Challenges in Adaptation of Plant Disease Warning Systems to New Locations: Re-Appraisal of Billing's Integrated System for Predicting Fire Blight in a Warm Dry Environment

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ABSTRACT

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The purpose of this letter is to describe approaches and possible pitfalls when a fire blight model developed in one climatic area is

evaluated in a new location where weather conditions are markedly different. A case is described where a modified form of Billing's integrated system, BIS95, which was developed in a cool moist climate, was tested in a country where weather is warmer and drier. Prior to this, some features of fire blight epidemiology, management, and risk assessment are outlined.

Fire blight, caused by *Erwinia amylovora*, is a serious bacterial disease of pears and apples that is difficult to manage and limits commercial pear growing in some areas. The blossom period is the most dangerous time for spread and establishment of infection. Since the late 1950s, in countries where it was labeled (licensed) for use, the antibiotic streptomycin has been used to protect flowers during bloom; however, streptomycin resistance has become a problem in some areas (16). Thus, most warning systems were developed for the optimal timing of the application of this or other antibiotic agents.

The use of warning systems has helped to reduce the number of protective spray applications used during bloom. However, Breth and Aldwinckle (12) warn of several factors that should be considered when models are used for the prediction of blossom blight. The user needs to understand the limitations of models. Weather records and forecasts must be accurate; recording equipment must be in a representative place; growers need to assess the potential for dewfall at all sites in an orchard; and occasions when conditions are just below a risk threshold need to be noted. Previously, Billing (7) had warned about unrealistic expectations of models and doubted if the quality and quantity of the weather and field data input would ever match the desired output.

Weather and the biology of blossom blight. Thomson (33) describes the disease cycle from the extension of overwintering cankers to leaf fall, but most warning systems are concerned only with the blossom period. In warm dry weather, epiphytic multiplication of the pathogen can be rapid on the stigma surfaces of open flowers and populations may reach 10^6 to 10^7 CFU in 2 to 4 days (36). Bees and flies promote further spread, especially in warm dry weather. Dew or rain may then wash large numbers of bacterial cells from the stigma into the hypanthium where nectar-thodes provide ideal portals of entry into flower tissue. The period before dawn, when host tissue water potential is likely to be high and a water continuum can form, is particularly favorable for infection.

Weather records. Most models use daily temperature and rainfall records, but there is now increasing use of surface wetness records to supplement grower observations of dewfall. The incidence of damaging storms varies widely among different climatic areas, but records of unusually heavy rain, hail, and strong gusty winds are important throughout the growing season (11). Daily temperature records are used in different ways in different models. Degree day (DD) and degree hour (DH) sums (the daily or hourly sum of degrees above a chosen threshold) are used to assess rates of stigma colonization and of disease development following infection. DH sums are likely to give a more accurate guide than DD sums in climatic areas where there is a wide difference between the daily maximum and minimum temperature (19). Estimates of DH may be made from a sine curve (19,25) but this can result in errors, especially on cloudy days (37).

Terminology. In this letter, the day when temperature and wetting requirements have been met is called an infection risk (IR) day (others use the term infection event). The term infection period is avoided because it has been used in different ways by different fire blight workers (21,31). With the fire blight pathogen, the time between the wetting event and tissue penetration by the bacteria may be very short. For Billing's integrated system (BIS95) (8) and BIS98, a later version (9), the term wet (W) IR day is used when there is ≥ 2.5 mm rain with a mean temperature $\geq 13^\circ\text{C}$ on the day of rain or the day before (not after as in the Maryblyt model). WIR days apply throughout the growing season; rain spreads inoculum as well as promoting infection of young green tissue or open flowers. On such a day, a warmth/wetness score can be used, if desired, to judge the relative risk of infection (not of disease incidence) on the WIR day; this is based on temperature and rainfall levels (8,9). Following infection, the time between an IR day and the appearance of early symptoms or signs is called the disease development period or the D-period.

Features of fire blight models. Models that have been evaluated most often, give guidance on optimal timing of protective spray applications during bloom. They include: the mean temperature line, MTL (35); Maryblyt, MB (31,32); Cougarblight, CB (28-30); and Billing's integrated system, BIS95 (8). Descriptions of these and other models and their development are described elsewhere (10). All rest on the concept that *E. amylovora*

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multiplies on stigma surfaces when temperatures are favorable during bloom and that, if a wetting event (dew or rain) occurs when bacterial populations have reached high levels, disease establishment is likely to follow. More recently, a simpler approach has been developed in Israel where temperature levels on the day of wetting and wetness duration are the only considerations in a decision support system called Fire Blight Control Advisory (FBCA) (26,27). Weather analyses are used in conjunction with field risk assessments in all models with or without specific guidance.

Evolution of BIS. Billing developed three distinct systems: Billing's original system (BOS) was published in 1980 (3,4), a revised system (BRS) in 1990 and 1992 (5,6), and the integrated system (BIS) in 1996 (8); the first version was called BIS95. A second version, referred to in this letter as BIS98, was published in 1999 (9); it contains a single change, the exclusion of days $>32^{\circ}\text{C}$ (accidentally omitted from BIS95). In BOS and BRS, the top limit was 30°C . These limits were based on results from in vitro growth rate experiments (2) and on a claim by Powell (24) that temperatures above 30°C interfered with blossom infections.

BOS, BRS, and BIS are working hypotheses. They are also distinct systems, not versions of a single system because, on test, the first two proved inadequate in practice; major changes were made at each stage to improve precision and guidance. They do, however, share important common features. Streptomycin is not licensed (labeled) for use in England and the management policy is "seek and destroy." Thus, any risk assessment system needs to apply to all orchard hosts and to alternative hosts and over the whole growing season (33), not just to the blossom period. In addition, it is important to take account of frost and storm damage (11). Weather analyses need to be used in conjunction with field risk assessments by the user. All three systems define IR days with special guidance during primary blossom periods. They also describe methods for judging times when early symptoms or signs of fire blight might be seen following infection (the disease development or D-period). Graphical presentations are important aids to data interpretation.

Major differences between the systems as they evolved were as follows: greater emphasis on field risk assessments, improvement of IR day assessments, and improvement of graphical presentations. In BIS, the use of potential daily doublings of the pathogen, based on in vitro growth rate experiments (2,25), is abandoned. There is increased emphasis on stigma colonization, prior to a wetting event on an IR day. Following infection, D-period length calculations are based solely on daily temperature data, without combination with a moisture factor as in BOS and BRS. BIS integrates some modified features of BRS and some concepts of the MB blossom infection model (31) but there are important practical differences. The aim was simplicity. More detail of the evolution of BOS, BRS, and BIS is available elsewhere (10) and in the original descriptions of the systems.

Model evaluation. Most models are developed, initially, in a single climatic area based on field experience in that area and, often, with emphasis on a particular host. When evaluating a model, it is essential, at first, to strictly follow the original specifications. Failure to do this may lead to an inappropriate conclusion that the model is inadequate. If a model fails to give satisfactory results in a new area, adaptations appropriate to the climate in that area can then be tested. If simple adaptations fail, and modifications prove necessary, a new model should be created and given a new name; this was the case with BIS (8,9). In cases of further difficulty, consultation with the designer may be advantageous.

For evaluation of a model, a reliable and adequate collection of case histories ranging from high to low incidence is needed. Fire blight is a sporadic disease and, too often, evaluations cover too few seasons and apply to a limited range of orchard conditions. Evaluations of MB have been made over periods of 10 to 15 years

in Germany (23) and the United States (20). In a study using sensitivity analysis and 243 historical cases from different climatic areas (14), CB predicted fewer false positive cases than MB, but regional differences in predictive ability were evident. BIS95 and BIS98 (8,9) were based on more than 200 cases over a 30-year period, including both shoot and blossom blight on different hosts in different countries. These were published and unpublished cases in which the likely IR day was known or suspected. A detailed evaluation of BIS95 was made over a period of 11 years in southwest France at one location (17). BIS95 has also been evaluated for 3 years in Turkey (13) and for 10 years in Germany (22,23).

Too little is known about the effects of temperature values above 30°C on disease initiation and development to give firm guidance on risk assessments at such levels. BIS98 omits hot days ($>32^{\circ}\text{C}$) from risk assessments pending further research. Another area of uncertainty in warm dry climates is the validity of the BIS IR day criteria when maximum temperatures are $\geq 27^{\circ}\text{C}$ and/or mean temperatures are $\geq 20^{\circ}\text{C}$ and there is no recorded evidence of wetting as judged by no trace rainfall in a rain gauge. However, limited evidence suggests that symptom development is sometimes delayed in hot dry weather (E. Billing, *unpublished data*). Thus, workers in hot dry climates may need to take a cautious approach to some risk assessments developed in cooler climates and guard against false positive IR day predictions and premature searches for new signs of disease.

Evaluation of BIS95 in Israel. Where weather during bloom in a new location differs markedly from that where the model was developed, adaptation of the model may be necessary. BIS95 was developed in England where low temperatures mean that primary pear blossom blight is rare; weather during bloom in Israel is much warmer and drier. Shtienberg et al. (27) began their study in 1997 and they used BIS95, the original version of BIS published in 1996 (8), not the current version, BIS98 (9), which excludes days with temperatures $>32^{\circ}\text{C}$. As part of an analysis of models for fire blight in Israel, Shtienberg et al. (27) concluded that MB, CB, and BIS95 were not suitable for use in Israel. However, because they tested a modified and incomplete version of BIS95, it is possible that their conclusions may not have been correct. They apparently did not consider possible adaptations of BIS95 for use in Israel, nor did they consult the designer to discuss application of the model to a hot and dry climate. Essential features of BIS95 for assessments of IR days during bloom are $\text{DD} \geq 18^{\circ}\text{C}$ sum ≥ 17 , prior to wetting by dew or rain, with a mean temperature $\geq 15^{\circ}\text{C}$ on the day of wetting or, without a prior warm period, rain ≥ 2.5 mm with a mean temperature of 13°C on the day of rain or the day before (not after). Blossom infection may also occur when the maximum temperature is $\geq 27^{\circ}\text{C}$ or the mean temperature $\geq 20^{\circ}\text{C}$ when there is no rain ($<\text{trace}$) in the rain gauge and wetting by dew has not been reported. (This does not necessarily mean that there was no wetting.)

Shtienberg et al. (27) noted that BIS95 required rainfall records for operation, but not all the weather stations used in their evaluations recorded daily rainfall. To enable them to use all available orchard records for their simulation experiments, they needed to use daily hours of wetness instead of rainfall totals. The arguments in favor of this modification were that rainfall is uncommon during bloom in Israel; the success rate of BIS95 in preliminary experiments was low when using rainfall data (27) (as later shown, low success rate was due to other factors, not to the use of rainfall data); and they wished to avoid the likelihood of false negative predictions. To achieve the latter, they used a low daily wetness value (equivalent to light dew) of >2 h as the moisture threshold for flower infection in the place of rainfall data. However, by excluding rainfall data, they would exclude potential WIR days (an essential feature of BIS95 and BIS98) and therefore, increase the likelihood of false negative predictions on days with ≥ 2.5 mm rain (3.0 mm when rounded).

In Shtienberg et al. (27), it was correctly concluded that BIS95 might provide false positive predictions in Israel when maximum temperatures are 27°C and/or mean temperatures are ≥20°C and there is no evidence of wetting. This is evident in Figure 2 of their report (27) in which, on most such days, the wetness record was zero. Use of a surface wetness recorder in addition to a rain gauge would have been advantageous when running BIS95 or BIS98; using >2 h of wetness as the threshold for infection would be an appropriate adaptation in such cases. Billing (8) was unwise to suggest that at higher temperatures, wetting might be unnecessary for infection, but lack of wetting was based on zero rain gauge readings. Another reason for false positive predictions when using BIS95 was the inclusion of days with temperatures >32°C; such days are excluded in BIS98 (9). In addition, Shtienberg et al. (27) did not test BIS95 in full; they did not estimate the subsequent disease development rates following infection for the detection of early signs of blossom blight or when checking likely IR days (19); they only tested the model during the blossom period, not over the whole growing season.

Having identified the main reasons why the modified version of BIS95 used by Shtienberg et al. (27) could give rise to both false negative and false positive predictions in Israel, it is worth asking if adaptations of the model, with the inclusion of both rainfall and wetness records, might have led to better performance. Unfortunately, full weather records were not available for such an exercise but an attempt was possible using incomplete data. Daily mean temperature values, hours of wetness, and limited rainfall records were shown in Figure 2 of the Israeli report for 1998 to 2000 at one location and temperature and wetness records for 1998 and 1999 were supplied by D. Shtienberg. Using these incomplete records, an alternative form of BIS95 is suggested (Table 1). All days with temperatures >32°C are omitted, as in BIS98 (9); all warm days (≥27°C maximum and/or ≥20°C mean) are omitted unless there is wetness >2 h; rain days (≥2.0 mm in Figure 2 of Shtienberg et al. [27]) are included as WIR days if there was >16 h of wetness and the mean temperature was ≥13°C on the day of rain or the day before. Moreover, the long period of wetness suggests that the total rainfall on such days was likely to have been ≥2.5 mm as required for a WIR day.

With the form of BIS95 suggested above, many suspected false positive IR days are eliminated and four suspected WIR days are added to those shown in Figure 2 of Shtienberg et al. (27). There is now close agreement between FBCA and BIS95 on potential IR days (Table 2). Because the weather data are incomplete, these suggestions are speculative but they indicate a need for a proper evaluation of BIS95 and BIS98 (8,9) in Israel in a variety of locations using both rainfall and wetness records before making definitive conclusions about the suitability of these models. At first glance, it seems curious that two such different models should

be in close agreement on potential IR days. However, upon closer examination, the IR day criteria are not in fact widely different. FBCA (26): maximum temperature >15°C/wetness >16 h; mean temperature >15°C/wetness >8 h; and minimum temperature >15°C/wetness >4 h. BIS95 (8): mean temperature ≥13°C/rain ≥2.5 mm; mean temperature ≥15°C/rain < 2.5 mm or heavy dew; and mean temperature ≥20°C/wetness >2 h (adaptation).

Thus, the conclusion that BIS95 could not be successfully implemented in Israel may have been premature and a re-evaluation is justified. However, FBCA weather-related IR day criteria are simpler than those of BIS, so if the model gives good guidance in Israel, there seems to be no advantage in changing to BIS for risk assessment during bloom; use of the full system over the whole growing season could be advantageous. Evaluation of FBCA in other climatic areas also would be of interest. The question of the interactions between temperature and wetness duration remains an open one (27). Too little is known about the effects of temperatures >32°C on infection risks and disease development and Israel would be a good area to study such effects.

Conclusions. Most models can offer useful guidance on fire blight risks, provided users understand their values and limitations and simple adaptations are made where necessary. When a model is evaluated in a new climatic area, initially the original specifications should be carefully adhered to. Subsequently, simple adaptations appropriate to the new area can then be tested. Some valuable simple adaptations of fire blight models include the use of reliable surface wetness records as supplementary guides to dewfall during bloom and the use of degree hour temperature sums or sine wave estimates. Running two or more models in parallel has also proved useful. Risk assessments on days >32°C need to be treated with caution pending future research. If major modifications are made to a model, the model should be renamed. In such cases, it might be advantageous to consult the designer.

Suggested future research. All warning system users need to collect good quality case histories. Reasons for anomalies (nonfit cases) need to be explored whenever possible at the time of occurrence. Research is needed in warmer climates on the effects of high daily temperatures (>32°C) on fire blight epidemiology (10). Better methods for the assessment of inoculum potential at the start of bloom need to be developed. Conditions favoring secondary and late blossom production and infection on pears and their control need to be more fully explored (38). There is also a need to learn more about the formation of near-mature twig cankers at the end of the growing season. Conditions favoring extension of twig cankers and ooze production in spring need to be better understood and chances of prebloom infections determined. Late-season and early-season tree inspections for overwintering canker risks and spring activity are difficult and time consuming and are rarely adequate. Fresh, watery ooze production needs to be studied early in the day as it may not be visible later.

Finally, models need to be suitable for use with new chemical and biological protective agents (1,15,18). BIS might usefully

TABLE 1. A comparison of the modified form of the fire blight model BIS95 used by Shtienberg et al. (27) with a suggested form for use with incomplete weather records

BIS95 feature	Shtienberg et al.	Suggested form
Days >32°C	Included	Omitted (6)
Daily rainfall	Wetness >2 h	Rain ≥2.0 mm Wetness >16 h
Potential WIR days ^a	Omitted	Included (5,6)
IR days ^b	Mean temp. ≥15°C Wetness >2 h	Mean temp. ≥15°C Wetness >2 h
	Max. temp. ≥27°C or Mean temp. ≥20°C Wetness 0 h	Max. temp. ≥27°C or Mean temp. ≥20°C Wetness >2h

^a Wet infection risk (WIR) days are days with ≥2.5 mm rain and mean temperature ≥13°C on the day of rain or the day before.

^b Infection risk (IR) days are days during bloom only, after the sum of degree days above 18°C is ≥17.

TABLE 2. A comparison of dates for alerts for infection risk (IR) days suggested by Fire Blight Control Advisory (FBCA) and by the adjusted form of Billing's integrated system (BIS95)

Year	Dates of alerts for IR days	
	FBCA ^a	Adjusted BIS95 ^b
1998	<u>30</u> and <u>31</u> March ^c <u>5</u> and 17 to 20 April	<u>30</u> March <u>5</u> and 18 to 20 April
1999	29 and 30 March <u>1</u> , <u>7</u> , and 13 April	30 March <u>1</u> , <u>7</u> , and 13 April
2000	4, 5, 7 to 9, 15, and 16 April	4, 5, 7 to <u>9</u> , and 14 to 16 April

^a Data from the report by Shtienberg et al. (27).

^b Suggested form of BIS95 provided in Table 1.

^c Underlined dates indicate days when there was >2 mm rain.

take account of the effects of flower age on stigma colonization, as in the CB model where a 4-day degree hour temperature accumulation, prior to wetting, is used as a guide to blossom infection risks (15,30,36). In warm dry areas, a 3-day sum may be more appropriate (34).

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