability arose from a 14-day period at the end of the season (days 52 through 66) in which all daily values of F were between 0.6 and 1.0. This favorable period occurred too late to have much effect on the two epidemics. For the previous 41 days (days 11 through 52), only 4 days were very favorable for infection ($F > 0.5$). These slowly progressing epidemics were predicted by the model. For the seasons of July and September 1986 and October 1989 at Piracicaba, the epidemics developed so slowly (slopes ≤ 0.002) on Carioca that the increase in pustular areas barely managed to keep up proportionally to the increase in host areas (Table 1; Fig. 1).

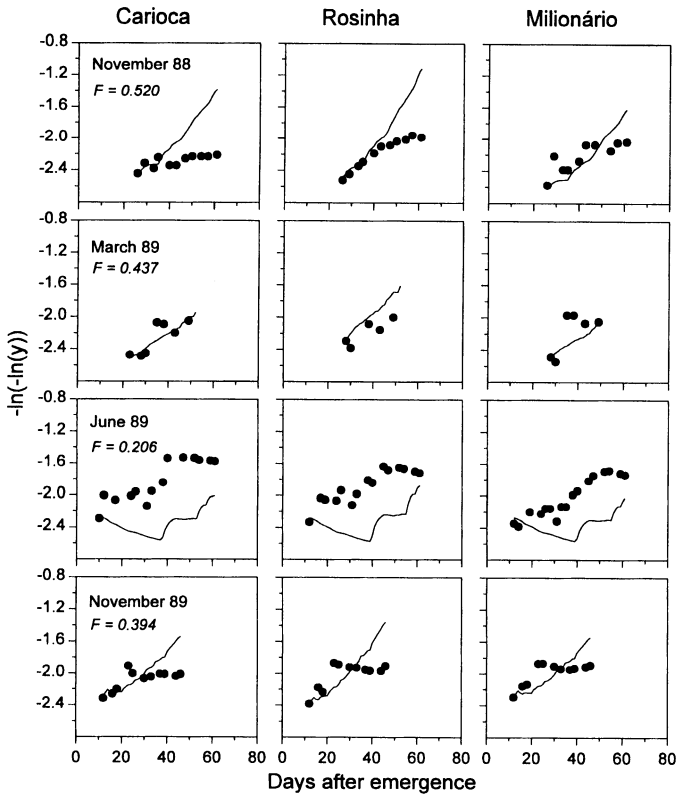

Fig. 3. Observed (dots) and simulated (solid lines) curves of Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, in Viçosa, Brazil, during November 1988 and March, June, and November 1989 on cvs. Carioca, Rosinha, and Milionário.

Of the 14 rust epidemics at Piracicaba, the model gave very good predictions of the increase in pustular area for 11 of them, i.e., there was no significant difference between observed and simulated curves for both slope and intercept of the regressions. Two of the exceptions were the epidemics during September 1986 (Table 1; Fig. 1) in which the weather was very favorable for infection, because 14 days between days 22 and 50 had favorability values of $F \geq 0.4$.

Of the 21 epidemics at Viçosa, the model gave good predictions for 10 of them. The epidemics on the three cultivars during each of the seasons of November 1988 and 1989 and June 1989 were poorly predicted by the model (Table 2; Fig. 3). For November 1988 and 1989, the model greatly overpredicted epidemics during conditions very favorable for infection (F = 0.52 and 0.394, respectively). For June 1989, there were problems with initiation of the simulated epidemics, because the predicted curves were greatly dislocated in time and intensity, and with slower epidemic rates (Fig. 3). The low intensity, slowly progressing epidemics during August 1990 were not satisfactorily predicted for cvs. Rosinha and Milionário (Table 2; Fig. 4). Overall, there were no significant differences for slopes or intercepts for regressions of Gompertz-transformed proportions of pustular area between observed and predicted epidemics in 60.0% of the cases. Intercepts only of the regressions were predicted slightly better (71.4%). The rust epidemics in Piracicaba were predicted much better (78.6%) then the epidemics in Viçosa (47.6%).

DISCUSSION

The daily cohort model (2) has many of the features Jeger (9) assigned to an analytical model. The cohort model was based on a modification of the paralogistic equation of van der Plank (24). Functions for host growth, defoliation, latency, and environmental favorability for infection were incorporated to adapt the model for bean rust. Weather data acted as driving variables. The simulation model that resulted from these modifications maintained the main characteristics of an analytical model (9) with a simple structure and few variables, parameters, and inputs.

The current FERRUGEM simulator predicted the increase in pustular area only; other symptoms, such as haloed areas, yellowing, defoliation, etc., were not included in the model. Con-

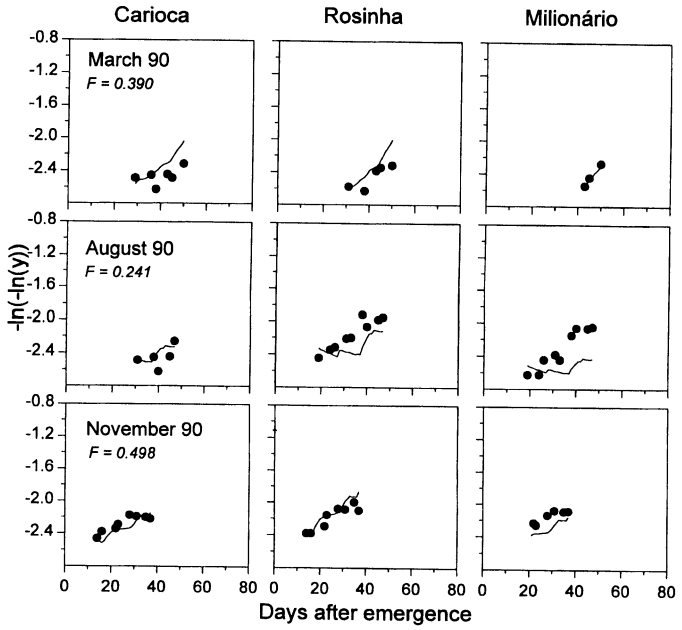

Fig. 4. Observed (dots) and simulated (solid lines) curves of Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, in Viçosa, Brazil, during March, August, and November 1990 on cvs. Carioca, Rosinha, and Milionário.

sequently, the final pustular area in most epidemics was below 3% of the total leaf area. If the other symptoms had been included, the final amount of disease would have been more than 25% in most epidemics.

The simulator was validated by comparing observations from a large number (35) of natural epidemics to the outcomes generated by the model. Since the final proportion of pustular area for most epidemics was usually low ($y_f < 0.03$), the calculation of epidemic rates was problematic. When the logistic transformation of these proportions was tried, small changes in the pustular areas caused large changes in the calculated epidemic rate, as was reported earlier (16). The use of the Gompertz transformation of the proportion of pustular area provided some relief from this problem. The various patterns in environmental favorability, effects of specific weather events on dispersal and infection, adult plant resistance, and possible inadequate sampling for pustular areas caused large changes in the within-season epidemic rates. Subsequently, not all curves could be effectively linearized by the Gompertz transformation. The coefficients of determination in the regressions of Gompertz-transformed values had a large range: $0.25 < R^2 < 0.99$ for the observed and $0.02 < R^2 < 0.99$ for the simulated epidemics. Since all the regression slopes (b) were near zero ($-0.004 < b < 0.039$), the values of b had a major reductive effect on the R^2 values (6). Therefore, the value of R^2 was not a useful statistic to judge the effectiveness of the Gompertz model to linearize the curves. In cases of low values of b, the residual sums of squares (RSS) and the residual mean squares [RSS/(N – 1 degrees of freedom)] were more reliable statistics to judge the fit of the model (6). Despite the large variety and severity in shapes of the transformed curves for the 70 observed and simulated epidemics, the RSS was reasonably low (<0.1) for 54 (77.1%) of them.

Generally, the epidemics had faster rates when the average environmental favorability values (F) were higher. However, the average values of favorability did not always provide an accurate measure of the effect of environment on the epidemic because the pattern of favorable periods was ignored. In the majority of the 35 epidemics, the general shape of the simulated curves was similar to the curves of the observed epidemics, and the quantitative agreement between observed and simulated data was quite reasonable. In certain situations (Fig. 2), the generated values were sufficiently similar to allow predictive possibilities with the simulator.

TABLE 1. Intercepts and slopes of regression lines of Gompertz-transformed proportions of pustular area for Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, monitored in Piracicaba, Brazil, and epidemics generated with the simulator FERRUGEM

		Intercept[a]		Slope[a]		R^2		RSS[b]	
Cultivar	Sowing date	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Carioca	Jul. 1986	–1.70	–1.98	0.001	0.006	0.25	0.31	0.0046	0.0901
	Sep. 1986	–2.03	–2.78*	0.002	0.026*	0.52	0.93	0.0016	0.0255
	Jun. 1989	–3.41	–3.71	0.017	0.025	0.50	0.92	0.1078	0.0183
	Oct. 1989	–2.46	–2.34	0.002	–0.004	0.04	0.51	0.1547	0.0170
	Jul. 1990	–2.58	–2.59	0.014	0.015	0.90	0.98	0.1228	0.0240
	Jul. 1991	–2.84	–2.95	0.011	0.009	0.83	0.90	0.1105	0.0348
	Jul. 1992	–3.17	–2.97	0.016	0.008*	0.97	0.80	0.0282	0.0611
Rosinha	Jul. 1986	–1.96	–1.97	0.015	0.009	0.91	0.40	0.0183	0.0886
	Sep. 1986	–2.33	–3.09*	0.012	0.037*	0.72	0.93	0.0281	0.0556
	Jun. 1989	–3.30	–3.70	0.017	0.027	0.64	0.91	0.1253	0.0517
	Oct. 1989	–2.41	–2.51	0.004	0.002	0.35	0.23	0.0402	0.0270
	Jul. 1990	–2.76	–2.79	0.020	0.020	0.87	0.98	0.2839	0.0363
	Jul. 1991	–2.72	–2.85	0.010	0.008	0.87	0.74	0.0245	0.0372
	Jul. 1992	–3.04	–3.04	0.017	0.013	0.90	0.83	0.1424	0.1478

[a] * indicates that simulated values were significantly different ($P = 0.05$) from observed values.

[b] Residual sums of squares.

TABLE 2. Intercepts and slopes of regression lines of Gompertz-transformed proportions of pustular area for Phaseolus bean rust epidemics, caused by *Uromyces appendiculatus*, monitored in Viçosa, Brazil, and epidemics generated with the simulator FERRUGEM

		Intercept[a]		Slope[a]		R^2		RSS[b]	
Cultivar	Sowing date	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Carioca	Nov. 1988	–2.52	–3.32*	0.005	0.031*	0.64	0.98	0.0206	0.0296
	Mar. 1989	–2.91	–2.94	0.018	0.019	0.69	0.98	0.0766	0.0038
	Jun. 1989	–2.33	–2.53	0.014	0.005*	0.79	0.29	0.1968	0.2651
	Nov. 1989	–2.29	–2.63*	0.007	0.022*	0.44	0.96	0.0871	0.0236
	Mar. 1990	–2.76	–3.29	0.007	0.024*	0.28	0.95	0.0357	0.0083
	Aug. 1990	–2.67	–2.41	0.005	0.001	0.31	0.02	0.0559	0.0234
	Nov. 1990	–2.57	–2.73	0.011	0.015	0.79	0.96	0.0155	0.0055
Rosinha	Nov. 1988	–2.87	–3.60*	0.016	0.039*	0.93	0.98	0.0257	0.0519
	Mar. 1989	–2.77	–3.03	0.015	0.027	0.79	0.99	0.0201	0.0018
	Jun. 1989	–2.33	–2.62	0.012	0.008	0.80	0.39	0.1256	0.3385
	Nov. 1989	–2.31	–2.83*	0.010	0.030*	0.48	0.97	0.1483	0.0359
	Mar. 1990	–3.15	–3.53	0.017	0.029	0.74	0.94	0.0206	0.0120
	Aug. 1990	–2.82	–2.47*	0.020	0.006*	0.93	0.34	0.0322	0.0752
	Nov. 1990	–2.60	–2.73	0.016	0.023	0.84	0.96	0.0251	0.0099
Milionário	Nov. 1988	–2.75	–3.42*	0.012	0.028*	0.67	0.97	0.0977	0.0353
	Mar. 1989	–3.05	–3.03	0.023	0.019	0.49	0.99	0.1749	0.0015
	Jun. 1989	–2.55	–2.54	0.015	0.005*	0.85	0.22	0.1428	0.2863
	Nov. 1989	–2.24	–2.63*	0.009	0.022*	0.52	0.96	0.0953	0.0236
	Mar. 1990	–4.14	–3.85	0.037	0.031	0.99	0.99	0.0003	0.0001
	Aug. 1990	–3.11	–2.67*	0.024	0.004*	0.91	0.45	0.0413	0.0174
	Nov. 1990	–2.67	–2.73	0.017	0.015	0.89	0.96	0.0182	0.0054

[a] * indicates that simulated values were significantly different ($P = 0.05$) from observed values.

[b] Residual sums of squares.

The model FERRUGEM did not predict the increase in pustular area well in two characteristic situations: first, when the initial proportion of disease was very low (<0.000005), making the predicted outcome dephased in relation to the observed data, and the increase in pustular area was underestimated as a result (crop of July 1992 in Piracicaba [Fig. 2] and crop of June 1989 in Viçosa [Fig. 3]); and second, when the proportion of pustular area ceased to increase despite the fact that the weather remained favorable for infection (crops of November 1988 and 1989 in Viçosa, [Fig. 3]).

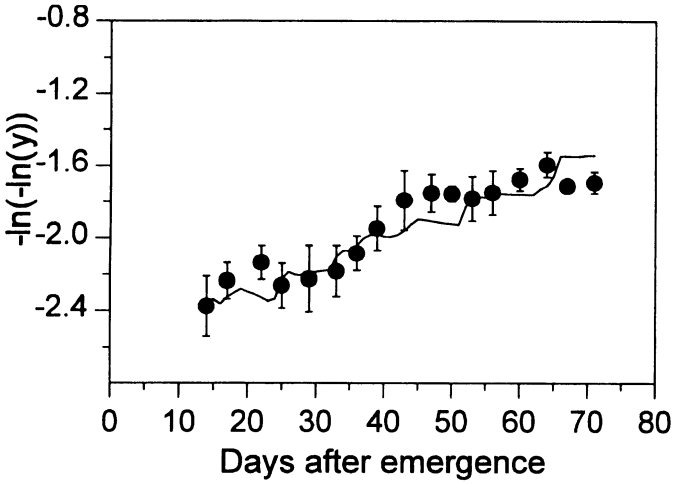

Fig. 5. Observed disease (dots) with standard deviations (vertical lines) and simulated disease (solid line) for a Phaseolus bean rust epidemic, caused by *Uromyces appendiculatus*, on cv. Carioca in Piracicaba, Brazil, during July 1990.

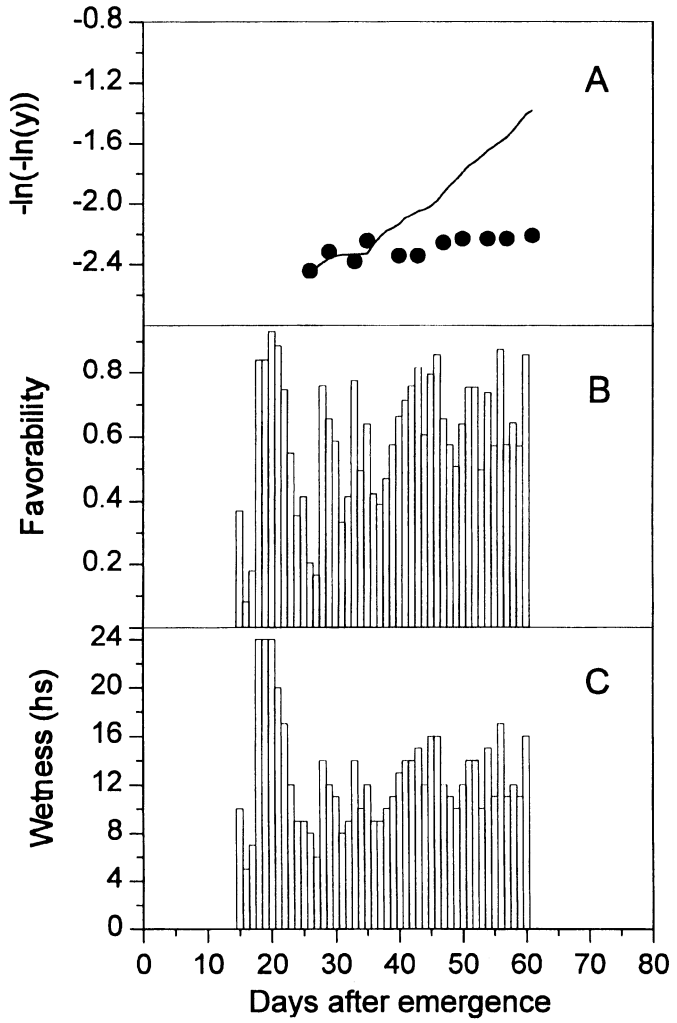

Fig. 6. A, Progress curves for observed disease (dots) and simulated disease (solid line) for a Phaseolus bean rust epidemic, caused by *Uromyces appendiculatus*, on cv. Carioca; **B,** favorability of weather for infection of beans by *U. appendiculatus*; and **C,** duration of leaf wetness in Viçosa, Brazil, during November 1988.

The problem of the offset in time for the simulated curves was primarily caused by the lack of agreement of the estimate for the proportion of initial infected area (which became the pustular area one latent period later) and the estimate of the pustular area on the first day of assessment. When the time and level of the initial proportions of infection were artificially adjusted, the simulated curves became much closer to the curves of the observed epidemic (data not shown). Several authors (5,10,23) have drawn attention to the problems that arise from inaccurate estimates in initial values of state variables. These values should be as accurate as possible to regulate the subsequent epidemic (10). The pustular area observed in the field on the first evaluation sometimes had an extremely low value and high variability (Fig. 5). The high variability arose from inadequate sampling for a variable of this low intensity and irregular spatial pattern (10). A sequential sampling method (4) might provide a better estimate of the rust intensity at the beginning of the epidemic. Errors in sampling and in estimating disease may be more important than those errors that arise from imperfections in the model (15). For example, overestimation of eggs of *Hypera brunnipennis* (Egyptian alfalfa weevil) by a simulation model was due to errors made in the sampling of eggs in the field (8).

There are several possible reasons that could explain the discordance between the observed and simulated curves in Viçosa for plantings during November 1988 and 1989 (Fig. 3). During both seasons, there were many long periods of leaf wetness that led to high values of environmental favorability and the corresponding prediction of severe infection (Fig. 6). Although long periods of leaf wetness are favorable for infection, the same conditions may inhibit other aspects of the pathogenic cycle. The effect of relative humidity on sporulation of *U. appendiculatus* is controversial. High relative humidity reportedly enhances (13,28), reduces (19), or does not have any effect (12) on the sporulation of this fungus. If one assumes that long periods of leaf wetness do not inhibit sporulation of *U. appendiculatus*, then these conditions could still have a suppressive effect on the epidemic because the growth of hyperparasites is promoted (7,18) and the viability of urediniospores is reduced (20), as has been seen in other rusts. The model FERRUGEM did not have any special routine for sporulation nor for dispersion of the pathogen; these components were incorporated into the function to calculate the basic infection rate for the individual cohorts. Experiments specifically designed to examine the effect of long periods of leaf wetness on the sporulation and dispersal of the bean rust pathogen should be conducted before the model is implemented.

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