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Controlling Fire Blight of Pear and Apple by Accurate Prediction of the Blossom Blight Phase

Fire blight, caused by the bacterium *Erwinia amylovora* (Burr.) Winsl. et al, has been one of the most erratic and unpredictable diseases of pear and apple (29). Our perplexity is due mainly to our lack of fundamental knowledge of the bacterium and the mode of infection, especially just before and during bloom. Infection processes are closely related to environmental factors, in particular temperature and moisture.

In spite of considerable efforts to control fire blight, the disease still causes significant tree damage and crop loss. Coupled with poor economic returns, blight has been a major factor in the decision to abandon apple or pear orchards or to top work trees to more resistant varieties. The development of streptomycin resistance in California in the early 1970s resulted in a partial return to the use of fixed copper treatments for control. Under certain weather conditions, these copper compounds may induce fruit russeting, which reduces the value of the crop. These facts, together with the considerable cost of applying the necessary protective materials and of removing diseased tissue, have resulted in a continuing quest for improved methods of controlling the disease, including accurate prediction of the blossom blight phase.

The Bacterium

E. amylovora can exist and be disseminated in three distinct forms: 1) as bacterial ooze or exudate (Fig. 1A), usually originating from active cankers (2,28) in the spring or blighted blossoms and shoots during the growing season; 2) as dry bacterial tendrils or strands (15) on shoots and fruit (Fig. 1B and C), occurring seldom and usually only under low humidity conditions; and 3) as bacterial cells produced in or near infected tissues (1,14). Ooze is spread mainly by insects and wind-driven rains, and bacterial strands are spread mainly by wind currents (15). Bacterial cells of *E. amylovora* may exist epiphytically on the surface of various host tissues (Fig. 1D) and endophytically inside the vascular system of the plant (10).

E. amylovora is frequently present as an epiphyte on various parts of rosaceous plants. This has been clearly demonstrated on pear, apple, and pyracantha blossoms in California (26); on pear and apple blossoms in Michigan (24), New York (20), and West Virginia (31); and on pear and apple blossoms, leaves, and dormant buds in Ontario (5,9). Recently, similar findings on hawthorn and cotoneaster have been reported from West Germany (6) and the Netherlands (18).

Epidemiology

The earliest detailed studies of the epidemiology of fire blight were made in the late 1930s by Hildebrand (11) in New York and by Rosen (22) in Arkansas. Both scientists showed quite conclusively that *E. amylovora* could enter unwounded blossoms through natural openings in the stigma, nectary, anthers, and sepals. They reported that in pears the nectarial surface appeared to be the most vulnerable avenue for invasion, whereas in apples the stigmas and anthers proved to be the main centers of penetration. Thomson (25) demonstrated that stigmas of pear and apple pistils provide sites for significant multiplication of *E. amylovora*. Transfer of these high populations from the stigma to the hypanthium by rain or heavy dew resulted in blossom infections.

Beer and Opgenorth (2) investigated the effect of environment on the presence of *E. amylovora* on holdover canker surfaces. The number of *E. amylovora* cells on cankers was positively correlated with warm (>17 C), moist conditions occurring at least 1 day before sampling. In inoculation studies of apple and pear blossoms, the rate of fire blight development increased significantly with increasing temperatures (20). The rate of disease development was slower when blossoms were inoculated with 10^4 than with 10^6 cfu per blossom. In California and Utah, however, natural bacterial populations of 10^3 to 10^7 cfu per flower were detected on pistils of blossoms of several rosaceous hosts, often without causing disease (25). *E. amylovora* survived at least 14 days on 80% of pistil-inoculated flowers, whereas bacteria were reisolated from only 20% of the flowers inoculated on the hypanthium. The restricted colonization of the

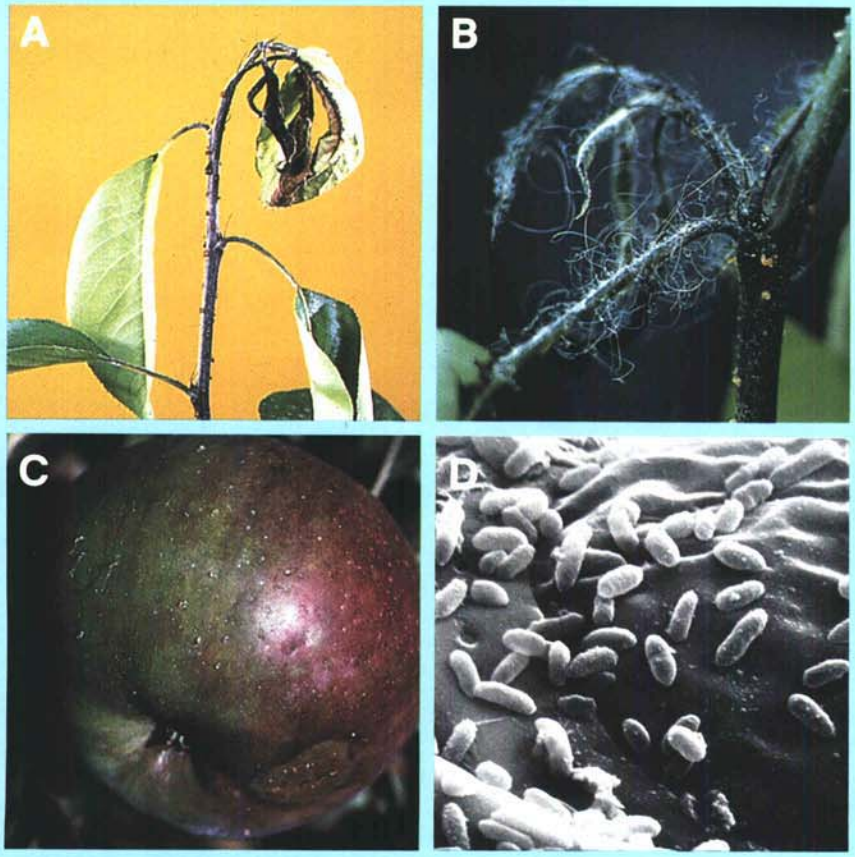

Fig. 1. Characteristic forms of *Erwinia amylovora* on apple and pear: (A) Bacterial ooze droplets on infected succulent pear shoot. (B) Bacterial strands on pear shoot. (C) Bacterial tendrils on apple fruit. (D) Bacterial cells on stigmatic surface of pear pistil.

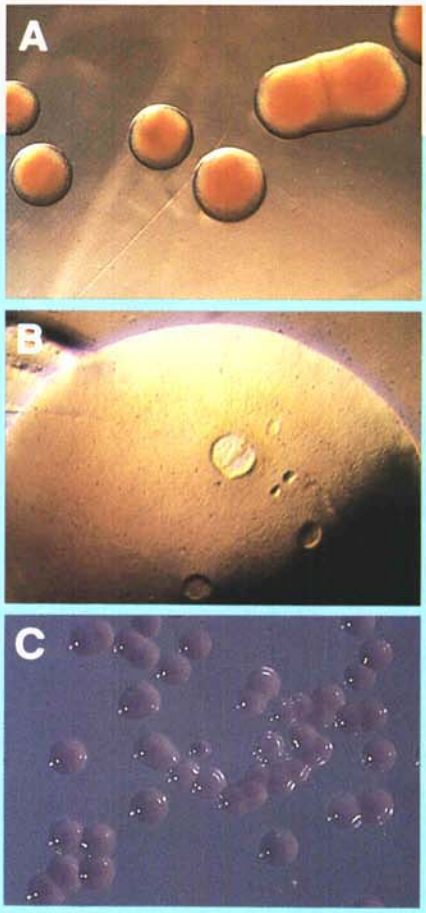

Fig. 2. Characteristic colony morphology of *Erwinia amylovora*: (A) Smooth, orange-yellow colonies with deep orange centers on Miller-Schroth (M-S) medium. (B) Cratered surface on 60-hour-old smooth, whitish tan colonies on Crosse-Goodman (C-G) medium. (Courtesy R. N. Goodman) (C) Light purple, opalescent colonies with a faint purplish center on Ishimaru-Klos (CCT) medium. (Courtesy C. Ishimaru)

hypanthium under low relative humidities confirms the findings by Hildebrand (12) in 1937.

Monitoring Procedures

Standard procedures to sample pear and apple flowers for the presence of *E. amylovora* were to collect bulk samples of 100–200 flowers (random selection) once or twice each week from about a 1.5- to 4.0-ha orchard block. Blossoms for each sample were collected with disposable gloves and kept on ice until processing (usually 2–4 hours) in the laboratory. Tap water (0.5 ml per flower) was added to the bulk sample in a clean polyethylene collection bag. The bag was shaken for 30 seconds, and a 0.1-ml sample of wash water was spread on Miller-Schroth (M-S), Crosse-Goodman (C-G), or Ishimaru-Klos (CCT) selective medium (8,13,17). A 1:100 dilution was made from the original sample wash, and 0.1 ml of this dilution was spread on a second plate. Plates were incubated at 79 F (26 C) for 48–72 hours, and the number of *E. amylovora* colonies was counted.

Initial identification was based on colony morphology: typical orange-yellow colonies with deep orange centers and a clear margin on M-S medium (Fig. 2A), a cratered surface on colonies after 60 hours of incubation on C-G medium

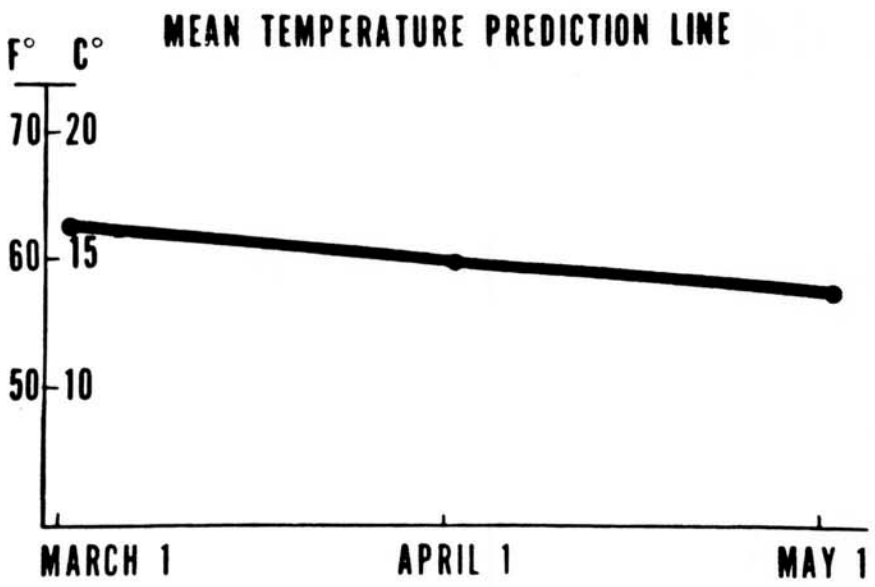

Fig. 3. Mean temperature line between 1 March and 1 May, used to predict blossom blight on pear in California.

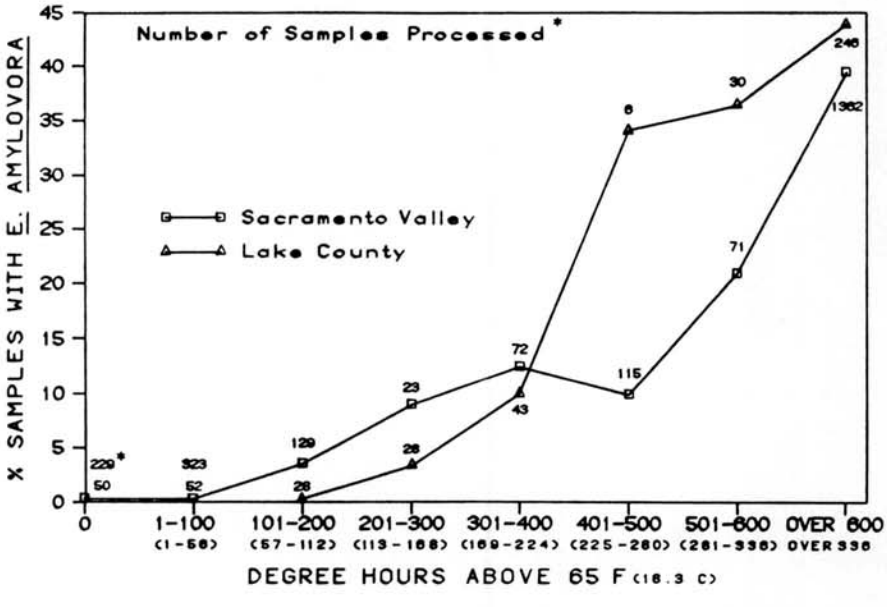

Fig. 4. Percentage of samples colonized with *Erwinia amylovora* vs. degree hours above 65 F (18.3 C) since last 3-day period with no temperature above 65 F (1972-1976).

Table 1. Potential doubling (PD) of *Erwinia amylovora* in vitro in relation to minimum and maximum temperatures[a]

Maximum temperature F (C)	Minimum temperature F (C)				
	<50 (<10.0)	50 (10.0)	55 (12.8)	60 (15.6)	>60 (>15.6)
<50 (<10.0)	0.0				
50 (10.0)	0.0	0.5			
55 (12.8)	0.5	1.0	1.5		
50 (15.6)	1.5	2.0	2.5	*4.5*	
65 (18.3)	*3.5*	*4.5*	*5.0*	*7.0*	**10.5**
67 (19.4)	*5.0*	*6.0*	*7.0*	**9.0**	**11.0**
70 (21.1)	*7.0*	*8.0*	**9.0**	**10.5**	**12.0**
>75 (>23.9)	**9.0**	**10.5**	**11.0**	**11.5**	**12.5**

[a] After Billing (3,4). Regimes with PDs of 3.5 or more are in italics and those with PDs of 9.0 or more are in boldface.

(Fig. 2B), or light purple, opalescent colonies with a faint purplish center on CCT medium (Fig. 2C). Surface craters were also observed on colonies on CCT within 24–48 hours after plating. Suspect colonies were transferred onto nutrient-yeast-dextrose agar grid plates (24 grids per plate) with a sterile toothpick, maintained at room temperature for 24 hours, and then stored at 41 F (5 C) in the refrigerator for future testing. Assuming that each colony was derived from a single bacterial cell in the blossom wash water, a colony count provides an estimate of the number of bacterial cells per flower. Colony types suspected to be *E. amylovora* were verified by green pear pathogenicity tests.

Risk Assessment Systems

Development of currently used predictive systems began about 1955 in New York, where Mills (19) studied correlations between degree days above 60 F (15.6 C), 65 F (18.3 C), or 70 F (21.1 C) and the occurrence of fire blight. He claimed successful forecasting of blossom blight in apple using degree days above 65 F (1 degree day equals 1 day of maximum temperatures 1 degree above 65 F) and reported significant positive correlations between 60–80 F degree days plus precipitation during bloom and severe fire blight in Lake Ontario apple orchards during 1918–1954. During the next 5-year period, Luepschen et al (16) observed that a minimum of 2 favorable days was required for severe blossom infections.

A few years later, this concept was used in Illinois by Powell (21), who developed a similar method for predicting fire blight blossom infections based on the number of degree days above 65 F (18.3 C). He concluded that 30 F-degree days (= 18 C-degree days) between the last freeze and early bloom, combined with maximum temperatures of 70–80 F (21–27 C) and a light rain or high humidity, were adequate for fire blight infections. This system has been used successfully to recommend blossom blight sprays in Illinois.

During the first half of the 1970s, Thomson et al (26) conducted studies in California to determine the extent of colonization of pear flowers by epiphytic *E. amylovora* during the bloom period. Bacteria were detected in most orchards within 2 weeks after the daily mean temperature exceeded a prediction line drawn from 62 F (16.7 C) on 1 March to 58 F (14.4 C) on 1 May (Fig. 3). During 1974–1976, *E. amylovora* was detected in 93% of the orchards 22 days or more after the mean temperature exceeded this prediction line.

Zoller and Sisevich (34), also in California, determined that 10% of pear blossom samples contained bacteria when 350 F-degree hours (= 200 C-degree hours) were reached, whereas 40% of

blossom samples were contaminated when over 600 F-degree hours (336 C-degree hours) were accumulated (Fig. 4). One F-degree hour equals 1 degree above 65 F for 1 hour (one C-degree hour equals 1 degree above 18.3 C for 1 hour; 100 F-degree hours equal 56 C-degree hours). A temperature of 70 F (21.1 C) for 2 hours thus will generate 10 F-degree hours (5.6 C-degree hours). Degree hours are accumulated each hour of the day until 3 consecutive days below 66 F (18.9 C) occur. The accumulation of degree hours is then reduced to zero. This empirical system is based on blossom monitoring experiences of epiphytic populations and field observations of locations of new infections. This monitoring showed that continuously cool weather below 66 F (18.9 C) may eliminate small epiphytic populations and reduce large populations already present in blossoms prior to the cool weather (32). By this reasoning, the bacteria initially colonize flowers in warm weather but decline during an intervening cool period of sufficient duration.

In England, Billing (3,4) studied the relationship between maximum and minimum temperatures and the potential doubling (PD) of the fire blight bacterium. With an average generation time of about 1.5 hour (12), PD may vary from one doubling at maximum temperature of 55 F (12.8 C) and minimum temperature of 50 F (10.0 C) to 12.5 doublings at 75 F (24 C) with a minimum of 60 F (15.6 C) or higher (Table 1). From this, Billing (4) concluded that 30 doublings were required for one bacterial cell to reach a population of 10^9 cells and that a minimum of 3 days were required to reach this total and complete an incubation period. Thus, three consecutive incubation periods may result in severe blossom blight. Billing (4) also devised a table of daily risks for spring blossom infection based on PD and precipitation. Conditions for high-risk days were proposed with a PD of 7–8 plus precipitation of 2.5 mm or more or a PD of 9 or more with any precipitation.

The Experience in Utah

An examination of the weather and monitoring results in 1985 and 1986 indicates why fire blight was serious in Utah County, Utah, in those years. A small amount of blight found in an orchard in 1984 may have been responsible for a high level of inoculum in 1985. The critical mean temperature (26) in 1985 was exceeded at the beginning of apple bloom. The period of bloom was generally warm, with 5 days exceeding the critical mean temperature during the bloom period. Epiphytic *E. amylovora* was detected during full bloom, and 3 high-risk days occurred during the bloom period. All of these conditions resulted in significant blight on every tree, with a few trees sustaining over 300 strikes. In 1986, the weather was also conducive for blight, with the critical mean temperature occurring and epiphytic bacteria detected during the main bloom period. Three high-risk days also occurred during that period. Blight was not as severe, however, probably because many of the spurs and flowers had been destroyed by fire blight and removed by pruning in 1985.

In Cache County, fire blight is not a major problem on pears. The bloom period is short, lasting only 1–2 weeks, and usually occurs at a time when temperatures are still quite low. Warm days are usually dry, and when rain occurs, the mean temperature usually drops below 62 F (16.7 C). Between 1979 and 1986, blight was observed on pears in only 1981 and 1983 and was significant in only 1981. In most years, the major bloom was complete before the daily mean temperature exceeded the prediction line (Fig. 3). Only a few blooms per tree remained available for epiphytic colonization or infection by the time the critical mean temperature was reached. In 1981 and 1983, blight occurred when the critical mean temperature was reached and epiphytic bacteria were present during the main bloom. In 1985,

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Table 2. Comparison of fire blight control on apple cultivar Rome Beauty in Utah County, Utah, using tree phenology (flower stage, 10% bloom), mean temperature (27), or high-risk days (4) as the indicator for initiating streptomycin[a] applications, 1984–1986

Basis of first application	Number of applications	Number of infections per tree
1984		
Flower stage	3	2.1
Mean temperature	3	2.5
High-risk days	2	6.1
Check	0	5.5
1985		
Flower stage	3	5.1
Mean temperature	3	3.2
High-risk days	3	6.6
Check	0	40.0
1986		
Flower stage	3	0.5
Mean temperature	2	0.7
High-risk days	2	7.2
Check	0	10.0

[a] Streptomycin sulfate (17%), 700 g in 935 L/ha.

Table 3. Comparison of fire blight control on pear cultivar Bartlett in three California counties, using monitoring,[a] mean temperature (27), or tree phenology (flower stage, 10% bloom) as the indicator for initiating streptomycin[b] applications, 1976

Basis of first application	Number of applications	Number of infections per tree[c]
Yolo County		
Flower stage	14	2.0 x
Mean temperature	6	4.0 x
Check	0	29.0 y
Santa Clara County		
Flower stage	16	1.0 x
Mean temperature	6	12.0 x
Detection	5	8.0 x
Check	0	50.0 y
Solano County		
Flower stage	7	1.6 x
Mean temperature	2	2.0 x
Detection	2	2.4 x
Check	0	7.6 x

[a] Detection of *Erwinia amylovora* in a sample of 100–200 pear flowers.
[b] Streptomycin sulfate (17%), 700 g in 935 L/ha.
[c] Means followed by different letters are significantly different at $P = 0.05$ according to Duncan's multiple range test. Each orchard was analyzed separately.

the growing season appeared to be an exception. The critical mean temperature was exceeded early in the bloom period, and the bacteria were detected in flowers during the main bloom. There were also 2 high-risk days during the bloom period, but blight did not occur on pears. Apple trees in the same orchards, however, sustained approximately two strikes per tree. In 1986, the critical mean temperature was exceeded during main bloom, and no epiphytic bacteria were detected on pear flowers during the season. There was also 1 high-risk day during bloom, but no blight developed.

In a commercial orchard in Utah County during 1983–1986, three methods of applying streptomycin sulfate were compared in 0.5-ha plots of the apple cultivar Rome. In the first method, applications were initiated at 10% bloom. In the second, treatments were initiated when the daily mean temperature exceeded the mean temperature line drawn from 62 F (16.7 C) at the beginning of flowering and dropping 1 F (0.5 C) every 15 days (Fig. 3). With both the first and second methods, subsequent sprays were applied at 5-day intervals. In the third method, treatments were given within 24 hours of high-risk days (4). (A high-risk day is one in which temperatures allow for sufficient potential doubling of the bacteria and rain occurs.) Streptomycin sulfate (17%) at 700 g/ha was applied to all plots by the grower with a concentrate sprayer using 935 L/ha of water. Control plots received no treatments and comprised five to 10 trees. Applications were discontinued in all plots at the same time. Flowers were monitored for the presence of epiphytic *E. amylovora* using techniques previously described (27), and infections were counted during July.

Fire blight was controlled on Rome apples by initiating applications when 10% bloom occurred and repeating applications about every 5 days during the bloom period. In most cases, the bloom lasted less than 2 weeks, and three applications were sufficient. The initiation of streptomycin applications based on mean temperature provided control equal to sprays based on flowering (Table 2). Spraying based on mean temperatures did not always result in an economic savings, since the same number of sprays was often necessary, but the mean temperature model did indicate years with high blight risk.

Sprays applied only after high-risk days did not provide control equal to those based on flower stage or mean temperature. In 2 of the 3 years, plots treated only after high-risk days occurred had substantially more blight. High-risk days may indicate a true high risk only if the critical mean temperature has been exceeded and epiphytic populations of bacteria are present. There were several high-risk days which occurred before the presence of epiphytic bacteria, and fire blight did not develop. Medium-risk days occurred so frequently that sprays based on such days would be too numerous and provide no savings, when compared with spraying based on tree phenology.

The Experience in California

Methods for determining when to initiate bactericide applications were compared in orchards of the pear cultivar Bartlett in different counties during 1976 and 1977. Each orchard was divided into three sections, and applications were initiated using one of three methods. In the first method, applications were begun at 10% bloom and continued every 5 days until flowering was complete. In the second method, treatment was initiated when the mean temperature exceeded the threshold mean temperature prediction line between 1 March and 1 May (Fig. 3). In the third method, treatment was initiated when fire blight bacteria were first detected in the flowers; treatments were applied as soon as possible after bacteria were detected, usually within 24 hours but occasionally within 48 hours.

Data from representative orchards indicated that fire blight control by the temperature prediction method was as good as the normal calendar program (sprays every 5 days from 10% bloom) in orchards where the first application of bactericide was delayed until the mean temperature in the orchard exceeded the 62–58 F (16.7–14.4 C) prediction line (Table 3). In 1976, the number of bactericide applications was reduced by more than 60% because mean threshold temperatures were exceeded late in the bloom period. The spring of 1977 was warm, however, and the mean temperature threshold was crossed early, resulting in a savings of only one or two applications. Delaying applications until detection of *E. amylovora* in flowers usually resulted in fewer applications, but occasionally at the expense of slightly higher levels of infection.

Use of the daily mean temperature to predict the need for bactericide applications usually results in more applications than use of the flower monitoring technique. However, the temperature technique is simple and inexpensive and can be accomplished by the grower with a recording thermograph or even with a maximum-minimum thermometer.

The percentage of healthy blossom samples that contained detectable *E. amylovora* was determined in two areas of California during 1972–1976 (34) and plotted as a function of accumulated degree hours above 65 F (18.3 C). A direct relationship was noted between the accumulated degree hours and the incidence of epiphytic *E. amylovora*. For example, no bacteria were detected at 0–100 F-degree hours, whereas at 600 F-degree hours, about 40% of the blossom samples contained *E. amylovora* (Fig. 4).

The relationship between fire blight

infections and environmental conditions was determined with data from the mid-Sacramento Valley during 1976–1986. Degree hours above 65 F (18.3 C) during periods with precipitation as well as during periods when the temperature was at least 57 F (13.9 C) and relative humidity (RH) was 90% were accumulated from early bloom through 15 days past full bloom. Full bloom was generally 25 March–1 April. Accumulations of infections were determined by recording the number of infections observed during a 30-minute visit per 10 ha of orchard through 31 May. There was a strong correlation of these degree hours with the incidence of random new fire blight per holdover infection (RNB/HO) counted during weekly visits to commercial orchards (Fig. 5). Although there is some linear correlation ($r = 0.63$) obtained by regression analysis of the RNB/HO occurrence in the field with the sum of accumulated degree hours coinciding *only* with measurable precipitation, the linear correlation is much higher ($r = 0.86$) when degree hour totals during precipitation are combined with degree hour totals during simultaneous 57 F (13.9 C) and 90% RH. Data for 10 of the 11 years (excluding 1986) show a high linear correlation ($r = 0.96$). In other words, blossom blight infections are randomly initiated by the epiphytic population when bacteria are present during warm weather accompanying precipitation and during warm, humid weather not accompanying precipitation. This has been a clearly observed situation in the field during some years (e.g., 1985) when new blight infections were found on blossoms before rain fell on them (Zoller, *unpublished*).

Summations of accumulated degree hours during early bloom through full bloom, early bloom through 15 days past full bloom, and early bloom through 30 days past full bloom were tabulated. Each of these was compared with random new blight and with RNB/HO as accumulated during the same weekly visits through 1 May, 15 May, and 31 May. The highest correlation was obtained using the coordinates of Figure 5. The correlation coefficient ($r = 0.86$) was significant ($P = 0.001$) for the 11 years of observations.

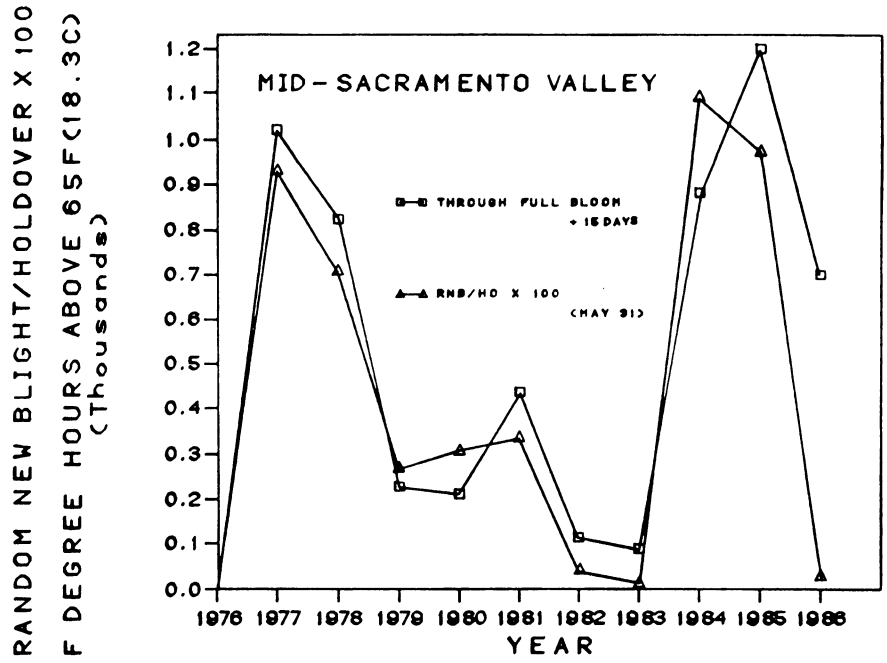

Fig. 5. Sum of accumulated degree hours above 65 F (18.3 C) coinciding with precipitation or simultaneous temperature of 57 F (13.9 C) and 90% relative humidity. Accumulated seasonal sum since last 3-day period with no temperature above 65 F and since the last day of precipitation or simultaneous 57 F and 90% RH conditions during the period early bloom through 15 days past full bloom. Random new blight/holdover (RNB/HO) counted in weekly visits to 100–240 ha of Bartlett pear orchards (30 min/10 ha/visit). Numbers are the accumulated total through 31 May.

Table 4. First incidence of fire blight on blossoms of 4-year-old apple trees at the Appalachian Fruit Research Station, May 1985

Cultivar	Trees planted (no.)	Trees with blossom blight (%)	Blighted blossoms (no.)
York	243	86.5	5,671
Golden Delicious	343	90.8	1,641
Stayman	296	83.3	2,851
Rome	116	79.5	578
McIntosh	144	72.9	832
Delicious			
Nonspur	315	46.4	1,338
Spur	344	27.4	130
Winter Banana	72	23.6	19

The Experience in West Virginia

The first apple and pear orchards were planted at the Appalachian Fruit Research Station (AFRS) in the fall of 1979, but it was not until the fall of 1984 that a few pear trees out of several thousand cultivar and seedling trees showed minor symptoms of fire blight. Commercial orchards with blight (some years quite severe) are located within 1.0–2.5 km to the north and northwest of the station. By May 1985, about a month after a week in April of optimum weather conditions for blight development, symptoms of blossom blight were noted in all of the apple blocks of the station (Table 4). Thus, in 3–5 years, the bacterium had spread rapidly and become established on the trees. This confirmed a similar observation in Michigan in 1975 (24).

In 1983, a cooperative research effort was initiated between the USDA (AFRS) and the states of West Virginia, Virginia, Maryland, and Pennsylvania (30) to devise a fire blight warning system based on the methodology developed in the western states and Great Britain. During 1984–1986, 50 orchards (two at AFRS and 12 in each state) were selected, on the basis of previous occurrences of fire blight, for intensive study. Weather data were collected from 1 March until 1 August. Pear and apple blossoms were tested for the presence of epiphtyic *E. amylovora* twice a week during April and May. A van was equipped to serve as a field laboratory for rinsing collected blossoms in plastic bags and pipetting samples of the rinse liquid onto culture plates containing selective media. Plates were returned daily to the AFRS laboratory and evaluated for bacterial colonies after an incubation period of 24–72 hours.

Fire blight risks, based on the various blight assessment schemes described earlier, were compared during the spring of 1984, 1985, and 1986 at Kearneysville, West Virginia, and are outlined in Figure

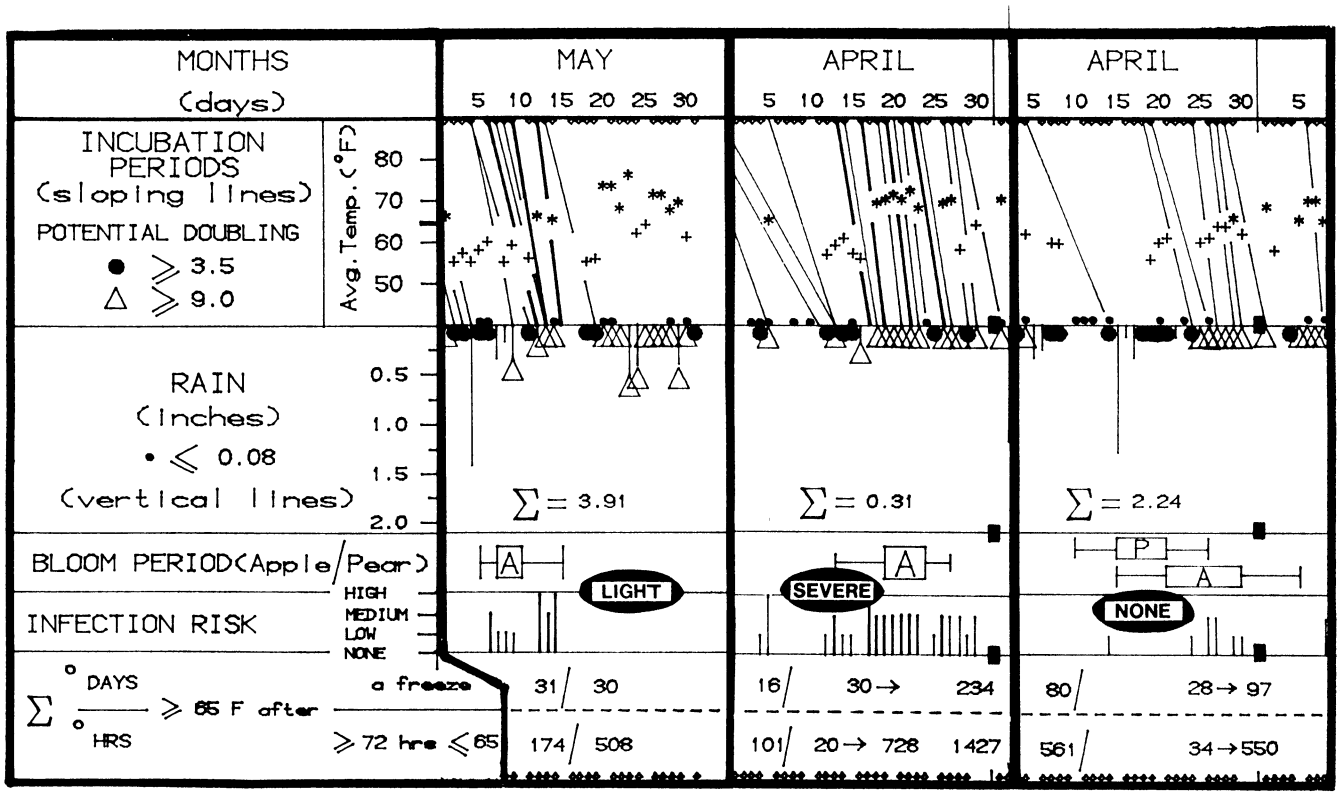

Fig. 6. Research model to determine the risk assessment for light (1984), severe (1985), and no (1986) fire blight for Kearneysville, West Virginia, based on climatological and phenological data collected, calculated, and assembled according to existing prediction systems (3,21,27,34). Incubation periods (sloping lines), starting on days with a minimum of 0.1 in. (2.5 mm) rainfall (downward vertical lines and small black dots above the line) and ending when a total of 30 potential doublings of the bacterium (black circles and white pyramids) are accumulated, usually correlate with days of low, medium, or high infection risk (upward vertical lines) shown directly below the bloom period. Average daily temperatures above 55 F (12.8 C) and 65 F (18.3 C) are indicated by plus signs and asterisks, respectively.

6. Data for the other three states generally fit the same pattern.

In 1984, temperatures just before and during bloom remained generally below 65 F (18.3 C) and 4 days of rainfall totaled 0.87 in. (23 mm). A total of 31 F-degree days (30 required by Powell's [21] definition) above 65 F were reached by 30 April, followed by generally cool (below 65 F) weather up to and during bloom. According to the Zoller (34) temperature system, 189 F-degree hours were reached by 30 April and a new count of 174 F-degree hours was reached by petal fall. Even though there were 2 potential days with high infection risk during bloom, the number of potential doublings of *E. amylovora* was insufficient (30 required by Billing [4]) to initiate blossom blight. These data closely coincided with the near lack of *E. amylovora* colonies from the sampled flowers on the selective culture media. All risk assessment systems indicated 1984 to be a very *LIGHT* blight year. Only a few blight strikes occurred in the pears and none in the apples.

In 1985, maximum temperatures during full bloom were in the 80s (average about 70 F) for 6 consecutive days. No rainfall occurred during this period, and total rainfall for April was only 0.31 in. (8 mm). A total of 41 degree days (152 degree hours) above 65 F were reached by 30 March, another 16 (101 degree hours) by 5 April, and 30 more by 16 April. A total of 728 degree hours were reached by full bloom, with the final total of 1,427 hours reached soon after petal fall. The Billing (4) system conclusively showed 9 medium- to high-risk days, even in the absence of rain. *E. amylovora* was recovered throughout the full bloom season, and all risk assessment systems indicated 1985 to be a *SEVERE* blight year, which it certainly proved to be.

In 1986, the bloom period for Kearneysville was 10–25 April for pears and 15 April–5 May for apples. Temperatures during full bloom of both hosts were under 55 F (12.8 C). Even though 80 degree days (561 F-degree hours) were accumulated by 8 April (before bloom), similar accumulations (550 degree hours) were not reached again until 30 April, well past full bloom for both pears and apples. *E. amylovora* was recovered just before apple bloom and during petal fall but not during the cool weather during full bloom periods of pears or apples. There were no high-risk days, and no blossom blight was observed on pears and only occasional blight strikes on the susceptible apple cultivars York and Red Rome, resulting from infection of late blossoms.

Conclusions

Development of the epiphytic population in pear and apple flowers in spring is a phenomenon that can be used to predict fire blight outbreaks. Monitoring studies in California have shown that the mean temperature threshold near 60 F (15.6 C) has some value in predicting the presence of epiphytic *E. amylovora* in pear flowers (27,32,33). In practice, the mean temperature threshold does not reliably predict infection periods. However, in some years in California, use of this threshold delayed initiation of needed treatments or, conversely, when the threshold was crossed early, suggested application of bactericides before such treatments were necessary. Use of the mean temperature threshold system is all or none, yielding no information about the magnitude of the fire blight risk and therefore the frequency of necessary treatments. Over the past 11 years, some orchardists and advisors in California have replaced the mean temperature threshold with a degree hour system for predicting the blossom population (32,33).

The exceptional year, 1986, in which far less new blight was initiated than predicted by accumulated degree hours coinciding with measurable precipitation or simultaneous warm, humid conditions, shows there are still unknown factors that influence the epiphytic populations of *E. amylovora* in the Sacramento Valley. Additionally, monitoring experiences in Lake County, a climatically distinct and less blight-prone pear district, have suggested that more accumulated heat is necessary in this district than in the Sacramento Valley to generate detectable *E. amylovora* in blossoms. However, populations may be more prevalent in the Lake County district than in the Sacramento Valley at higher degree hour accumulations (Fig. 4). These differences suggest that, as different geographical areas are studied, factors other than temperature may result in an array of kinetic expressions relating temperature to epiphytic population development.

All experiences with utilizing the degree hour system in California since 1976 have shown agreement with it or, at worst, have shown the system to be conservative in predictive ability (such as in Lake County or during the exceptional year, 1986, in the Sacramento Valley). Applications of bactericides become more crucial as the number of degree hours increases. Growers must protect orchards within the 24 hours before precipitation or warm, humid conditions when degree hours have accumulated in excess of 150 and constitute a threat. Applications are not necessary when weather has been cool enough so that no degree hours have accumulated over 65 F, even if rain occurs. Treatments should be made within the 24 hours preceding rain in the Sacramento Valley when 1–150 F-degree hours (0.5–84 C-degree hours) have accumulated. Treatments missed in this period will result in new infections near inoculum sources. Treatments are suggested every 3–4 days when accumulations exceed 150 F-degree hours (84 C-degree hours) because the epiphytic population is predicted to be so prevalent that failure to treat within the 24-hour period before fire-blight conducive weather will result in more serious numbers of new infections more randomly distributed in orchards. Alternate-day treatments are recommended in the Sacramento Valley if F-degree hours surpass 500 (280 C-degree hours) in conjunction with major bloom periods. If the orchard is being irrigated, the humidity threshold is reduced to simultaneous 57 F (13.9 C) plus 80% RH, as measured outside the orchard. The accumulated degree hour total is not reduced by continuous cool temperatures below 66 F (19 C) if the total surpasses 400 F-degree hours (224 C-degree hours) and has coincided with precipitation or warm, humid infection periods of at least 57 F (13.9 C) and 90% RH. Use of these treatment guidelines in commercial orchards in the Sacramento Valley during the past 11 years has resulted in improved control of blight. Even with this method, however, the incidence of fire blight is 10 times greater in years when accumulated degree hours coinciding with infection periods approach 600 than in years with only 100 accumulated F-degree hours (Fig. 5). The elimination of holdover inoculum sources by careful pruning is still a valuable management tool that cannot be overlooked.

In Utah, the mean temperature model does not attempt to indicate when fire blight will occur. The model's value appears to be in determining when epiphytic *E. amylovora* is likely to be present in flowers. In California and Utah, initiating bactericide applications after the daily mean temperature exceeds the threshold mean temperature prediction line has been shown to protect against fire blight as much as spraying during the entire bloom period.

This mean temperature threshold system has been successfully used in Utah for 3 years. Temperatures and precipitation in representative orchards are assessed daily by computer and evaluated for the potential fire blight risk. When environmental conditions are conducive for disease, a fire blight warning is issued to growers via a Code-a-Phone and through the National Weather Radio Service. Growers who have followed the recommendations have not had serious blight outbreaks, whereas other growers have sustained significant losses with blight.

In the Appalachian region, observations during 1984–1986 provided three distinct climatic conditions during bloom of apple and pear to assess the fire blight risk systems. The following conclusions were made: 1) Temperatures below 65 F during bloom (1984, 1986) resulted in little or no blossom blight, even with rainfall; 2) temperatures between 65 and 85 F (av. 70 F) during bloom (1985), combined with no rainfall, resulted in severe blossom blight; 3) the Zoller (33,34) degree hour prediction system proved considerably more accurate than the Powell (21) degree day system in forecasting blossom blight; and 4) calculations of Billing's (3,4) potential infection days, based on potential doubling of *E. amylovora*, showed a close correlation with the two temperature systems. The recent revision of Billing's PD table by Schouten (23) considerably increases the number of potential doublings between 55 and 65 F (12.8 and 18.3 C), thus shortening the incubation period and effecting an even closer correlation with the temperature systems.

It is of interest that artificial inoculations of pear blossoms with *E. amylovora* during full bloom in 1986 in West Virginia resulted in severe blossom blight, whereas no natural blight was recorded that year. Because of the usual fluctuating temperatures, we have not been able to determine a general mean temperature line for blossom blight prediction in the Kearneysville area. The mean temperature line of 62–58 F (16.7–14.4 C) between 1 March and 1 May, established in California and modified to start at first flowering of pears in Utah, appears applicable 1 month later (1 April–1 June) for the Appalachian fruit-growing region. Apple orchards that were sprayed in 1985, especially those with the cultivars York, Jonathan, or Rome Beauty, experienced considerably less fire blight than orchards that were not sprayed or were sprayed after blossom blight symptoms appeared.

An effective predictive system must be able to adequately explain historical fire blight epidemics as well as predict when to apply bactericides to provide protective control. The predictive abilities of most published "predictive" systems have not been verified in tests conducted to demonstrate fire blight control. The mean temperature model has been effective in determining when to apply bactericides in numerous control tests over 10 years and in three geographical locations (7,27). The model is quite conservative, however, and applications are probably made in excess. In some years, the model indicates that sprays are advised but fire blight does not occur. This suggests that other factors may eventually be found that will improve the model and make it more accurate. Therefore, until a universal predictive system is developed, it still appears that the most conservative control of fire blight is to apply streptomycin sprays several times during bloom when maximum temperatures are above 65 F, especially when accompanied by rain or high humidity.

Literature Cited

1. Baldwin, C. H., and Goodman, R. N. 1963. Prevalence of *Erwinia amylovora* in apple buds as detected by phage typing. Phytopathology 53:1299-1303.
2. Beer, S. V., and Opgenorth, D. C. 1976. *Erwinia amylovora* on fire blight canker surfaces and blossoms in relation to disease occurrence. Phytopathology 66:317-322.
3. Billing, E. 1980. Fire blight in Kent, England in relation to weather (1955–1976). Ann. Appl. Biol. 95:341-364.
4. Billing, E. 1980. Fire blight (*Erwinia amylovora*) and weather: A comparison of warning systems. Ann. Appl. Biol. 95:365-377.
5. Bonn, W. G. 1981. Monitoring of epiphytic *Erwinia amylovora* and the incidence of fire blight of apple and pear in southwestern Ontario. Acta Hortic. 117:31-36.
6. Brulez, W., and Zeller, W. 1981. Seasonal changes of epiphytic *Erwinia amylovora*

on ornamentals in relation to weather conditions and the course of infection. Acta Hortic. 117:37-43.
7. Covey, R. P. 1981. Feasibility of using mean orchard temperature for timing pear fire blight spray in Washington. (Abstr.) Phytopathology 71:104.
8. Crosse, J. E., and Goodman, R. N. 1973. A selective medium for and a definitive colony characteristic of *Erwinia amylovora*. Phytopathology 63:1425-1426.
9. Dueck, J., and Morand, J. B. 1975. Seasonal changes in the epiphytic population of *Erwinia amylovora* on apple and pear. Can. J. Plant Sci. 55:1007-1012.
10. Goodman, R. N., and White, J. A. 1981. Xylem parenchyma plasmolysis and vessel wall disorientation caused by *Erwinia amylovora*. Phytopathology 71:844-852.
11. Hildebrand, E. M. 1937. The blossom-blight phase of fire blight and methods of control. N.Y. Agric. Exp. Stn. Cornell Mem. 207. 40 pp.
12. Hildebrand, E. M. 1937. Infectivity of the fire blight organism. Phytopathology 27:850-852.
13. Ishimaru, C., and Klos, E. J. 1984. New medium for detecting *Erwinia amylovora* and its use in epidemiological studies. Phytopathology 74:1342-1345.
14. Keil, H. L., and van der Zwet, T. 1972. Recovery of *Erwinia amylovora* from symptomless stems and shoots of Jonathan apple and Bartlett pear trees. Phytopathology 62:39-42.
15. Keil, H. L., and van der Zwet, T. 1972. Aerial strands of *Erwinia amylovora*: Structure and enhanced production by pesticide oil. Phytopathology 62:335-361.
16. Luepschen, N. S., Parker, K. G., and Mills, W. D. 1961. Five year study of fire blight blossom infection and its control in New York. N.Y. Agric. Exp. Stn. Cornell Bull. 963. 19 pp.
17. Miller, T. D., and Schroth, M. N. 1972. Monitoring the epiphytic population of *Erwinia amylovora* on pear with a selective medium. Phytopathology 62:1175-1182.
18. Miller, H. J., and van Diepen, H. 1978. Monitoring of epiphytic populations of *Erwinia amylovora* in The Netherlands. Acta Hortic. 86:57-63.
19. Mills, W. D. 1955. Fire blight development on apple in western New York. Plant Dis. Rep. 39:206-207.
20. Norelli, J. L., and Beer, S. V. 1984. Factors affecting the development of fire blight blossom infections. Acta Hortic. 151:37-39.
21. Powell, D. 1965. Factors influencing the severity of fire blight infections on apple and pear. Mich. State Hortic. Soc. Annu. Meet. 94:1-7.
22. Rosen, H. R. 1936. Mode of penetration and of progressive invasion of fire blight bacteria into apple and pear blossoms. Arkansas Agric. Exp. Stn. Bull. 331. 68 pp.
23. Schouten, H. J. 1987. A revision of Billing's potential doublings table for fire blight prediction. Neth. J. Plant Pathol. 93:55-60.
24. Sutton, T. B., and Jones, A. L. 1975. Monitoring *Erwinia amylovora* populations on apple in relation to disease incidence. Phytopathology 65:1009-1012.
25. Thomson, S. V. 1986. The role of the stigma in fire blight infections. Phytopathology 76:476-482.
26. Thomson, S. V., Schroth, M. N., Moller, W. J., and Reil, W. O. 1975. Occurrence of fire blight of pears in relation to weather and epiphytic populations of *Erwinia amylovora*. Phytopathology 65:353-358.
27. Thomson, S. V., Schroth, M. N., Moller, W. J., and Reil, W. O. 1982. A forecasting model for fire blight of pear. Plant Dis. 66:576-579.
28. van der Zwet, T. 1969. Study of fire blight cankers and associated bacteria in pear. Phytopathology 59:607-613.
29. van der Zwet, T., and Keil, H. L. 1979. Fire blight—a bacterial disease of rosaceous plants. U.S. Dep. Agric. Handb. 510. 200 pp.
30. van der Zwet, T., Steiner, P., Barrat, J. G., Hickey, K. D., and Yoder, K. S. 1987. Development of a blossom blight prediction system for the Appalachian fruit growing region. Acta Hortic. 217:125-132.
31. van der Zwet, T., and Van Buskirk, P. D. 1984. Detection of endophytic and epiphytic *Erwinia amylovora* in various pear and apple tissues. Acta Hortic. 151:69-77.
32. Zoller, B. G. 1978. Trends in integrated pear insect pest management and *Erwinia amylovora* fire blight control in California. Oreg. Hortic. Soc. Proc. 69:57-71.
33. Zoller, B. G. 1985. Predicting epiphytic populations of *Erwinia amylovora* in California pear orchards. Assoc. Appl. Insect Ecol. Newsl. 5(1):6-7, 5(2):10-11.
34. Zoller, B. G., and Sisevich, J. 1979. Blossom populations of *Erwinia amylovora* in pear orchards vs. accumulated degree hours over 18.3 Celsius, 1972–1976. (Abstr.) Phytopathology 69:1050.