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A revision of Billing's potential doublings table for fire blight prediction

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Abstract

In her fire blight prediction systems, E. Billing (1978, in: P.R. Scott & A. Bainbridge (Eds), Plant disease epidemiology, p. 159-166) has used the parameter 'potential doublings per day' (PD) of the fire blight causing bacterium, *Erwinia amylovora*. Reconsideration of her calculations of PD revealed, however, that the PD values in Billing's table were underestimated. This leads to overestimation of the duration of incubation periods. A corrected PD table is presented. Sensitivity analyses indicated that day-of-the-year and latitude have little effect on the values in the PD table.

Additional keywords: prediction system, incubation period, *Erwinia amylovora*.

Introduction

In the fire blight prediction systems of E. Billing (1978), the parameter 'potential doublings per day' (PD) of the bacterium *Erwinia amylovora* (Burril) Winslow et al., the causal organism of fire blight in pears and other Rosaceae, is crucial. Billing (1974) investigated the relationship between temperature and potential doublings in vitro (pd) of *E. amylovora* (Fig. 1). She translated the potential doublings in vitro to potential doublings over one day (PD) according to Equation 1, using naturally occurring daily temperature courses.

$$PD = \frac{1}{24} * \sum_{t=1}^{24} (pd_{T_t}) \qquad (1)$$

where: PD = estimated potential doublings per day (day^{-1}); t = solar time (hours); T_t = temperature at hour t (°C); pd_{T_t} = potential doublings per day in vitro at temperature T_t (day^{-1}).

To estimate the average daily temperature courses at different combinations of T_{min} and T_{max}, Billing examined thermogrammes from 15 growing seasons in southern England. Her results are given in Table 1.

Where the temperature is constant during the whole 24 hours period, PD should equal pd. In other words, the PD values of Table 1 on the diagonal line $T_{min} = T_{max}$ should equal the pd values of Fig. 1. However, they do not. At 13 °C, for instance, pd = 5 day^{-1}, while in Table 1 PD = 1.5 day^{-1}. Apparently Billing made a small, although notable error. The present paper presents a corrected PD table. In addition,

Table 1. Billing's estimation of potential doublings per day (PD) in relation to daily minimum and daily maximum temperature (T_{min} and T_{max}) (Billing, 1980).

T_{max} (°C)	T_{min} (°C)				
	< 10	10-11	12-14	15-17	18-20
< 10	0.0				
10-11	0.0	0.5			
12-14	0.5	1.0	1.5		
15-17	1.5	2.0	2.5	4.5	
18-20	3.5	4.5	5.0	7.0	10.5
21-23	7.0	8.0	9.0	10.5	12.0
24-30	9.0	10.5	11.0	11.5	12.5

attention will be given to the effects of month and latitude on the values in the PD table.

Methods

The first step to reconstruct the PD table was to fit a curve to Billing's experimental data on the potential doublings in vitro, pd. The second step was to simulate an average daily temperature course, with input variables: daily minimum temperature (T_{min}), daily maximum temperature (T_{max}) and daylength. T_{min} was assumed to be reached at sunrise. As illustrated in Fig. 2, the temperature at day-time was approximated with a sinus-function with amplitude ($T_{max} - T_{min}$):

$$T_t = (T_{max} - T_{min}) * \sin(d_t) + T_{min} \quad (2)$$

$$d_t = \tfrac{1}{2}\pi * \frac{(t - t_{sunrise})}{\tfrac{1}{2} * \text{daylength} + A} \quad (3)$$

$$t_{sunrise} = 12 - \tfrac{1}{2} * \text{daylength} \quad (4)$$

where A = average time (hours) between 12:00 solar time and the moment that T reaches T_{max} (A = 2.3).

For night temperatures a rectilinear interpolation was used (see Fig. 1):

$$T = T_{sunset} + (T_{min} - T_{sunset}) * \frac{B}{(24 - \text{daylength})} \quad (5)$$

where B = time since sunset (hours).

The temperature at sunset, T_{sunset}, in Equation 5 was approximated with Equations 2, 3 and 4. Daylength was calculated according to Goudriaan (1982), as a function of day-of-the-year and latitude.

The PD values for various combinations of T_{min} and T_{max} were calculated with Equation 1. The effects of day-of-the-year and latitude on the values in the PD table were examined by way of the variable daylength.

Table 2. Estimated potential doublings per day (PD) on June 1, at 50° North latitude, in relation to daily minimum and maximum temperatures (T_{min} and T_{max}).

T_{max} (°C)	T_{min} (°C)																		
	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
0	0.0																		
2	0.0																		
4	0.1	0.2	0.3																
6	0.3	0.4	0.5	0.7															
8	0.6	0.7	0.9	1.1	1.4														
10	1.0	1.1	1.4	1.6	2.0	2.4													
12	1.6	1.7	2.0	2.3	2.7	3.2	3.8												
14	2.3	2.5	2.8	3.2	3.6	4.2	4.8	5.5											
16	3.1	3.4	3.7	4.2	4.7	5.3	5.9	6.7	7.6										
18	4.1	4.5	4.8	5.3	5.9	6.5	7.2	8.0	9.0	9.9									
20	5.3	5.6	6.1	6.6	7.2	7.8	8.6	9.5	10.4	11.4	12.5								
22	6.5	6.9	7.3	7.9	8.5	9.3	10.1	11.0	11.9	12.9	14.0	15.0							
24	7.7	8.1	8.7	9.2	9.9	10.7	11.5	12.4	13.4	14.4	15.4	16.5	17.4						
26	8.9	9.3	9.9	10.5	11.2	12.0	12.8	13.7	14.7	15.7	16.7	17.7	18.5	19.2					
28	9.9	10.4	10.9	11.5	12.2	13.0	13.9	14.8	15.7	16.7	17.6	18.5	19.2	19.7	20.0				
30	10.6	11.1	11.6	12.2	12.9	13.7	14.5	15.4	16.3	17.1	18.0	18.7	19.3	19.7	19.7	19.3			
32	10.8	11.3	11.8	12.4	13.1	13.8	14.6	15.4	16.2	17.0	17.7	18.3	18.7	18.9	18.7	18.0	16.8		
34	10.5	10.9	11.4	12.0	12.6	13.3	14.0	14.7	15.4	16.0	16.6	17.0	17.2	17.1	16.7	15.7	14.2	12.2	
36	9.5	9.9	10.4	10.9	11.4	12.0	12.6	13.2	13.8	14.3	14.6	14.9	14.8	14.5	13.7	12.5	10.7	8.4	5.5

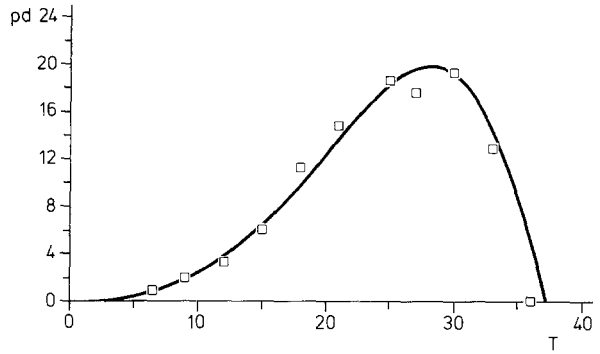

Fig. 1. Potential doublings per day of *Erwinia amylovora* in a shaking culture in relation to temperature. Billing's (1974) observed values (□) and the outcome of curve fitting by means of Equation 6 are shown. T = temperature (°C), pd = potential doublings per day in vitro (day^{-1}).

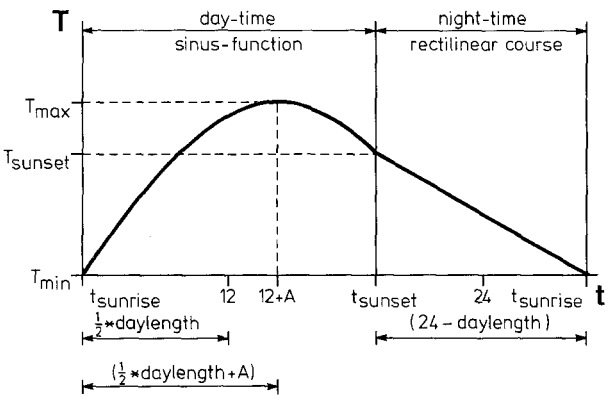

Fig. 2. Simulated temperature course during a period of 24 hours. t = solar time (hours), T = temperature (°C).

Results

For $0 < T < 36$ °C, the relation between T and pd (Fig. 1) was approximated by the equation:

$$pd = 20 * \sin(4.2 * 10^{-4} * T^{2.46}) \qquad r^2 = 0.99 \qquad (6)$$

The corrected PD values, for the latitude of Billing's East Malling Research Station are given in Table 2 and Fig. 3. Fig. 3 is composed of optimum curves with constant T_{min} values and optimum curves with constant T_{max} values. The PD course in the diagonal plane $T_{min} = T_{max}$ equals the pd course of Fig. 1.

The outcome of the sensitivity analyses of day-of-the-year and latitude is illustrated in Fig. 4 and 5. The curves in these figures are optimum curves valid for $T_{min} = 10$ °C.

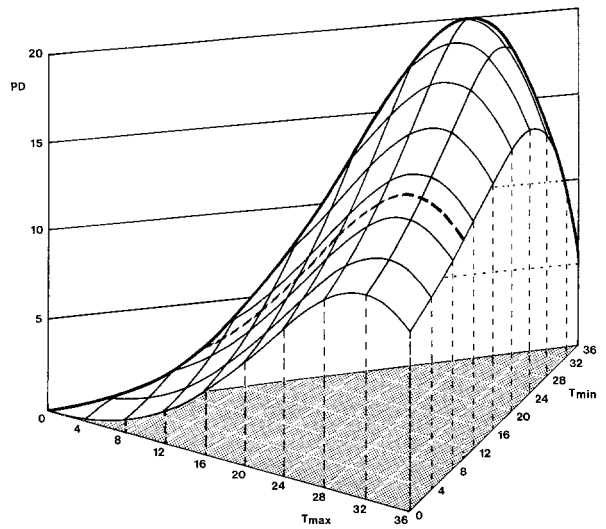

Fig. 3. Estimated potential doublings per day (PD) of *Erwinia amylovora* on June 1, at 50° North latitude, in relation to daily minimum and maximum temperatures. T_{min} = daily minimum temperature (°C), T_{max} = daily maximum temperature (°C), PD = estimated potential doublings per day (day^{-1}).

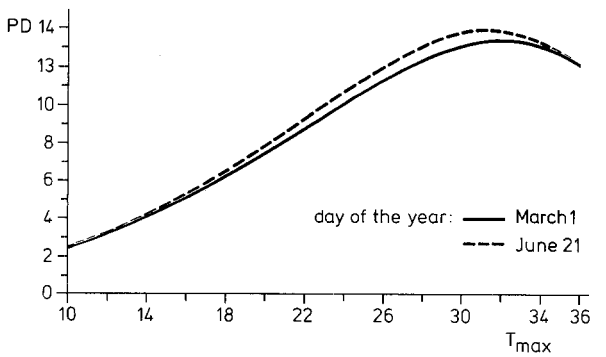

Fig. 4. Estimated potential doublings per day on March 1 and June 21, at 50° North latitude, calculated for T_{min} = 10 °C. T_{max} = daily maximum temperature (°C), PD = estimated potential doublings per day (day^{-1}).

The curves correspond with the dotted curve in Fig. 2. Optimum curves with other values for T_{min} showed similar variation. Fig. 4 and 5 show that day-of-the-year and latitude have little effect on PD values.

Discussion

The differences between Table 1 and Table 2 reveal that Billing's PD estimations were 0 to 5 day^{-1} (0 to 80 %) too low. In Billing's fire blight prediction systems, the PD

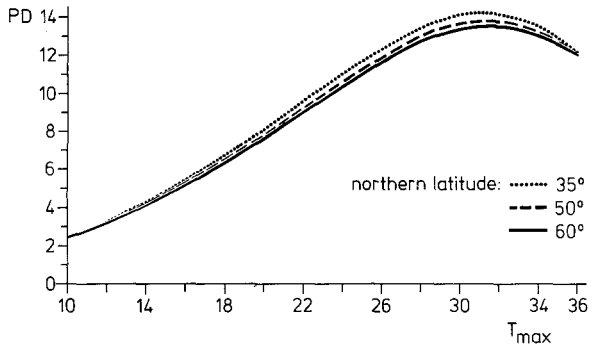

Fig. 5. Estimated potential doublings per day at three latitudes, on June 1, calculated for T_{min} = 10 °C. T_{max} = daily maximum temperature (°C), PD = estimated potential doublings per day (day^{-1}).

values are used to estimate the duration of the incubation period. An incubation period is expected to be completed when the number of accumulative potential doublings (after infection) exceeds a certain threshold. This threshold is dependent on rainfall. When Billing's table is used, the PD values are underestimated. Thus, it takes a longer time for the accumulative PD value to exceed the threshold, and therefore the duration of the incubation period will be overestimated. In a warning system this may lead to warnings that are too late for effective pruning out of diseased tree parts.

Samenvatting

Herziening van Billings potentiële-verdubbelingentabel voor bacterievuurvoorspelling

Billing maakte in haar systemen waarin de ontwikkeling van bacterievuur wordt voorspeld, gebruik van de parameter 'potentiële verdubbelingen per dag' (= PD) van de bacterievuur veroorzakende bacterie *Erwinia amylovora*. Uit herberekeningen blijkt echter, dat de PD-waarden in Billings tabel onderschat worden. PD-onderschattingen leiden in haar systemen tot overschattingen van de duur van incubatieperioden. Een gecorrigeerde PD-tabel werd samengesteld. Uit gevoeligheidsanalyses bleek dat de dag van het jaar en de breedtegraad een gering effect hebben op de waarden in de PD-tabel.

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