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# Confidence intervals for the estimation of the incubation period of fire blight following Billing's prediction system 1

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**Abstract**

An equation of Billing's system 1 permits an estimate of the length of the incubation period (I) of fire blight *(Erwinia amylovora)* in rosaceous plants. The confidence interval of I was determined using Billing's own data (90 % confidence interval: $\hat{I} \pm 6.3$ days). By transformation of I, the confidence interval could be reduced ($\hat{I} \pm 3.5$ days). Temperature was more important than rain with respect to the rate of development of fire blight. The effects of temperature and rain on the rate of development showed a strongly positive interaction.

*Additional keyword: Erwinia amylovora.*

## Introduction

In England, E. Billing developed a system to predict outbreaks of fire blight, a serious disease of rosaceous plants caused by the bacterium *Erwinia amylovora* (Burrill) Winslow et al. Her system 1 (Billing, 1976, 1978) is under investigation in several countries of western Europe. Until now however, no statistical tests have been applied. The question, 'What is the precision of Billing's system 1?' has not yet been clearly answered.

Originally, Billing assumed that the incubation period (I) was determined by temperature only. She transformed temperature to 'potential doublings' of *E. amylovora* using the tempeature-growth relationship of the bacterium in shake culture (Billing, 1974). With the temperature course during the incubation period and the temperature-growth relationship, the number of potential doublings at the end of the incubation period ($\Sigma$PD) can be calculated. Billing assumed $\Sigma$PD to be constant, irrespective of the temperature course during the incubation period. From field observations on five rosaceous species, however, it appeared that $\Sigma$PD was not constant (Table 1). Therefore she took account of the influence of rainfall. The incubation period was expected to be completed when

$$\Sigma \mathrm{PD} \geqslant \frac{36}{\overline{\mathrm{R}}} - 6 \qquad (1)$$

where: $\Sigma$PD = number of potential doublings of *E. amylovora* after infection (−); $\overline{\mathrm{R}}$ = average R after infection (day$^{-1}$); R = 'rain score' per day (day$^{-1}$) determined as

follows:
if rain = 0 mm $day^{-1}$ then R = 0
if 0 < rain < 2.5 mm $day^{-1}$ then R = 0.5
if rain ≥ 2.5 mm $day^{-1}$ then R = 1

Billing obtained Equation 1 by means of regression analysis, with $\Sigma$PD being the dependent variable and $1/\overline{R}$ the independent variable. She provided no confidence limits.

In the present paper a confidence interval for I is constructed, and an alternative approach is offered, which gives smaller confidence intervals.

## Methods

*Method 1.* When the incubation period is completed, Equation 1 can be rewritten as

$$\Sigma PD = 36 * \frac{\hat{I}}{\Sigma R} - 6 \qquad (2)$$

which is equivalent to

$$\hat{I} = \frac{\Sigma R}{36} * (\Sigma PD + 6) \qquad (3)$$

where: $\hat{I}$ = estimated incubation period (days); $\Sigma$R = sum of R-values over the estimated incubation period (–).

The error of estimation $|\hat{I} - I|$ for each case can be calculated from Table 1 and Equation 3. Using the estimated standard error, a confidence interval for I can be constructed.

$$SE_{\hat{I}} = \sqrt{\frac{(\hat{I} - I)^2}{(n - 1)}} \qquad (4)$$

The 90% confidence interval for I is:

$$< \hat{I} - SE_{\hat{I}} * t \quad ; \quad \hat{I} + SE_{\hat{I}} * t >$$

where $SE_{\hat{I}}$ = estimated standard error of $\hat{I}$ (days); $t$ = Student's number at a certain confidence level (–).

*Method 2.* Another approach to estimate I is to establish the parameter 'rate of development'. The average rate of development during an incubation period equals 1/I ($day^{-1}$). Probably 1/I will depend on $\overline{PD}$ and $\overline{R}$. This relation was analysed by means of regression analysis and the data which are given in Table 1.

## Results

Method 1 leads to:

$SE_{\hat{I}}$ = 3.6 (days)

With 90% confidence, I will be within the interval

$$< \hat{I} - 6.3 \quad ; \quad \hat{I} + 6.3 > \text{(days)}$$

Method 2 leads to a smaller standard error of $\hat{I}$:

$$\widehat{\left(\frac{1}{I}\right)} = 0.024 * (\overline{PD} * \overline{R}) + 0.013 \tag{5}$$

$r^2 = 0.91 \quad ; \quad SE_{\hat{I}} = 2.5$ (days)

In Equation 5 the effects of $\overline{PD}$ and $\overline{R}$ on (1/I) are not additive but interactive. Increase of $\overline{PD}$ wil increase (1/I) more at high $\overline{R}$ levels than at low $\overline{R}$ levels. To investigate the effects of $\overline{PD}$ and $\overline{R}$ separately, a ln-transformation was used:

$$\widehat{\ln\left(\frac{1}{I}\right)} = 0.18 * \overline{PD} + 1.8 * \overline{R} - 4.5 \tag{6}$$

$r^2 = 0.92 \quad ; \quad SE_{\hat{I}} = 2.4$ (days)

Both regression coefficients (0.18 and 1.8) differed significantly from 0 ($P < 0.005$). The products of the regression coefficients and standard deviations indicate that $\overline{PD}$ was relatively more important than $\overline{R}$:

| | |
|---|---|
| $s_{\overline{PD}} = 2.5$ ($day^{-1}$) | $0.18 * s_{\overline{PD}} = 0.45$ |
| $s_{\overline{R}} = 0.14$ ($day^{-1}$) | $1.8 * s_{\overline{R}} = 0.26$ |

where s = standard deviation, calculated from Table 1.

The effects of $\overline{PD}$ and $\overline{R}$ on the average rate of development are illustrated in Fig. 1.

$SE_{\hat{I}}$ can be reduced further by multiple regression:

$$\widehat{\ln\left(\frac{1}{I}\right)} = 0.28 * \overline{PD} + 3.1 * \overline{R} - 0.19 * (\overline{PD} * \overline{R}) - 5.2 \tag{7}$$

$r^2 = 0.93 \quad ; \quad SE_{\hat{I}} = 2.0$ (days)

In a warning system I can be estimated as follows. The incubation period is completed as soon as

$$t * \left(\frac{1}{I}\right) = 1$$

where t = time after infection (days). (1/I) may be estimated using Equation 5, 6 or 7.

For Equation 5 the 90% confidence interval is $<\hat{I} - 4.4 \; ; \; \hat{I} + 4.4>$,
for Equation 6 $<\hat{I} - 4.2 \; ; \; \hat{I} + 4.2>$
and for Equation 7 $<\hat{I} - 3.5 \; ; \; \hat{I} + 3.5>$.

Table 1. Data for outbreaks of fire blight (column 1 to 5 from Billing, 1976).

| Host | Observed incubation period (days) | $\Sigma PD$ (–) | $\Sigma R$ (–) | Estimated incubation period according to Billing's equation (days) | Estimated incubation period according to Equation 7 (days) |
|---|---|---|---|---|---|
| stranvaesia | 6 | 48 | 4.5 | 6.8 | 5.9 |
| quince | 8 | 69 | 4.5 | 9.4 | 7.4 |
| hawthorn | 10 | 68 | 5 | 10.3 | 11.4 |
| pear | 11 | 80 | 3.5 | 8.4 | 14.5 |
| apple | 13 | 103 | 4 | 12.1 | 13.2 |
| pear | 15 | 94 | 6 | 16.7 | 15.0 |
| pear | 16 | 110 | 5 | 16.1 | 15.7 |
| pear | 16 | 57 | 9.5 | 16.6 | 17.2 |
| pear | 16 | 99 | 8 | 23.3 | 12.7 |
| apple, hawthorn | 16 | 46 | 11 | 15.9 | 16.4 |
| pear | 17 | 72 | 9 | 19.5 | 17.1 |
| apple, hawthorn | 17 | 129 | 4.5 | 16.9 | 15.1 |
| hawthorn | 20 | 37 | 12 | 14.3 | 23.0 |
| pear | 29 | 49 | 14 | 21.4 | 29.2 |
| pear | 37 | 59 | 17.5 | 31.6 | 30.2 |

For meaning of symbols: see text.

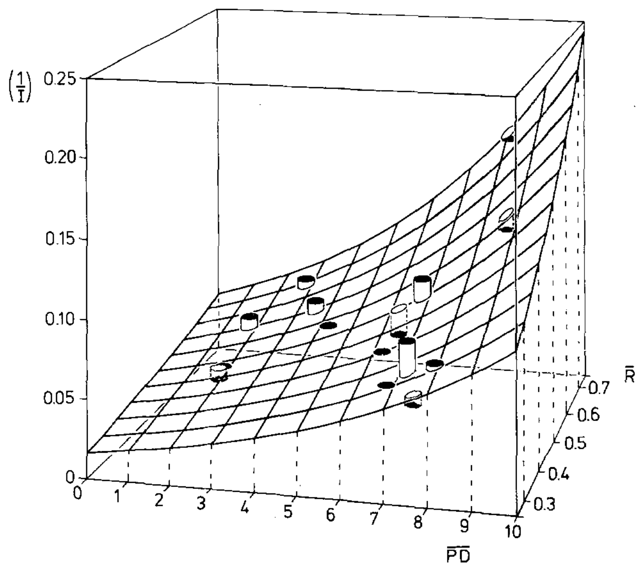


Fig. 1. Relation between the dependent variable: average rate of development of *Erwinia amylovora,* and the explanatory variables: average potential doublings and average rain number. The plane is drawn according to Equation 6. The points indicate the observed average rates of development (see Table 1). $\overline{PD}$ = average potential doublings (day$^{-1}$), $\overline{R}$ = average rain number (see text) (day$^{-1}$), 1/I = average rate of development (day$^{-1}$).

## Discussion

The input data for the construction of the regression equations and confidence intervals were of the following extent

$1.6 < \overline{PD} < 8.6$ and $0.27 < \overline{R} < 0.75$.

Outside these intervals of $\overline{PD}$ and $\overline{R}$, extrapolation occurs, which may lead to serious misjudgment.

The estimations and confidence intervals of I have been derived from observation in south-east England. Applying the equations in other countries may lead to loss of precision.

The regression equations are based on correlations. Correlation, however, is no proof for a causal relation. Possibly, the availability of fast growing plant parts is a more important limiting factor than the potential doublings of *E. amylovora*. The $\overline{PD}$-value is probably highly correlated with plant growth.


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## Samenvatting

*Betrouwbaarheidsintervallen voor schattingen van incubatieperioden in Billings bacterievuur-voorspellingssysteem 1*

De lengte van de incubatieperiode van bacterievuur (*Erwinia amylovora*) kan geschat worden met een formule uit Billings voorspellingssysteem 1. Om enig inzicht te verkrijgen in de nauwkeurigheid van Billings systeem, werd het betrouwbaarheidsinterval van de geschatte incubatieperiode berekend aan de hand van Billings eigen proefgegevens. Bij een betrouwbaarheid van 90 % werd een afwijking van 6,3 dagen gevonden. Het betrouwbaarheidsinterval kon verkleind worden door middel van transformatie van de regressieparameters en toepassing van meervoudige regressie (bij 90 % betrouwbaarheid een afwijking van 3,5 dagen).

De temperatuur had meer invloed op de ontwikkelingssnelheid van bacterievuur dan regen. Verder vertoonden temperatuur en regen een sterk positief interactief effect op de ontwikkelingssnelheid.

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