Fire Blight of Apples and Pears: Epidemiological Concepts Comprising the Maryblyt Forecasting Program

Alan R. Biggs, Kearneysville Tree Fruit Research and Education Center, West Virginia University, P.O. Box 609, Kearneysville, WV 25443; and W. W. Turechek, United States Horticultural Research Laboratory, USDA-ARS, Ft. Pierce, FL 34945

Corresponding author: Alan R. Biggs. abiggs2@wvu.edu


Abstract

This article describes the fire blight prediction model Maryblyt, developed by Steiner and Lightner, and its recent release in the first Windows-compatible version. A brief discussion of the biological basis for the model is provided, including its integrated use of multiple cumulative heat unit "clocks." Furthermore, we describe the recent release of Maryblyt v. 7 for Windows, which is available for free.

Introduction

Symptoms of fire blight were first described over 200 years ago and, until 1919, when it was reported from New Zealand, the disease was limited exclusively to North America (10). It now occurs in at least 43 countries worldwide (5,8). Throughout most of its history, the disease has been frequently described as "characteristically erratic and unpredictable." Young orchards with no history of the disease could suffer severe tree losses in a single season, while other, more established orchards seemed to escape infection even though the disease may have been common the previous year. The destructiveness of fire blight and the highly sporadic nature of damaging epidemics have encouraged growers to adopt intensive management practices that depend heavily on the use of protective antibiotic sprays applied at frequent intervals every year. This approach, although generally adequate, seldom affords complete control, sometimes fails, and often seems excessive given the amount of disease that subsequently develops in comparable untreated orchards.

Many aspects of fire blight have been described since its discovery. More recently, some of the specific requirements governing the infection process, and how these affect the progress of epidemics, have been described. Maryblyt (11,14,15) was an early attempt to integrate much of what was known about the disease in apples and pears into a comprehensive model. The primary focus has been to construct a program that fruit growers can use as an aid in making decisions for controlling fire blight in apple and pear orchards. Because of its accuracy, Maryblyt has also found use in research, teaching, and extension programs.

Multiple Phases of Fire Blight

Fire blight epidemics develop in several phases, each of which can be identified by a distinctive set of symptoms. Recognizing these phases and understanding how each develops is important for assessing risks and for making decisions on the most appropriate control measures needed. There are at least five distinct kinds of infections associated with fire blight, not all of which occur every year or with equal intensity. The Maryblyt program predicts four of these: blossom, canker, shoot, and trauma blight. A fifth type, rootstock blight, has only recently been characterized and the bases for its prediction are not yet fully understood.
Understanding the Factors that Contribute to Blossom Infections

Blossom blight symptoms result from direct infections of open flowers with intact petals. Early symptoms develop as a darkening of the flower base or petiole, which may be accompanied by tiny droplets of ooze (Fig. 1). The infected petiole soon wilts and the pathogen invades the spur and other flowers in the cluster. In some cases, damage is limited to the fruiting spur, but the pathogen often continues to invade and kill a portion of the supporting limb or branch. Since blossom infections are usually the earliest to develop and occur in large numbers over a wide area, they are a major source of secondary inoculum that can fuel later epidemics of shoot blight. Several research articles have been published that provide data to validate the blossom blight component of Maryblyt (5,7,9,19).

The incidence of blossom blight is one of the most sporadic aspects of fire blight epidemics. The Maryblyt model was built on the assumption that there is an abundance of inoculum and that, for a blossom infection event to occur, four strict conditions must be met in sequence. These conditions and the required sequence are: (i) flowers must be open with stigmas and petals intact (stigmas exposed for colonization, flowers in petal fall are resistant); (ii) accumulation of at least 198 degree hours (DH) > 65°F (110 DH > 18.3°C) within the last 80 degree days (DD) > 40°F (44.4 DD > 4.4°C) for apples or within the last 120 DD > 40°F for pears [defines the epiphytic infection potential for the oldest open (and, hence, most colonized) flower in the orchard]; (iii) a wetting event occurring as dew or ≥ 0.01 inch (0.25 mm) of rain, or ≥ 0.10 inch (2.5 mm) of rain the previous day (allows movement of bacteria from colonized stigmas to the nectarthodes); and, (iv) an average daily temperature of ≥ 60°F (15.6°C) (this may influence the rate at which the bacteria migrate into the nectarthodes as well as the multiplication of bacteria needed to establish infections).

When all four of these minimum requirements are met in the sequence shown, infections occur and the first early symptoms of blossom blight can be expected to appear with the accumulation of an additional 103 DD > 55°F (57 DD > 12.7°C). In real time, this interval can vary from 5 to 30 (or more) days depending upon the prevailing temperatures. The occurrence of blossom blight symptoms a month after bloom is not at all unusual and seems especially true in cooler temperate climates. Since infections initiated in response to a single rain or dew event can occur within minutes, it is also characteristic for most symptoms to develop simultaneously. This may be one reason why symptoms appear suddenly rather than gradually and show about the same degree of wilt or necrosis when they first appear. As the epidemic progresses, however, the severity of individual infections varies due to inoculum density, multiple infection cycles and the physiological status of the tissues involved.

When the orchard conditions are less than these minimum requirements, few or no symptoms occur and no significant epidemic develops. However, the degree to which any one or more of these thresholds is exceeded provides a subjective basis for estimating the severity of any given blossom infection event. Thus, many open flowers pose a greater risk than few or no open flowers (i.e., more infection sites); an EIP of 200 to 300 poses a greater risk (i.e., more
flowers colonized) than a marginal EIP of 100; thorough wetting by heavy dew or prolonged rain is more important than intermittent showers; and, average temperatures > 60°F are likely to support more infections. While the greatest proportion of open (=susceptible) flowers occurs at full bloom, the risk period for damage to fruiting spurs is much longer. This is because single flower infections usually destroy the supporting spur. Thus, the period between 20% bloom and 80% petal fall, when there is at least one colonized but uninfected blossom per spur, represents an extended period of high risk.

Bloom that continues over an extended period, typically beyond the normal bloom period and referred to as "rat-tail" bloom, also results in an extended period of high risk, especially for cultivars with this inherent trait, such as Pink Lady. Temperatures are usually much warmer during this period and the risk of fire blight is usually high during this period. Not all flowers in the orchard open (=susceptible) or begin petal fall (=resistant) at the same time. Because all of the flowers open on any one day have not been equally exposed for colonization by the bacteria they are not all equally subject to infection. Only those flowers that have been open long enough for colonization are likely to become infected. This helps explain the often erratic differences in the number of infections that occur with different cultivars in the same orchard. The proportion of open flowers colonized by *E. amylovora* as a function of cumulative degree hours > 65°F (18.3°C) was adapted from research on pears in California (20) and shows the rate at which open flowers are colonized by the pathogen as a function of cumulative DH > 65°F (18.3°C). A similar relationship seems true for apples (15).

While the estimates for spur loss based on proportion of open blossoms are useful for estimating maximum risk, they should not be used when deciding whether a particular infection event is severe enough to justify treatment. On the contrary, treatment decisions for blossom blight should be based strictly on whether an infection event is expected or has occurred, not on how severe it might be. This is because even a few early blossom infections provide many new sources of bacteria throughout the orchard to fuel a later epidemic of shoot blight.

Cool weather has a negative effect on the epiphytic infection potential, EIP. The rate at which flower buds open slows and the rate that bacteria colonize flowers is reduced. Also, at temperatures above 40°F (4.4°C) some already colonized, but uninfected, flowers will continue to mature and become resistant as they enter the petal fall stage.

A 3-day cool period during bloom can reduce the risks for blossom blight significantly. For this reason, the Maryblyt program reduces the risk for infection due to cool weather by making incremental reductions in the cumulative DH total. For one and two consecutive days with no temperature above 64°F (17.8°C), the total DH accumulation is reduced first by one-third and then by one-half, respectively, and to zero for a third consecutive cool day or in response to any one day with a freezing temperature greater than 24°F (-4.4°C). Once the DH total exceeds 400 (EIP=200), however, no negative adjustments are made. If the temperature falls below 24°F (-4.4°C), 90% of the blossoms will be killed and the EIP automatically resets to zero, even if the DH has exceeded 400; this is a new rule in v. 7.0.

A wetting event during bloom provides a means for the bacteria colonizing the stigmas to move down into the nectarthodes at the base of the flower where infections take place (18). The presence of a continuous film of water between the stigma and the nectary may allow substances in the nectar to establish a chemical gradient, which the bacteria can detect and follow into the infection sites (2). From a risk standpoint, therefore, heavy dew may contribute to more infections than a small rain shower because of the thoroughness of the wetting that occurs in a greater number of flowers. This may explain why blossom blight occurs more frequently and more severely in low areas of the orchard where heavy dew is common.

Note, too, that when all other conditions for flower infection exist, simply spraying the trees with water is enough to trigger the development of blossom blight. On this basis, it appears that infections can be initiated within minutes and that high volume, water-based fungicide sprays for other diseases and overhead irrigation should be avoided during bloom. We have no evidence to
indicate a similar risk occurs with low volume sprays (e.g., approximately 100 gallons per acre or 1,000 liters per hectare).

**When Cankers Overwinter**

Canker blight symptoms develop as the result of renewed activity by the pathogen at the margins of overwintering cankers established during the previous season. Unlike other phases of the disease, canker blight occurs regularly every year in areas where the disease is established (15). The earliest symptom of canker blight is the appearance of a narrow, water soaked zone in the healthy bark tissue bordering active cankers (Fig. 2). This can be seen by cutting through the bark across the canker margin. Within a few days after this, brownish streaks can be seen in the inner bark tissue. The bacteria then invade nearby vegetative shoots internally, causing them to wilt and die. Such shoots, especially water sprouts, are often mistaken for symptoms of early shoot blight.

This event (CMS in Maryblyt) can be predicted quite reliably with the accumulation of at least 196 DD > 55°F (109 DD > 12.7°C) after green tip (usually about petal fall ± one week) (15). Typical canker blight symptoms (CBS) that result from the internal invasion of nearby vegetative shoots by the bacteria follow CMS with the accumulation of an additional 103 DD > 55°F (57 DD > 12.7°C).

When blossom blight is severe, canker blight symptoms can be easily overlooked. Also, when compared to the large amount of inoculum available from infected blossom clusters, such late canker activity probably adds little to the overall risks for shoot blight. However, when blossom blight does not occur or is very light, these active cankers represent a primary source of inoculum for the shoot blight phase (12). Thus, orchards must be monitored closely when canker blight symptoms are expected (about 300 DD > 55°F or 167 DD > 12.7°C after green tip). Prompt removal of these active cankers before extensive necrosis develops should help delay the appearance of shoot blight. This seems especially true in orchards that are isolated from other sources of inoculum.

**Epidemic Progression into Shoot Blight**

Shoot blight symptoms result from direct infections of vegetative shoot tips. From this initial site of infection, the bacteria then invade and kill the entire shoot and, often, a portion of the supporting branch. The earliest symptom of shoot blight is tip wilt, which causes the tip to curve downward like a shepherd’s crook (Fig. 3). For shoot blight to occur, there must first be a local source of inoculum. This is available from tissues showing symptoms of either blossom or canker blight (15). Since wind and insects can disperse the pathogen from other orchards and wild trees, the primary inoculum sources need not be within the orchard being monitored. As with blossom blight, early dispersal of the pathogen and its colonization of foliar surfaces or substomatal areas prior to infection occurs seems likely with the shoot blight phase of fire blight epidemics.
The exact mechanism and the amount of inoculum needed for shoot tip infections is not known, but insects with sucking or piercing mouthparts seem to be associated in many locations. Our observations suggest that bacterial colonies may develop independently on leaf surfaces or substomatal areas, having arrived there via rain, wind or by casual insect visits. Actual inoculation then occurs later when various insects with sucking mouthparts arrive and begin probing any of the top three shoot tip leaves in search of a suitable feeding site. In a fewer number of cases, the bacteria may be transmitted to a healthy shoot tip by an insect that has fed previously on other tissues containing the pathogen, but not yet showing symptoms.

The insects that are most important in contributing to shoot blight epidemics will, undoubtedly, vary from site to site and from region to region. In Maryland, and many other parts of the United States, early shoot blight symptoms are most closely associated with the activity of winged adults of the white apple leafhopper. These are first available about 675 DD > 40°F (375 DD > 4.4°C) after green tip. In areas where the white apple leafhopper does not occur, the accuracy of shoot blight predictions should be improved by changing the vector availability threshold for a more appropriate vector. Later in the season, and where white apple leafhoppers are not present, suitable insect vectors may include different species of leafhoppers and other insect species. Clarke et al. (6) recently published information from Pennsylvania indicating that the green apple aphid is not an effective vector for the fire blight bacterium. An important role for potato leafhoppers has been proposed by Pfeiffer et al. (13). The feeding habits of potato leafhoppers seem particularly suited to creating wounds in tender tissues that could become infected if inoculum was present and environmental conditions were suitable.

Shoot blight forecasts using Maryblyt are limited to only the first early shoot blight symptoms and are based on the assumption that insect vectors are present. These early symptoms usually develop with the accumulation of 103 DD > 55°F (57 DD > 12.7°C) after the first appearance of either blossom or canker blight symptoms in the immediate area when: (i) the average daily temperature is 60°F (15.6°C) or above, and (ii) suitable insect vector populations are present. Rain and wind help distribute the bacteria but they do not appear to be required for shoot blight to occur. Thus, in dry seasons, new shoot infections often appear limited to sites fairly close to earlier blossom or canker infections. In years with more frequent rainfall during the period of active shoot growth, the incidence of shoot blight is more widespread (i.e., leaf populations of the pathogen are also more widespread) (3). In either case, whether infections occur seems to depend on the overall availability of an epiphytic (=surface) inoculum and the presence and activity of insects with sucking mouthparts.

The appearance of the first shoot blight symptoms in isolated orchards with no history of fire blight may be later than that predicted by Maryblyt and is attributed to the late arrival of the pathogen from some distant source or late developing populations of insects with sucking mouthparts. This latter factor can also be influenced by insecticide treatments by the grower. In either case the number of shoot blight infections should be small; if they are numerous and widely dispersed, however, then look for another vector. After the first appearance of shoot blight, infections are incited more or less in a clustered pattern near the original infections, with occasional random occurrences.
(depending on epiphytic populations of bacteria, insect activity on shoot tips, and severity of windblown rain events) until vegetative growth is complete (3). Maryblyt does not attempt to predict these later shoot tip infections.

**Trauma Events and Disease "Explosion"**

Trauma blight symptoms develop on many different tissues and are associated with infections following injuries caused by late frosts ($\leq 28^\circ$F, $-2.2^\circ$C), hailstorms or high winds that damage the foliage. These injuries appear to breach defense mechanisms that normally confer resistance to fire blight in mature tissues of susceptible cultivars and in generally resistant cultivars like Red Delicious (17). Similar effects may occur when cuts are made to remove infected branches during the growing season, which often result in the formation of small cankers on the branch stubs (17). Such cankers may provide additional inoculum for continuing fire blight epidemics in subsequent years.

The actual risks for loss vary with the severity of the injurious event and the epiphytic population of the bacteria present when it occurs. Trauma blight incidents can be expected any time after early bloom when the EIP reaches 100, but are generally more severe when the EIP exceeds 200 to 250. While free water on the surfaces of leaves is likely during a late frost event or with hail, infections do occur in the absence of rain under high wind conditions that tatter the foliage or damage blossom clusters. Even here, however, if rain accompanies the high wind or follows it closely, the incidence and severity of damage is likely to be much greater.

**Tree Mortality on Susceptible Rootstocks**

Rootstock blight occurs when bacteria from blossom or shoot infections (including trauma situations) move systemically into the rootstock and initiate a localized canker that girdles and kills the tree. It is especially prevalent with apple cultivars on highly susceptible M-26, M-9, and Mark (Mac 39) rootstocks and C-6 interstems (16,17). It occurs most frequently when fire blight susceptible scion cultivars on these rootstocks become infected (blossom, shoot, or trauma blight), but it can occur with resistant cultivars following a trauma blight incident (e.g., Delicious on M-26 rootstock). The loss of $>30\%$ of the trees in an orchard with susceptible scions on M-26 rootstocks within 5 to 7 years after planting is not unusual. While resistant scions like Delicious on these rootstocks are generally more durable, high tree losses can still occur following incidents of hail or high wind (i.e., trauma blight).

**Putting it All Together - Monitoring and Predicting Fire Blight**

Maryblyt integrates the use of three cumulative heat unit "clocks" to indirectly monitor the development of the host, pathogen populations, insect vector availability and symptom development. The age of apple and pear flowers and the appearance of insect vectors (15), for example, can be monitored with reasonable accuracy using cumulative DD $>40^\circ$F (4.4°C). Cumulative DH $>65^\circ$F (18.3°C) is used in Maryblyt to establish the epiphytic infection potential (EIP) for assessing infection risks (14). The EIP is based on data relating cumulative heat units and blossom colonization by the bacteria (19), but it really encompasses much more (availability of open flowers, bee activity, etc.). Thus, an EIP of "zero" does not mean that all bacteria are dead, but only that the risk for infection is low. Once infection occurs, symptom development is predicted using cumulative DD $>55^\circ$F (12.7°C).

The degree days accrued in one day can be estimated by subtracting the base, or minimum threshold temperature from the daily average temperature. This approach was used successfully in earlier Maryblyt versions, but sometimes led to prediction errors in some climates, especially where there were wide differences between the daily minimum and maximum temperatures (e.g., the semi-arid US Pacific Northwest). Version 4.2 introduced the use of a mathematical sine wave function with a $90^\circ$F (32°C) maximum and various minimum temperature thresholds for DD and DH determinations that reduced some of this variability (1). That approach is continued in Version 7, but with additional user-determined choices for sine wave method (single or double) and the option to adjust the parameters of all the thresholds.
Practical use of the software involves the user creating a data file for a particular location, and if desired, individual orchard blocks within that location. The crop, apple or pear, can be selected at this time, and there is no longer any need to enter AG or PG to initialize the model. Required inputs include maximum and minimum temperatures, use of phenological indicators (only three are of critical importance), and indications of wetting (rainfall amount or presence of dew or fog) (Fig. 4). For phenological bud stage indicators, D (dormant) or ST (silver tip) can be entered early but do not affect the program. Three entries are required for the program to function: (i) GT (green tip) is when 50% of the buds show green tissue (this is a biofix to begin predictions); (ii) B or B1 (first bloom) is when the first flower opens in the orchard; and (iii) petal fall (PF) when the last open flower in the orchard is gone (stops blossom blight predictions). Any other entries in the phenology column are for notation only and do not affect the program. During bloom, the first character in this column must remain as B.

Fig. 4. Maryblyt v. 7 screen with data showing risk indications in color.

Graphical presentation of data and the program’s output may be appealing to some users (Fig. 5). Maryblyt v. 7 has the ability to toggle the graphical display, along with many options for choosing which data to show. Prediction mode is useful for determining the effect on fire blight risk of forecasted weather scenarios, and then using the information to make informed management decisions. Generally, begin data entry for Maryblyt just before green tip is expected and do not stop entering daily weather data until the prediction of early shoot blight symptoms (SBS), or until the last trauma blight symptom (TBS) if a trauma event occurred. During the early season, before bloom, data can be entered every few days or weekly; once bloom is about to start and when forecasts predict that an infection event or symptom appearance is near, data entries (and decisions) should be made daily.
Summary

Fire blight is a complex disease that can develop in a variety of distinct phases during the course of a season, not all of which occur every year or with the same intensity. Blossom blight is usually the first phase to develop and is most destructive in bearing orchards. Canker blight symptoms generally begin during late bloom, but may not be clearly visible on young shoots near canker sites until 1 to 2 weeks after petal fall. Tissues showing either blossom or canker blight symptoms provide a source of inoculum for the subsequent development of shoot blight. Shoot blight is often most destructive in non-bearing orchards where rapid vegetative growth is encouraged, but it also can result in much damage to major scaffold limbs in bearing orchards. Trauma blight is an unusual phase of fire blight where infections occur through injuries caused by severe weather events and can affect mature tissues that might otherwise exhibit resistance. Each phase develops in response to different conditions and can appear alone or in combination in any given orchard or season. Any incidence of blossom, shoot or trauma blight symptoms can lead to the loss of entire trees due to the subsequent development of rootstock cankers where susceptible rootstocks are used. Because the pathogen multiplies rapidly and is dispersed widely well before infection events occur, major epidemics can develop quickly even where the incidence of the disease has been low. Thus, once fire blight is known to occur in an area, good control is possible only through rigorous monitoring and an aggressive management program. For additional information and to download Maryblt, visit www.caf.wvu.edu/kearneysville/Maryblt.

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Literature Cited