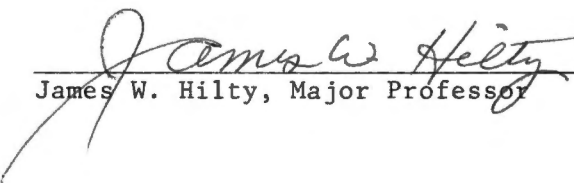


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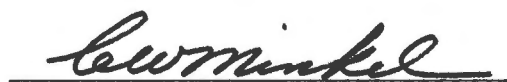

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FORECASTING OF EARLY BLIGHT ON TOMATOES FOR
MORE EFFICIENT CHEMICAL CONTROL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Joseph W. Williamson

June 1985

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Thesis

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ACKNOWLEDGMENTS

The author would like to express his sincere appreciation to Dr. James W. Hilty, his major professor, for encouragement, suggestions, friendship, and for partial funding of this research. Appreciation is also extended to Dr. Carroll J. Southards and Dr. Charles H. Hadden for their critique of this thesis, and for providing financial support for the author through the position of Plant Disease Diagnostician.

The author gratefully acknowledges the advice and counsel provided for data analyses by Don Broach, Senior Computer Consultant. Thanks are also extended to Dr. S. P. Pennypacker of Pennsylvania State University for granting permission to include tabular data and information necessary for the completion of this manuscript.

The author would like to thank his family and friends for their support, and especially his fiancée, Margaret Ragan, for her continuous encouragement during the writing of this thesis.

ABSTRACT

The forecasting system for *Alternaria solani* on tomatoes (FAST) was employed to determine if more efficient chemical control of early blight could be obtained on staked tomatoes in Tennessee. A comparison of three spray regimens based on the FAST method was made with the spray program currently recommended by the University of Tennessee Agricultural Cooperative Extension Service.

The combination of two forecasting models based on: the daily ambient temperature, rainfall, the daily period of relative humidity greater than 90%, the daily leaf wetness period, and the ambient temperature during the leaf wetness period, was used to determine an efficient spray schedule. Counts of air-borne conidia of *Alternaria solani* were also made for comparison to the timing of disease outbreak and increase.

During 1980 the best early blight control was achieved by the use of the recommended 5-day spray interval method (26 sprays). Disease control by the 7-day interval method (18 sprays) was significantly less efficient, but not different in disease controlling ability from that of two of the FAST-generated spray regimens (17 and 5 sprays, respectively). However, during 1983 the most frequently sprayed FAST-generated regimen (18 sprays) did provide disease control significantly greater than control by the 5- and 7-day spray interval methods (22 and 19 sprays, respectively), and a less often sprayed FAST-generated spray regimen (15 sprays).

With a modification of the environmental requirements which designate the spray schedule to better fit favorable conditions for disease outbreak, improved control could be possible. The quantities of air-borne conidia can help determine the timing for initial spray applications, but not subsequent sprays.

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CHAPTER I

INTRODUCTION

Early blight, caused by the fungal pathogen *Alternaria solani* (Ellis & Martin) Jones & Grout (21, 31), is one of the most destructive diseases of tomato, *Lycopersicon esculentum* Miller. The disease syndrome consists of collar rot of the seedlings, stem-end rot of the fruit, and target spot of the foliage and stems (1, 17, 36, 58). Seedling death due to stem girdling can result if the collar rot stage occurs. Defoliation of mature plants results if the disease is uncontrolled, which can cause significant yield and fruit quality reduction (12). The distribution of *A. solani* is world-wide with early blight being a very destructive disease in many countries (9, 14, 17, 52, 58, 81). Early blight appears to be more serious in the eastern United States, with the southeastern states reporting it to be the most limiting factor of trellised tomato production (1, 34, 39, 51, 52, 75).

Tomatoes are the leading cash value fresh market vegetable crop for Tennessee (3, 4). During recent years approximately 4500 acres per year have been under cultivation, with a value ranging from \$8.4 to 12.4 million (3). Commercially, in the United States, tomatoes are second in value only to lettuce for fresh market vegetables (4).

The present study was made to determine if more efficient chemical control of early blight could be obtained by forecasting based on various environmental parameters, than by following the recommended spray program for Tennessee. Three weather-determined spray regimens

were based on FAST: a forecast system for *Alternaria solani* on tomato developed by Madden and his co-workers (49). These FAST-generated spray regimens were compared to the recommended spray program by the Tennessee Cooperative Agricultural Extension Service (24).

CHAPTER II

LITERATURE REVIEW

The Influence of Environmental Parameters on Phases
of Life Cycle of *Alternaria solani*

Limiting Factors for Infection.

Factors affecting a pathogen's life cycle must be understood in order to forecast an epiphytotic.

Humidity.

Moore (54) stated that humidity is the principal limiting factor for infection, and the number of hours per day that the air is near saturation is most important for determining infection periods. The saturation point is the most important parameter for germination of conidia, but for subsequent ingress, a leaf-wetting must occur either by rainfall, overhead irrigation, or dew resulting from high relative humidity (46). Hodosy (27) found that at 96% relative humidity and 15-20 C, germination can take place in 1 to 2 hours, and ingress within 8 hours. Rands (58) also found that at 20 C the conidia can germinate in 1 to 2 hours with 5 to 10 germ tubes produced per conidium. Waggoner and Horsfall (84) determined that relative humidities greater than 83% will promote germination, and if followed by a few hours of leaf-wetting, infection can be ensured before drying could kill the germinated conidium. If the conidia germinate in a film of water, and the foliage dries before ingress occurs, the conidia may die. However, conidia that

germinate in humid air can survive subsequent arid conditions prior to ingress. Warm and cloudy conditions promote successful infections, as the foliage dries more slowly.

Dew.

The most important parameter enabling early blight development in arid regions is observed to be the dew (27, 61, 62). Rotem (62) determined that a relative humidity level of 96% is needed for germination, and levels rarely exceed 90% in Israel. The outer foliage of tomato plants tend to lose heat at night, through long-wave radiation emission, with the result that they become cooler than the air. The air surrounding the leaves then becomes cooler than the free air, and condensation, or dew, forms. Rotem (62) observed that dew forms on outer foliage despite atmospheric moisture being below the saturation point, and found significantly more disease on plants exposed to dew than on plants that were covered at night to prevent condensation.

Temperature.

Although ingress can result at all field temperatures, provided the foliage is sufficiently moist, there was found to be an abrupt increase in leaf-spot infections at and above 60 F (46). The temperature is not as important as the relative humidity or leaf-wetness for germination, but once the fungus is within the moist tissues of the host, the temperature becomes the most important factor (83). The optimum temperature for hyphal growth is 28 C, the minimum is 1-3 C, and the maximum is 37-45 C (46, 58, 61).

Ingress and Incubation.

Ingress can be through stomata or directly through the cuticle of stems and foliage, with younger leaves as easily infected as older ones (17, 29, 58). However, younger leaves possess a higher hexose content than do older leaves, and these sugars inhibit the destructive action of the pectinolytic and cellulolytic enzymes of *Alternaria solani*. In younger leaves enzymes are not needed to provide the sugar supply required by the pathogen, and as a consequence, damage to these leaves is reduced or delayed (7, 64, 66). As older leaves senesce, sugars are transported to newly developing plant parts, and an increased transport of sugars from fully expanded leaves begins at fruit set (64). The disease susceptibility of the plants increases as the load of fruit rises. Rowell (64) noted that the disease intensity is inversely related to the hexose level in the foliage.

Van der Plank (79) called the incubation period the "important slower of epidemics", since more time is required for incubation than for active infection, which includes symptom expression and sporulation. The incubation period during favorable climatic conditions takes 48 to 72 hours before the manifestation of lesions on older foliage.

Sporulation.

Sporulation can begin once the lesions are 3-4 mm in diameter, and consists of two distinct phases: conidiophore and conidium formation (10, 58, 84). The conidiophore formation is actually an extension of vegetative growth (29). Cool, moist conditions from frequent rainfall

and/or heavy dew are needed for optimum sporulation. Dry periods will decrease, but not stop the formation of conidiophores. However, when the substrate becomes dry, spore production is temporarily halted. Rainfall can also be detrimental to the propagation of *A. solani*. Waggoner and Horsfall (84) determined that 2/3 inch of rainfall decreases sporulation by one third on previously produced conidiophores. Following the rainfall, sporulation rapidly increases on new conidiophores produced due to the wet conditions. The temperatures for conidiophore and production of conidia are 22-24 C and 19-23 C, respectively, with maximum temperatures for production at 32 and 27 C, respectively (84).

Dissemination.

The timing of wet and dry periods is important in the life cycle of *A. solani* (84). Wet conditions aid *A. solani* in most steps of its life cycle, but dry conditions with brisk winds are more conducive for dissemination of the conidia. Air currents are the most important means of dissemination because the conidia are produced in a dry (xerosporus) manner (17, 58, 83, 84). Each conidiophore is capable of 2 or 3 crops of spores, resulting in the production of 1500-3000 spores per lesion during the season (58). Sporulation generally occurs in equal abundance on both leaf surfaces. Approximately 1/4 inch of rainfall will remove 99% of the conidia from tomato foliage, and in conjunction with wind, rain can splash conidia to additional susceptible plant tissue (84). The settling out and attachment of air-borne conidia are influenced by wind velocity, size of the conidia, leaf width, and wetness of the

foliage. Increased wind speed improves foliar attachment for larger conidia, such as those of *A. solani* (23, 83). Rainfall brings to ground many air-borne conidia, and then splashes them up from the ground onto lower portions of the plants. Overhead irrigation can act in a similar manner (58, 84).

Overwintering.

In the temperate regions primary fungal inoculum results from overwintered resistant forms, sheltered or dormant forms within host debris, or annual renewal from the tropics (83). Conidia and mycelium of *A. solani* are extremely resistant to heat and drought, and are capable of maintaining viability within host debris up to 18 months (58). Rotem (60) found that mycelium is more resistant to adverse conditions than conidia. In 1971 Basu (11) discovered the existence of chlamydospores in "curly type" mycelium, and a similar thickening within conidia. The chlamydospores were capable of overwintering not only within buried host debris, but survived for 7 months in soil without host tissue association. Rands (58) found that 10% of 17 month-old conidia retain viability *in vitro*. This longevity is probably due to chlamydospore formation.

Predisposition to Infection by Stress and Cultural Practices

Factors Promoting Stress.

Tomato plants can be predisposed to early blight by stressful climatic, soil, and cultural conditions, and by other pathogens which

result in a reduction of physiological vigor (8, 17, 25, 27, 30, 51, 52, 54, 58, 61, 64, 77, 85).

Temperature and Soil Moisture.

Heat and drought during summer months can create sufficient stress to increase active infection in tomato plants (58). Under these conditions, the respiration rate of the plants is increased, causing a drop in the foliar sugar content. This drop will promote symptom expression of early blight. The transpiration rate is also increased by heat and drought, with a further increase due to infection by *A. solani* (14).

Soil Fertility.

Mineral nutrition can play a role in the susceptibility of tomato plants to early blight, and many factors and their interactions determine to what degree the mineral nutrients affect disease severity (8, 17, 30, 52, 58, 77). The form and solubility of minerals, soil pH, temperature, aeration, moisture, microbial associations, competition by weeds, and the crop sequence can influence the host-pathogen interaction (30). Walker concluded that high fertility lessens the disease severity (85). Plants exhibiting moderate resistance or tolerance appear to be more influenced by changes in nutritional levels than highly susceptible or highly resistant plants. McCarter (51) reported that with excessive rainfall, leaching of soluble nutrients may occur, stressing plants and increasing susceptibility to early blight. Huber (30) reported that high levels of phosphorus (P),

potassium (K), or magnesium (Mg) depress infection by *A. solani*, and nitrogen (N) and calcium (Ca) levels may either increase or decrease infection in tomatoes. Thomas (77) found that the least number of leaf spots and defoliation occurs with high levels of N and P, and all levels of K. Both Thomas (77) and Barksdale (7) related increased early blight with the use of high N, low P, and medium to high levels of K. With dry conditions, damage to the foliage can be compounded by soluble salts from fertilization.

Other Cultural Practices.

Cultural practices such as type of irrigation used, mulching, plant spacing, direction of planting, and trellising can influence early blight development by affecting leaf wetness, relative humidity, and dissemination. Overhead irrigation aids in splash dissemination, and creates conditions for increased infection by causing leaf-wetness and raised relative humidity levels (25, 61, 84). However, adequate irrigation during dry periods, and the use of plastic or organic mulch can reduce stress. Mulching can delay disease development of early blight by covering the soil at the base of the plants which prevents the splashing of conidia onto lower foliage by rainfall and irrigation (33). Staked tomato plantings and less dense plantings will have greater aeration, resulting in more rapid drying of the foliage from rain and dew, and lower relative humidity within the canopy (61). Northern slopes and level areas will tend to have more dew than southern slopes (61).

Crop rotation can reduce the primary inoculum of *A. solani*, as conidia and mycelium overwinter in turned-under crop debris (11, 36, 58, 59). At the end of the growing season all crop debris should be removed and any remaining pieces immediately plowed under (11, 58). Damp soil will promote more rapid decomposition of any debris which decreases the overwintering ability of *A. solani* (60). Therefore, the use of post-season overhead irrigation to dampen dry soil can be advantageous. Volunteer tomato plants nearby should be destroyed to further reduce primary inoculum (36). Transplants should be disease free, and a high-phosphate starter fertilizer employed when transplanting into the field (1, 36). The soil pH should be adjusted and plant vigor maintained with adequate preplant and monthly fertilization (36, 52, 77). The use of more resistant cultivars can be one of the most important defenses against early blight (7, 8, 9, 86).

Chemical Control of Early Blight

Soil Fumigation.

In 1974 Basu (13) found that a fall application of methyl isothiocyanate (Vorlex®) at the rate of 50 gallons per acre can reduce the defoliation due to primary inoculum as much as 74%, as compared with the untreated control. McCarter and co-workers (51) tested several general purpose fumigants and found that all reduce disease incidence while increasing the vigor of the tomato plants. They determined that root growth and health to be highly correlated to the vigor of the above ground parts, and the reduction of soil-borne fungi and nematodes allows for the increased root quality. Their conclusion was that the reduction

of any stress to the plants will reduce the susceptibility to *A. solani*. The most improved plant vigor and least early blight incidence came from the use of sodium methyl dithiocarbamate (Vapam®) applied at 748 liters per hectare. In addition to the reduction of stress caused by soil-borne fungi and nematodes, the fumigants probably destroy a considerable portion of the conidia, mycelium and chlamydospores of *A. solani* residing in the turned-under host debris.

Foliar Applied Fungicides.

To obtain the most efficient control of early blight, many different fungicides have been employed. The rates of their active ingredients have been varied, and the time intervals between sprays have been maximized. In descending order of prevalence, the best chemical control of early blight by researchers in several states has been obtained by the use of chlorothalonil (Bravo 500®), mancozeb (Dithane M-45®), captafol (Difolatan 4F®), and anilazine (Dyrene 50W®). In many cases, higher than standard rates of active ingredients have been used with less frequent spraying to obtain adequate control (6, 37, 40, 41, 42, 43, 44, 45, 47, 53, 56, 63, 67, 68, 69, 71, 72, 73, 74, 76).

The persistence of the fungicidal residue on the plant is important to know for determining the spray schedule. Neely (55) found that the persistence of fungicides applied to foliage varies tremendously with the different fungicides and hosts. His tests list the average persistence of anilazine (Dyrene), chlorothalonil (Daconil 2787®), and captafol (Difolatan) to be 1.8, 2.8, and 5.6 weeks, respectively. These measurements are the averages for 12 hosts for which he found

persistence best correlated with the amount of pubescence on the foliage. Neely did not find rainfall to be correlated with fungicide removal from the plants.

Lukens and Ou (39) also found in tests with chlorothalonil (Bravo 6F®) that the loss of fungicide residue did not coincide with rainfall. The loss of residue and protection was directly related only to time in their test for persistence. It was observed that protection exists for 11 days on the upper and middle leaves of tomato plants and for 13 days on the lower leaves, with protection defined as a 50+% inhibition of appresoria of *A. solani*.

Persistence may vary with the formulation of a fungicide, and in the two previous tests, the chlorothalonil containing products were Daconil 2787 and Bravo 6F. Troiano and Butterfield (78) found that rainfall is an important factor in residue loss of the fungicide with the use of Bravo 500. With a rainfall rate of 1 centimeter per hour, the residue percentage remaining on foliage is 57, 54, and 45%, after 15, 30, and 60 minutes, respectively.

Large (38) designated the beginning of a disease progression curve at the point at which 0.1% of the foliage is blighted. He observed that if a fungicide treatment is applied prior to the 0.1% level of disease, a delayed progress curve results with a disease increase often parallel to that of the unsprayed control (Figure 1).

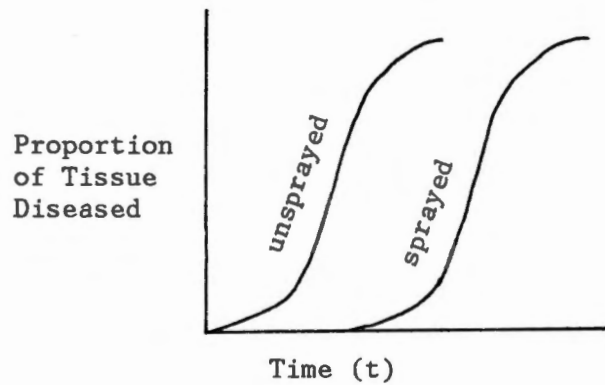


Figure 1. A typical early blight disease curve for unsprayed tomatoes and for those sprayed prior to the 0.1% level of disease.

However, if the initial spray program begins following the disease outbreak ($>0.1\%$), the disease increase starts simultaneously with that of the unsprayed control, and increases from that point at a less rapid rate (Figure 2).

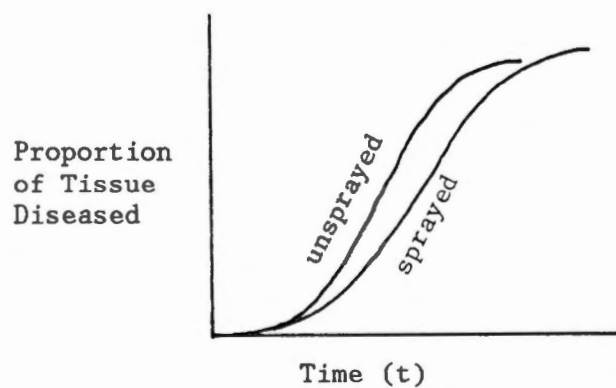


Figure 2. A typical early blight disease curve for unsprayed tomatoes and for those sprayed following the 0.1% level of disease.

Large (38) concluded that in Figure 2 the timing of the spray was too late to adequately control and delay mass infection, and could only lessen the rate at which disease increased. He also added that the entire spray program may fail if the initial application is delayed until the disease level is greater than 0.1%. The significance between spraying before and spraying following this initial outbreak, is that the former may prolong the growth period before the disease level is reached where yields are reduced. However, yields cannot be increased by even a properly timed spray program if the disease occurs too late during the growing period to significantly affect the yield.

Disease Forecasting

Requirements of a Forecast System.

Forecasting is a prediction of disease outbreak with an indirect prediction of yield (83). A forecast system is based on the understanding of 1) host susceptibility, with any predisposition to disease, 2) the environmental factors conducive to disease production, and 3) the requirements of the pathogen to cause disease, whether or not they are fulfilled (81, 83). The application of the protectants are timed to correspond with conditions favorable to disease buildup, so that fewer or less frequent applications can provide the same disease control as do regular-interval spray programs.

The usefulness of disease forecasting is determined by the accuracy or reliability of the forecast, the existence of adequate control, the benefit of control to cost-of-remedy ratio, and the speed and convenience of remedy application. Forecasting can be beneficial if the

disease occurrence varies in intensity from year to year, or if the timing of the initial yearly infection varies.

Several factors must be considered before farmers can employ a wait-until-warning spray program. The farmer must have enough labor and equipment to quickly and adequately apply the chemical protectant to the acreage, and the farm organization must not slow down the decision to begin treating upon receipt of a warning (83). The most important factor to be considered by the farmer is the risk of not treating versus the benefit and cost of doing so (70).

The reliability of a forecast system must be such that all serious outbreaks are forewarned. A few false alarms can be tolerated as long as no failures to forecast a major outbreak occur (70, 75). The success of any forecast system is based on the conditions that data is up-to-date and correct, the protectant applications are properly timed, and spray coverage is adequate.

Categories of Forecasting Systems, and Mathematical Modelling.

Populations of foliar pathogens can be measured directly by assessing the proportion of host material diseased, or directly by assaying the air-borne inoculum level. However, the quantities of the latter can be capricious, and are not necessarily directly related to the disease severity (5). Forecasting based upon inoculum potential, i.e., the inoculum density with propagules possessing a certain vigor and virulence, has the underlying assumption that the environmental conditions are favorable for disease development. The more unfavorable the weather for disease development, the greater the error of the forecast (70).

Basing the forecasting system entirely upon the weather assumes that the inoculum potential develops to a level for severe disease outbreak during the season. This may or may not be a safe assumption. For the highest reliability, a forecast system must consider and integrate the pathogen, the host, and the weather with a time factor (70).

Epidemic systems can be represented by abstract mathematical descriptions for an improved forecasting ability. These mathematical models may simply be descriptions of the disease progress curves. They may be predictive models based on regression equations, where the dependent variable is the disease proportion, and the independent variables are environmental parameters. Or they may be conceptual models that account for as many host, pathogen, and environmental interactions as possible. Some of the conceptual models have been transformed into computer-written, disease cycle simulators, for more rapid decision making guidelines (50).

Models can be classified under the categories of holistic or systems analytic. Holistic models deal with the epidemic more as a whole. They rely on average responses, and assume that environmental factors will always have the same effect on disease progression. These models are easier and less time consuming to develop and utilize, but are less sensitive to environmental changes. They are also unable to account for the dependence of some event on the prior occurrence of another event. The better holistic approaches to forecasting use multiple regression analysis, as this provides a more adaptive model (70).

Systems analytic models break the epidemic system into individual parts and account for variability in each. Single external factors can

exert varying or even opposite affects on disease progression, and this is something for which holistic models cannot account. The appropriately constructed systems analytic model is more capable of being adjusted to changes in host cultivar, the use of different chemicals for control, and variations in the pathogen. Changes can be incorporated in the proper component of the system, to adjust for the variation (70).

Forecasting of *Alternaria solani*.

The crucial item for disease progression by *A. solani* turns out to be what the weather is like at each phase in the disease cycle (75). Existing forecasting systems for early blight are late-warning systems, so environmental measurements used are for conditions that have already occurred, although the conditions may still exist (28, 49, 84). With the use of protectant fungicides, infections cannot be erased that occurred during the lag time between the environmental measurements and the application of the protectant. The control of the epidemic, after primary infection has taken place, is then through the control of secondary infection cycles (35).

When the progress of early blight on tomato is plotted against time, a typical sigmoid-shaped curve is produced (Figure 1). The disease progression begins slowly, increases more rapidly, and then levels off as availability of tissue for infection decreases. For the comparison of disease progress curves resulting from the use of different chemical protectants, varying rates of active ingredients, or using different spray intervals, straightening of the sigmoid curve is necessary (79).

Van der Plank (79) describes disease increase by either "simple" or

"compound interest". When the disease increases by simple interest, the primary inoculum remains the main source of inoculum. But when the disease increases by compound interest, the secondary inoculum soon becomes the predominate source. In the disease progression curve of a compound interest disease, the first portion of the curve increases slowly. This is the latent period, during which symptoms are present, but sporulation has not yet begun. Disease incidence is solely due to infection by primary inoculum. Soon the infection rate increases as sporulation begins, and secondary inoculum is produced (Figure 3).

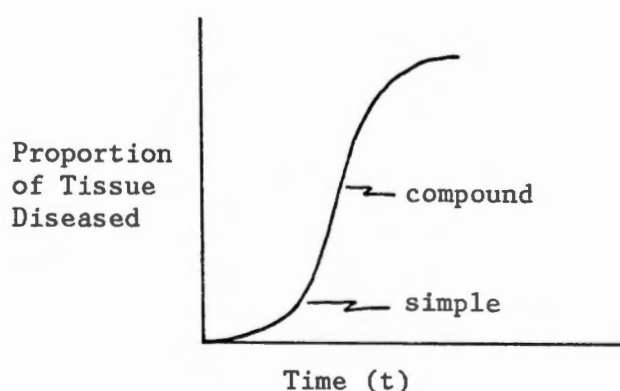


Figure 3. Simple interest and compound interest phases of a typical early blight disease progression curve.

Since early blight produces an autocatalytic epidemic, the disease progress, or proportion of tissue diseased, increases logarithmically. Therefore, plotting the logarithm of the disease proportion against time yields a considerably straighter line (Figure 4).

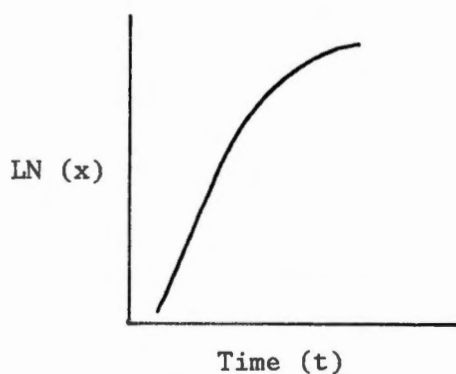


Figure 4. The straightening of an early blight disease progression curve by plotting the logarithm of disease (x) vs time (t).

Since there is a rapid decrease of available healthy plant tissue as the epidemic nears the end of its course, a correction factor, $(1-x)$, can be included in the expression to further straighten the curve (79) (Figure 5).

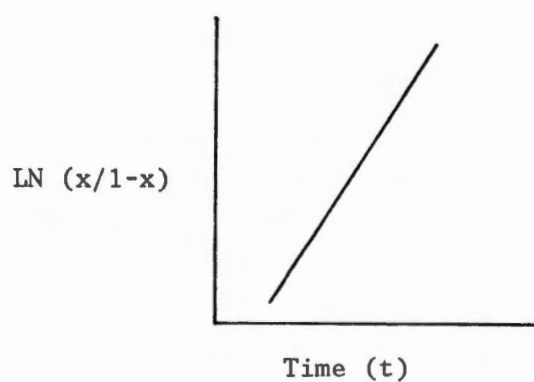


Figure 5. The further straightening of an early blight disease progression curve by plotting the logarithm of disease (x) with a plant tissue correction factor $(1-x)$ vs time (t).

Plotting progress curves would be considered holistic modelling, as the different factors concerning disease progression are ignored. However, the apparent infection rates of resulting lines can be calculated and compared between different disease controls. The basic equation for the resulting straightened line is:

$$\text{LN } (x/1-x) = a + rt \quad (\text{II-1})$$

where the regression coefficient of $\text{LN } (x/1-x)$ on t is r . This regression coefficient, which is the slope of the line in the equation, is also equal to the apparent infection rate (79). The constant, a , is the vertical axis intercept.

Through the use of multiple regression analysis, an expanded model can be produced, where many individual environmental parameters and inoculum density can be entered into the disease predicting equation (15, 48, 64). This form of predictive modelling with the inclusion of environmental factors is closer to the systems analytic type. However, using the averages of each weather factor and assigning a continuous influence to each assumes their effects on disease production are uniform throughout the life cycle. This form of predictive model is still classified as holistic. Interactions between these independent disease-influencing variables can also be included to further improve the predicting ability of the equation. The contribution of the interacting variables can improve the overall ability of the equation to account for the total variation in disease prediction (the dependent variable) (15, 32).

The general form of the multiple regression equation with interacting variables is:

$$\begin{aligned} \text{LN } (x/1-x) = & a + b_1 X_1 + b_2 X_2 + \dots + b_n X_n \\ & + b_{n+1} X_1 X_2 + b_{n+2} X_2 X_3 + \dots + b_{n+m} X_{n-1} X_n \end{aligned} \quad (\text{II-2})$$

where X_1 to X_n are independent variables, and b_1 to b_{n+m} are partial regression coefficients. These coefficients are estimates of the effect of the appropriate independent variable on the total outcome of the dependent variable. The constant, a , is the vertical axis intercept. The inclusion of independent variables and their interactions can be checked for adequacy, or usefullness in the equation, by calculation of the R-squared, which is the proportion of the total variation in the dependent variable, accounted for by multiple regression on the independent variables. This is a test of fit or adequacy, and when R-squared approaches unity, almost all of the variation has been explained. FAST, a forecast system for *Alternaria solani* on tomatoes is an advanced holistic type model, where the value of different environmental parameters (partial regression coefficients) could have been used to establish the prediction system (15).

In EPIDEM, the computer simulation of early blight (84), the individual environmental factors and their effects on each phase of the disease cycle have been considered. This forecast system with its higher level of complexity and efficiency is of the systems analytic

type. In order to produce forecast decisions quickly enough to be useful this type of model must be a computer based system.

CHAPTER III

MATERIALS AND METHODS

Plant Culture.

'Flora-Dade' (82) tomato seeds (*Lycopersicum esculentum* Mill.) were sown in flats containing an artificial soil mixture (Pro-Mix A, Premier Brands, Inc., 145 Huguenot St., New Rochelle, NY 10801) during mid-March of 1980 and 1983. The seedlings were transferred individually at the two true-leaf stage to 2 1/2 inch peat pots containing the same medium. All plants were grown in a greenhouse for 8 weeks, then hardened-off in a coldframe for 2 weeks.

Transplanting into the field was completed by May 24, 1980 and 1983 at the University of Tennessee, Knoxville Agriculture Experiment Station. The spacing between plants was 2 feet, with rows 5 feet apart. The plants were pruned twice and trained to a Florida weave staking system (65).

Preplant fertilization followed current recommendations based on a soil test each year. Sidedress fertilizer applications consisted of 90 lbs of ammonium nitrate per acre at monthly intervals beginning when the fruit on the first clusters were 1 inch in diameter (65).

Weeds were controlled by cultivation and insect control was achieved by recommended pesticides applied by a compressed-air sprayer. Overhead irrigation was utilized as needed (65).

Experimental Design.

A randomized complete block design was employed for six treatments with five replications in 1980 and six replications in 1983. Three different FAST-determined spray regimens were compared to treatments utilizing the current recommendation of 5- to 7-day spray intervals (24). The sixth treatment was the unsprayed control. Each plot consisted of three rows with eight plants per row. The six plants in the middle of each center row were rated for disease progression and harvested for comparison of treatment yields. The remainder of the plants in each plot comprised the border between plots, and were sprayed at the same schedule as the monitored plants of that plot.

Fungicide Application.

Bravo 500, a flowable formulation of the protectant fungicide chlorothalonil (Diamond Shamrock Corp., Agricultural Chemicals Division, 1100 Superior Ave., Cleveland, OH 44114) was applied to the tomato plants at the rate of 2.75 pints per acre. A Solo Junior backpack mistblower (Solo, Inc., 5100 Chestnut Ave., P.O. Box 5030, Newport News, VA 23605) was used to apply the fungicide.

Early Blight Assessment.

Weekly disease assessment ratings were taken of the six individual plants in the center of each treatment plot. The severity of disease was based on the percent infection including defoliation. The disease ratings were initiated on July 28 and continued until October 1 during 1980, and from July 2 until September 3 during 1983.

Yield Assessment.

Fruits from the middle six plants of the center row of each plot were harvested every 7-10 days. The fruit was picked at the mature green to pink stages, and graded according to U.S. standards (2). The marketable fruit category was composed of U.S. number 1 and 2 grades, and culls were divided into two categories: culls due to early blight fruit rot, and culls due to other blemishes or small size. The quantities of each category were also recorded.

Environmental Monitoring.

Measurements of environmental parameters began on June 1 during both growing seasons. To determine leaf wetness a monitoring system was employed which utilized five sensing elements per plant (Model A.R.C.P-2, Wong Laboratories, Cincinnati, OH) that were arranged on the plants as described by Getz (22). These leaf simulating sensors were printed circuit grids (5.8 x 7.8 cm) painted as described by Davis and Hughes (16) in order to achieve a similar emissivity to that of leaves. The moisture readings were recorded by a Rustrac impact recorder (Model 288, Gulton Industries, Inc., Gulton Industrial Park, East Greenwich, RI 02818) and the system was powered by a 20 VDC power supply. Sensors were activated by an adjustable timer (Dayton Electric Mfg. Co., 5959 Wittoward St., Chicago, IL 60648) for three 11-12 second "on" periods every 10 minutes (87). Recalibration of the monitoring system was performed biweekly. Thorough saturation of the sensing elements with water allowed for adjustment of the recorder to a 100% wetness reading. Two leaf wetness monitoring systems were maintained within the plots,

with instruments housed in National Weather Service, standard louvered shelters.

Relative humidity and ambient temperature were recorded with two 7-day hygrothermographs (Model H311, Weather Measure Corp., P.O. Box 41257, Sacramento, CA 95841) and were also housed in the instrument shelters. The hygrothermographs were recalibrated weekly. The relative humidity sensors were adjusted to 100% after wrapping the units in saturated towels for 10 minutes. The temperature sensors were calibrated to a standard mercury thermometer.

Rainfall was recorded within the plots with an 8-inch plastic rain guage, and compared daily to the adjacent weather station's rain guage for accuracy.

Spore Sampling.

Rotorod spore samplers with retractable collector sampling heads (Ted Brown Assoc., 26338 Esperanza Dr., Los Altos Hills, CA 94022) were used to measure the arrival of primary inoculum of *Alternaria solani* and levels of subsequent secondary inoculum.

In 1980 the average "on" time of the spore samplers was 30.4 minutes per hour, totalling 12.1 hours per day. Dust accumulation on the sampling rods often made spore identification and counting difficult. Therefore, in 1983 the "on" time was reduced to 2.5 minutes per hour, totalling 1.0 hours per day. The sampling rods were coated with silicone grease for a spore trapping efficiency of approximately 95% (20). The rods were replaced at 2 to 3-day intervals, and *A. solani* spores counted at 100× by using the Rotorod stage adapter with a compound microscope (26).

Forecasting Models.

The three FAST-determined spray regimens utilized two associated models which warned of conditions favorable for conidiophore and conidia formation and for disease outbreak.

The disease severity values (S) of the first model were based on the length of the daily leaf wetness period, and on the average air temperature during this time period (Table 1). The disease severity ratings (R) of the second model were based on the cumulative number of hours per day that the relative humidity was greater than 90% during the past 5 days, the average daily air temperature for the past 5 days, and the amount of total rainfall during the past 7 days (Table 2) (49).

The decision to initiate the spray schedule and timing of subsequent sprays for each of the three forecast-oriented treatments was based on 1) the cumulative disease severity value (S) for the past 7 days (CS), and 2) the cumulative disease severity rating (R) for the past 5 days (CR). Reaching the critical level of CS for each FAST-determined treatment specified when to begin a 7-day spray interval; also, reaching the critical level of CR specified the change to a 5-day interval (Table 3) (49).

Data Analyses.

Yields of 1) marketable fruits (U.S. Nos. 1 and 2 grades), 2) culls due to early blight, and 3) culls due to other blemishes or small size were compared between treatments at a 0.05 level of probability by Duncan's New Multiple Range Test (19).

TABLE 1. Early blight forecast model: disease severity values (S) as determined by length of leaf wetness period and average temperature during this period.

Mean Temp (C)	Daily Disease Severity Values ^z				
	0	1	2	3	4
	-----Leaf Wetness Period-(hrs)-----				
13-17	0-6	7-15	16-20	21-24	
18-20	0-3	4-8	9-15	16-22	23-24
21-27	0-2	3-5	6-12	13-20	21-24
26-29	0-3	4-8	9-15	16-22	23-24

^z The range of disease severity values (S) are from 0 (unfavorable weather conditions for *Alternaria solani* spore development) to 4 (highly favorable conditions).

Table data from Madden and co-workers (49).

TABLE 2. Early blight forecast model: disease severity ratings (R) as determined by number of hours of relative humidity greater than 90%, average daily temperature, and total rainfall.

Average Temp (C) ^a	Hours RH>90% ^b	Total Rainfall ^c	R ^d
<22	<72	<1.0	0
<22	>72	<1.0	0
<22	<72	>1.0	1
>22	<72	<1.0	1
>22	<72	>1.0	1
<22	>72	>1.0	2
>22	>72	<1.0	2
>22	>72	>1.0	3

^a Average daily temperature during last 5 days (C).

^b Hours of Relative humidity greater than 90% during last 5 days.

^c Total rainfall during last 7 days (inches).

^d The range of disease severity ratings (R) are from 0 (unfavorable weather conditions for *Alternaria solani* spore development and infection) to 3 (highly favorable conditions).
Table data from Madden and co-workers (49).

TABLE 3. Early blight disease control spray schedules as determined by recommendations for Tennessee and by cumulative disease severity models: CS and CR.

Treatment ^x	Critical Limit	Spray Interval
5	None	5-day
7	None	7-day
A	CS $\geq$ 16 ^y	7-day
	CS $\geq$ 16 and CR $\geq$ 12 ^z	5-day
B	CS $\geq$ 14	7-day
	CS $\geq$ 14 and CR $\geq$ 09	5-day
C	CS $\geq$ 11	7-day
	CS $\geq$ 11 and CR $\geq$ 08	5-day
K	None	None

^x Treatments A, B, and C have FAST-determined applications and intervals, and treatments 5 and 7 have set 5-day and 7-day spray intervals.

^y CS represents the 7-day cumulative disease severity value (S).

^z CR represents the 5-day cumulative disease severity rating (R).
Table data from Madden and co-workers (49).

Disease assessment was accomplished by a comparison of infection rates between treatments using analysis of variance and carried out by contrast statements under the General Linear Models (GLM) procedure of SAS82 (59). A logarithmic line straightening equation was employed for the sigmoid-shaped disease progression curves of each treatment. Once these curves were straightened, a comparison of the slopes of the lines could be made, with slopes of individual lines equal to the infection rates of the treatments.

Environmental variables that demonstrated a significant influence on disease outbreak were determined at the 0.05 level of probability by the use of the Correlation (CORR) procedure of SAS82 (59). Multiple regression analysis by the Stepwise procedure of SAS82 (59) was employed to produce prediction equations for early blight disease development using these significant environmental parameters. The spore counts were included in the equation in 1983.

CHAPTER IV

RESULTS AND DISCUSSION

Disease Progression Curves and Infection Rates

The disease ratings for 1980 and 1983 were plotted against time to produce typical sigmoid-shaped disease progression curves (Figures 6 and 7). For the comparison of infection rates between treatments, the disease progression curves had to be straightened. Line straightening was initiated by first taking the natural logarithm of the daily disease proportions and plotting the result against time (Figures 8 and 9). To further straighten the disease curves, a correction factor, $(1-x)$, was included to account for the reduction of healthy susceptible tissue toward the end of the seasons (Figures 10 and 11).

Infection rates were evaluated and compared at the 0.05 level of significance by the use of estimate and contrast statements (F-tests) under the GLM procedure of SAS82 (59). During 1980 the infection rate was lowest for the regimen employing a 5-day spray interval (26 sprays), followed by and significantly different from the treatment with a 7-day interval (18 sprays). During 1983 the most frequently sprayed FAST-generated regimen (18 sprays) resulted in a significantly lower infection rate than the next best treatment utilizing a 5-day spray interval (22 sprays) (Table 4).

The use of properly timed spray applications for protection during conditions favorable for infection should allow for the same efficiency in disease control as achieved by the most frequently sprayed standard

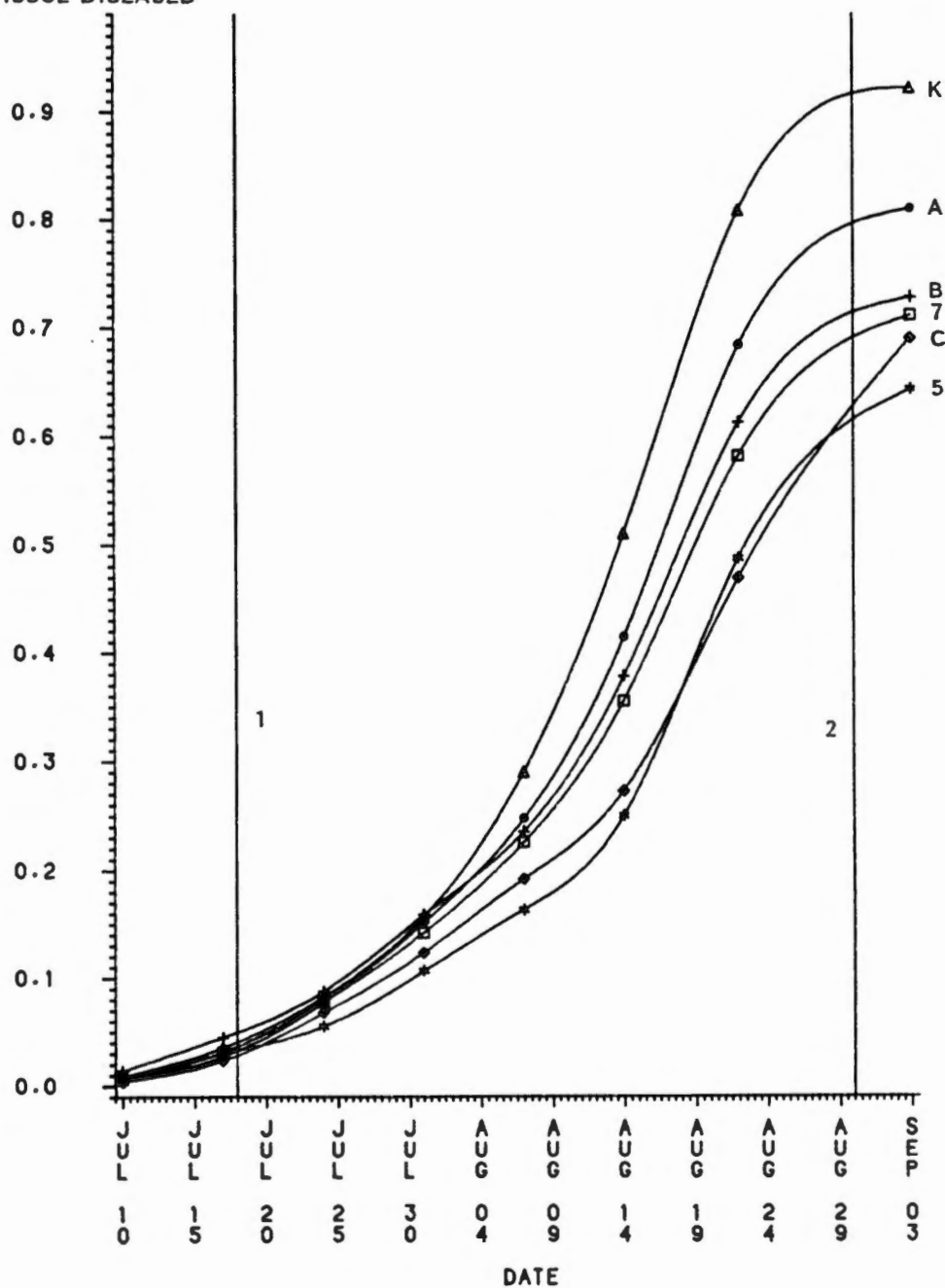
MEAN PROPORTION
OF TISSUE DISEASED

Figure 7. Development of tomato early blight in six treatments in 1983. Vertical lines (1,2) enclose the period analyzed for apparent infection rates. Treatments A, B, and C have FAST-generated spray intervals, based on environmental parameters of relative humidity, rainfall, leaf-wetness, and temperature, with 10, 15, and 18 sprays, respectively. Treatments 5 and 7 have 5-day and 7-day spray intervals with 22 and 19 sprays, respectively. Treatment K is the control.

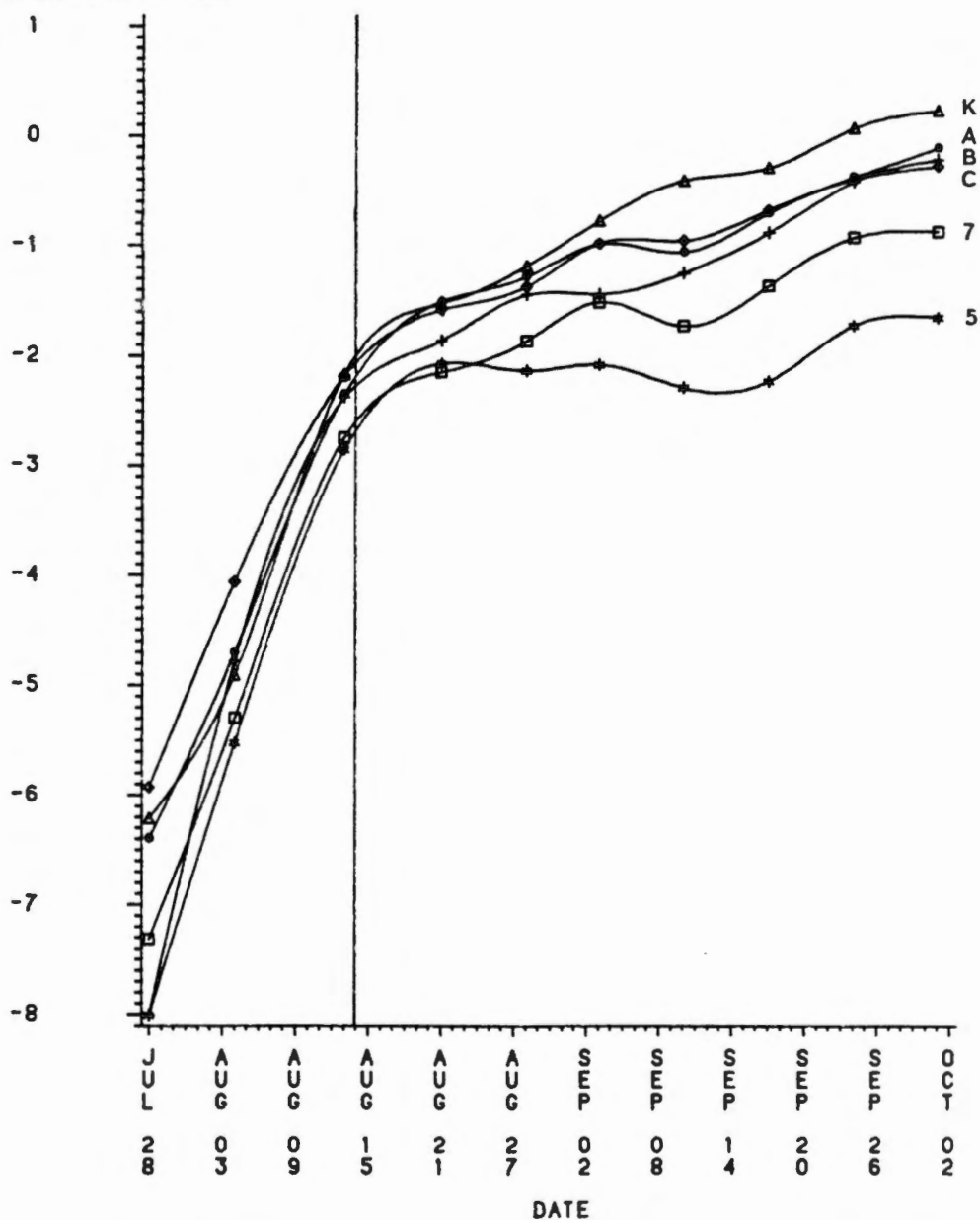
LOG OF DAILY
DISEASE PROPORTION

Figure 8. Logarithmic development of tomato early blight in six treatments in 1980. Period to right of vertical line was analyzed for apparent infection rates. In logarithmic development, $\ln x/(1-x)$, x is mean proportion of tissue diseased. Treatments A, B, and C have FAST-generated spray intervals, based on environmental parameters of relative humidity, rainfall, leaf-wetness, and temperature, with 5, 12, and 17 sprays, respectively. Treatments 5 and 7 have 5-day and 7-day spray intervals with 26 and 18 sprays, respectively. Treatment K is the control.

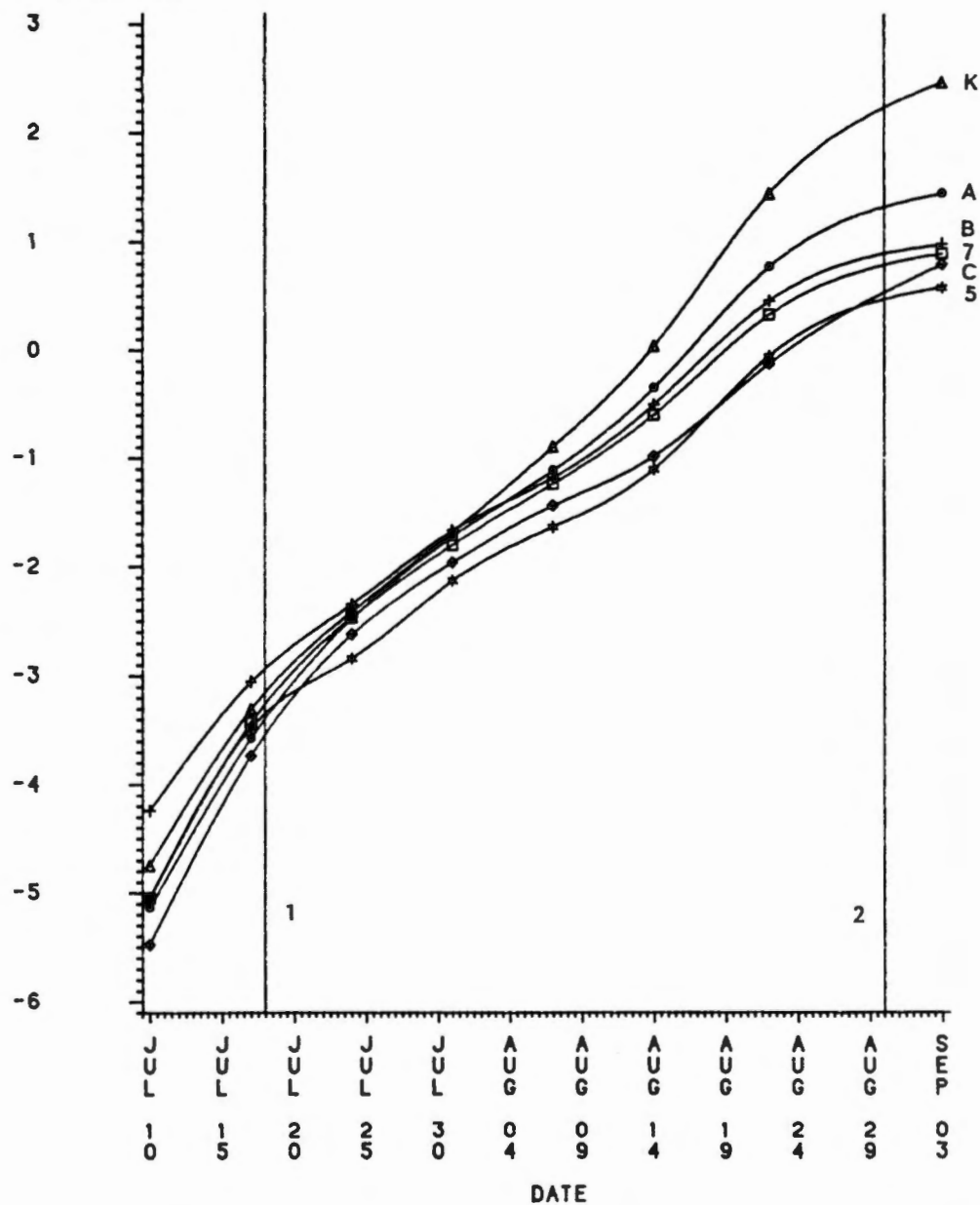
LOG OF DAILY
DISEASE PROPORTION

Figure 9. Logarithmic development of tomato early blight in six treatments in 1983. Vertical lines (1,2) enclose period analyzed for apparent infection rates. In logarithmic development, $\ln x/(1-x)$, x is mean proportion of tissue diseased. Treatments A, B, and C have FAST-generated spray intervals, based on environmental parameters of relative humidity, rainfall, leaf-wetness, and temperature, with 10, 15, and 18 sprays, respectively. Treatments 5 and 7 have 5-day and 7-day spray intervals with 22 and 19 sprays, respectively. Treatment K is the control.

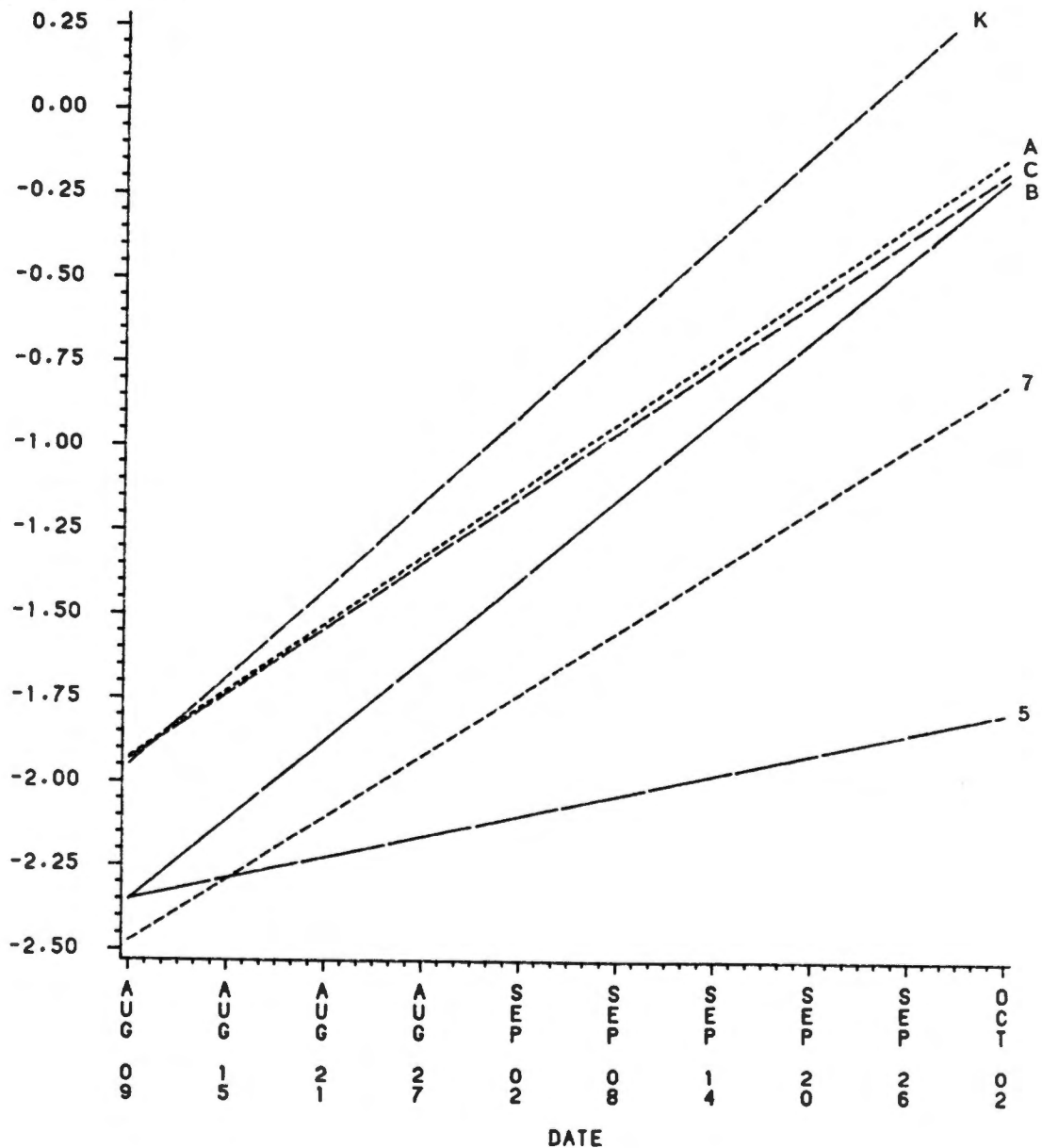
LOG OF DAILY
DISEASE PROPORTION

Figure 10. Best fitting straight lines to logarithmic disease development curves for six treatments in 1980. Slopes of lines are apparent infection rates for early blight disease progression. In logarithmic development, $\ln x/(1-x)$, x is mean proportion of tissue diseased. Treatments A, B, and C have FAST-generated spray intervals, based on environmental parameters of relative humidity, rainfall, leaf-wetness, and temperature, with 5, 12, and 17 sprays, respectively. Treatments 5 and 7 have 5-day and 7-day spray intervals with 26 and 18 sprays, respectively. Treatment K is the control.

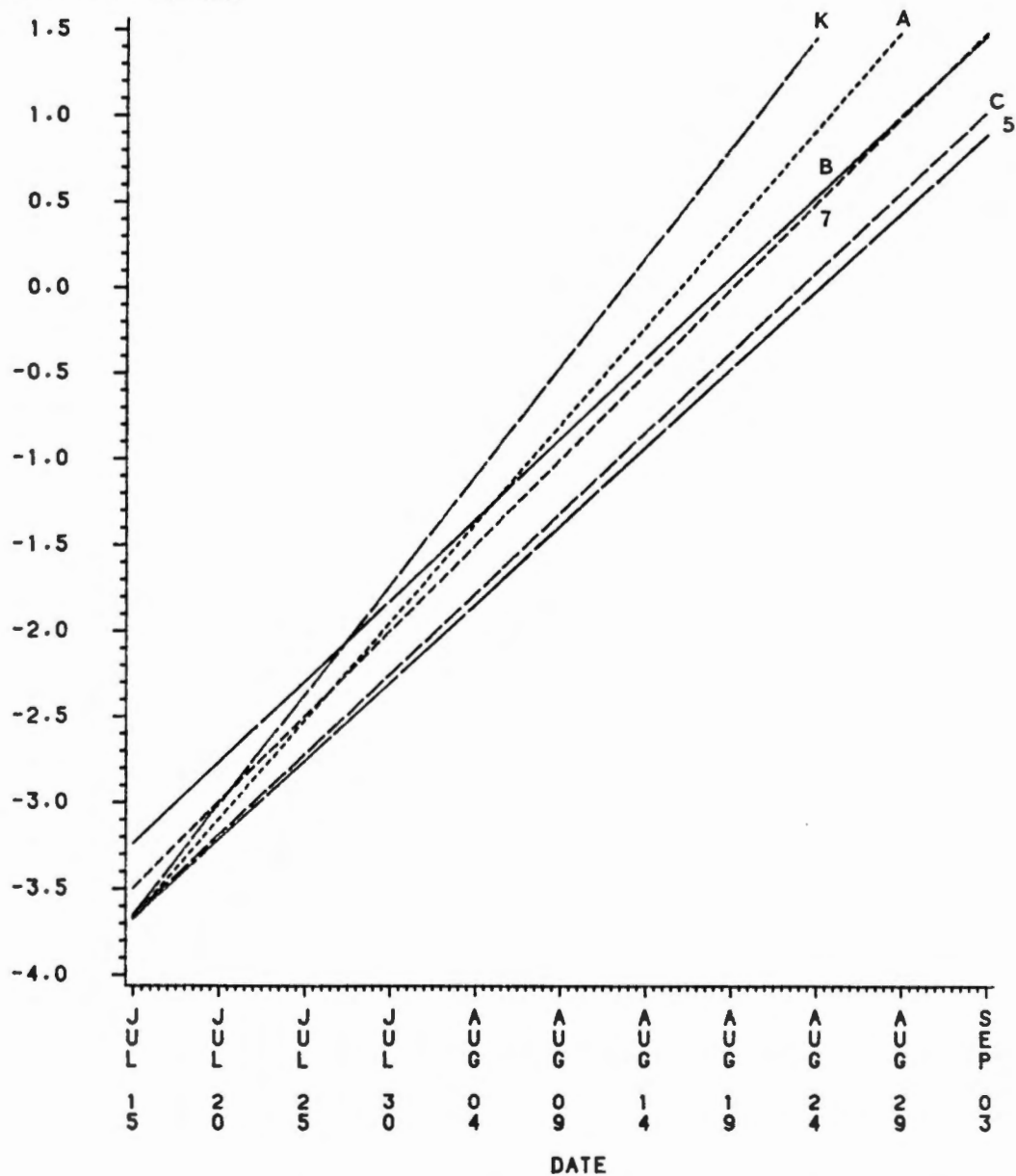
LOG OF DAILY
DISEASE PROPORTION

Figure 11. Best fitting straight lines to logarithmic disease development curves for six treatments in 1983. Slopes of lines are apparent infection rates for early blight progression. In logarithmic development, $\ln x/(1-x)$, x is mean proportion of tissue diseased. Treatments A, B, and C have FAST-generated spray intervals, based on environmental parameters of relative humidity, rainfall, leaf-wetness, and temperature, with 10, 15, and 18 sprays, respectively. Treatments 5 and 7 have 5-day and 7-day spray intervals with 22 and 19 sprays, respectively. Treatment K is the control.

Table 4. Number of fungicide applications per treatment, and early blight disease infection rates for 1980 and 1983.

Treatment ^x	-----1980-----		-----1983-----	
	Number of Sprays	Infection Rate ^y (unit/day)	Number of Sprays	Infection Rate, ^y (unit/day)
5	26	0.0121 a	22	0.0947 b
7	18	0.0340 b	19	0.0977 b
C	17	0.0353 b	18	0.0900 a
B	12	0.0412 c	15	0.0958 b
A	5	0.0359 b	10	0.1145 c
CONTROL	0	0.0474 d	0	0.1402 d

^x Treatments A, B, and C have FAST-determined applications and intervals, and treatments 5 and 7 have set 5-day and 7-day spray intervals.

^y Infection rate values followed by the same letter are not significantly different at the 0.05 level of probability, as determined by contrast statements (F-tests) under General Linear Models (GLM) procedure of SAS82 (59).

interval treatment. The fewer the number of spray applications in the FAST-generated regimen, the more properly timed the remaining sprays must be, and the more accurate the forecasting ability. Four spray applications were eliminated by forecasting during 1983, while maintaining a high efficiency of disease control.

Initial Spray Applications

The decision of the initial application can be based on one of several factors, and its timing can greatly influence the outcome of a spray regimen, as noted by Large (38). The spray applications could be initiated at fruit set, as the plants begin to be stressed with the developing of fruit, but by this time the plants may have become highly infected, with infection remaining latent until foliar hexose levels drop. The applications could begin after symptoms are obvious in the field, but again, latent infections may have progressed to such a degree that adequate control is impossible. Delaying spray for a set number of days or weeks before the application also ignores the possibility of latent infection. Conversely, some of the sprays may be too early to be of benefit. The protectant application might be initiated with the occurrence of air-borne conidia, but it must be determined whether this is primary inoculum from an outside source or from host debris in and on the soil, or secondary inoculum being produced on the crop. If the conidia are primary inoculum, the prompt application of foliar protectants upon their arrival may offer adequate disease control. However, if they are a the result of a few infections that have already

reached the point of conidia production, the timing is again inadequate.

In order to reduce the number of fungicide applications, yet still offer protection, the timing of the initial spray can be based on the occurrence of favorable conditions for ingress, assuming some inoculum is present. The more favorable the conditions are for infection to occur, the more reduced can be the numbers of conidia needed to bring about a specific infection level (80). This was the basis for initial applications in the present study, and for the original study by Madden and co-workers (49). The timing of the initial spray dates may have had a large effect on the apparent infection rates of the treatments. During 1980 the initial spray dates of the 5- and 7-day spray interval treatments preceded that of the most frequently sprayed (C) FAST-generated treatment by 12 days, but during 1983 they preceded this FAST treatment by only 6 days. During both years approximately six more weeks elapsed before the initial applications of the least sprayed FAST-generated treatment (A) (Table 5).

The greater delay of the initial spray for the least sprayed FAST-generated spray treatment (A) during both years was the probable cause of the significantly higher infection rates. Excluding the treatment with the lowest infection rate each year, the next three lowest number spray treatments had infection rates that were not significantly different at the 0.05 level of probability (Table 4). It appears that the delay time was too long before initial applications and the environmental conditions were too favorable to adequately control early blight. The origins of the sigmoid disease progression curves of the sprayed treatments compared to the control treatment (Figures 6 and

TABLE 5. Initial spray application dates by treatment during 1980 and 1983.

Treatment ^a	Initial Fungicide Application	
	-----1980-----	-----1983-----
5	6/6	6/1
7	6/6	6/1
C	6/18	6/7
B	6/19	6/10
A	8/2	7/19

^a Treatments A, B, and C have FAST-determined applications and intervals, and treatments 5 and 7 have set 5-day and 7-day spray intervals.

7) were very similar to that of Figure 2. This indicates that the delay time for initial applications was too long for all treatments. Therefore spray applications began following the 0.1% disease proportion.

Spore Monitoring

During 1983 the concentration of *Alternaria solani* conidia increased slightly at the time of fruit set (June 22). The increase in numbers was gradual until August 7, which appeared to divide the season into two distinct periods (Figure 12). The section of Figure 12 prior to August 7 corresponded to a simple interest disease phase, where secondary inoculum had yet to be produced in sufficient quantities to significantly influence disease progression. Following August 7 the quantities reached much higher levels corresponding to a compound interest disease phase. This date also corresponds to the region of the disease progression curve where the increase in disease proportion became more rapid. This disease increase was more pronounced for the less sprayed and the control treatments (Figure 7).

Since low numbers of air-borne conidia were trapped from June 10 until fruit set (June 22), and symptom expression did not begin until July 2, the air-borne conidia were primary inocula from either soil debris or from an outside source. Their occurrence probably led to latent infections which did not produce symptoms until the plants were stressed with fruit development. During 1983 the early initial applications of the two most frequently sprayed FAST- generated

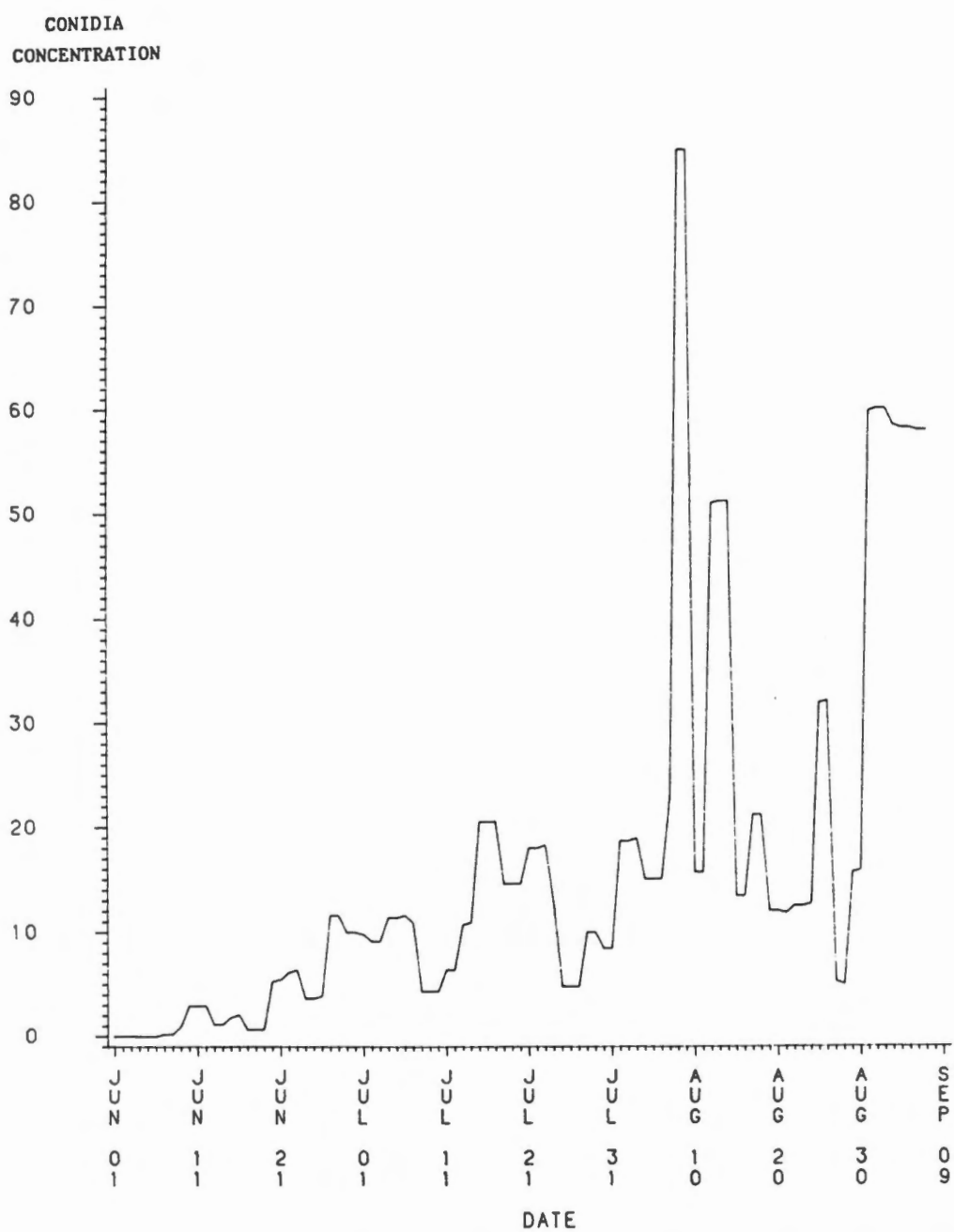


Figure 12. Daily counts of *Alternaria solani* conidia per cubic meter of air in tomato field during 1983.

regimens (June 7 and 10, respectively) preceded the arrival of the primary inoculum, and allowed for as efficient control as by the regular spray interval methods (5 and 7). This would indicate that the monitoring of air-borne conidia could be useful if a prompt spray application was made upon their arrival. Harrison (35) found spore traps to be a reliable indicator for timing the initial sprays.

Yield Losses

Large (38) noted that yield figures rarely respond to small differences in the protective effect of different treatments, and that the later disease occurs in the season, the less the effect of the treatments on the yields. Apparently these factors affected the yields each year. During 1980 an average of 88.3% of the yield had been harvested over all treatments before the disease level had even reached 50% in the control plot, and 100% of the yield was harvested before a 60% level of infection was reached (Figure 13). The final disease levels were higher in 1983 possibly due to the presence of debris in the soil from the previous field trial. An average of 83.5% of the total yield had been harvested before a 50% infection level was reached in the control plot (Figure 14). The 'Flora-Dade' cultivar has a somewhat concentrated production of fruit that came early enough both years to precede the higher disease levels, and subsequent defoliation. As a result, no significant reduction of yield occurred for the lesser-sprayed or the non-sprayed treatments. There was no difference

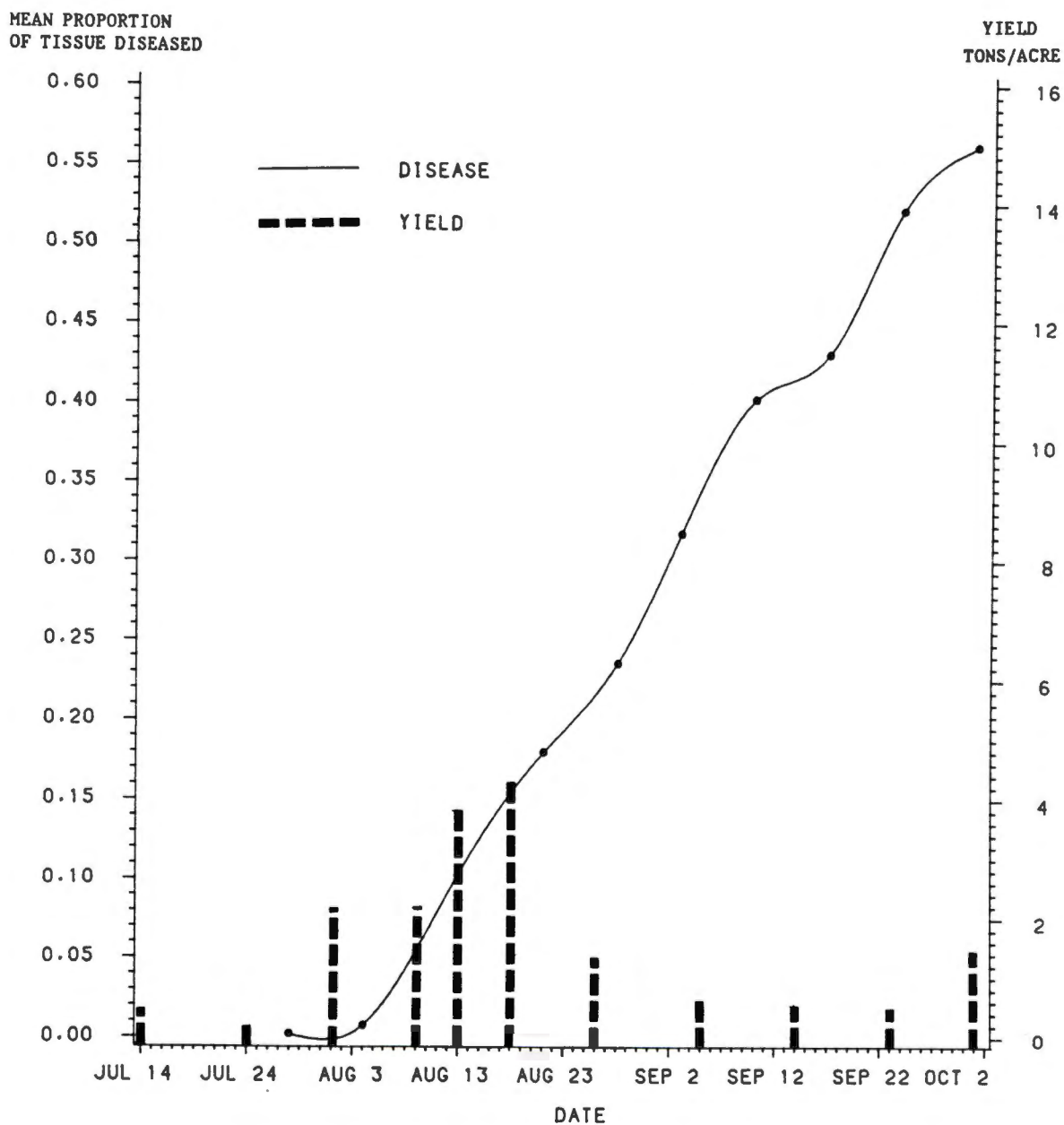


Figure 13. Relation of tomato early blight development in control plot in 1980, to mean yields of marketable fruit at harvesting dates.

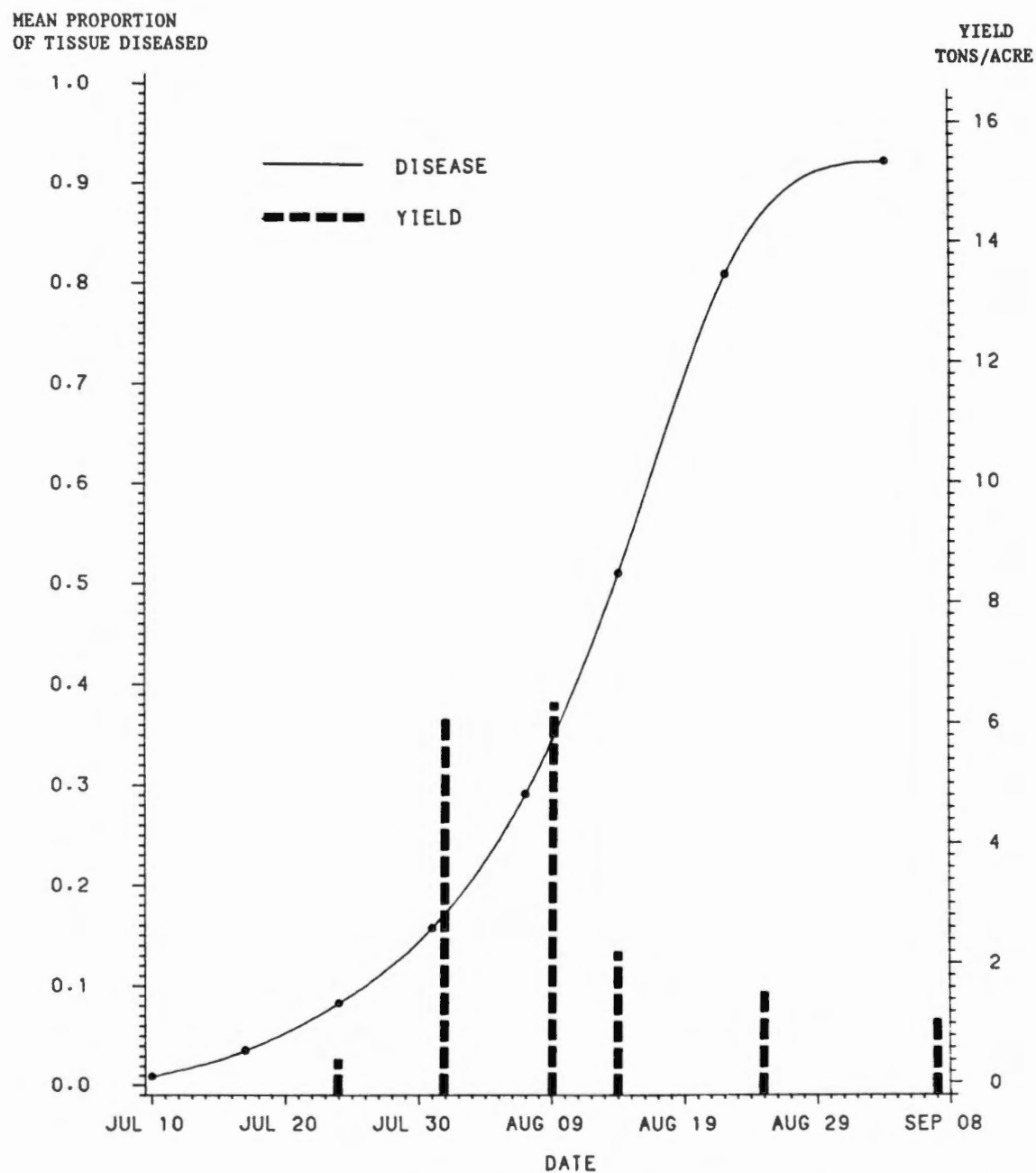


Figure 14. Relation of tomato early blight development in control plot in 1983, to mean yields of marketable fruit at harvesting dates.

between treatments in yields of marketable, cull, or early blighted fruit at the 0.05 level of probability during 1980 and 1983 (Table 6).

Correlation and Prediction Equations

All measured parameters were tested for a significant correlation with disease production by the Correlation procedure of SAS82 (79). All measured parameters were additionally tested for significant correlations with the three parameters related to foliar wetness: 1) number of daily hours of the leaf wetness period, 2) number of daily hours of relative humidity greater than 90%, and 3) the daily rainfall in inches (Tables 7 and 8). Since all parameters either were significantly correlated with disease production at the 0.05 level of probability, or with one of the three leaf wetness parameters, all were tested as potential independent variables in the disease prediction equations during 1980 and 1983. The control treatment was used for the correlation of environmental parameters with disease production. This was because the disease-depressing effect of the fungicide in any of the sprayed treatments would not allow for a precise measurement of the influence of these parameters on the disease level.

Due to the importance of moisture for spore germination, host penetration, and subsequent sporulation, the two sources of foliar wetting were examined. There was a very high positive correlation between the number of hours of the leaf wetness period and the hours of relative humidity greater than 90% (Table 7 and 8), a much higher

TABLE 6. Yields by treatment of marketable, cull, and early blighted fruit during 1980 and 1983.

Treatment ^y	-----1980-Yield- ^z -----			-----1983-Yield- ^z -----		
	Marketable	Cull	EB Cull	Marketable	Cull	EB Cull
5	19.96 a	6.22 a	0.00 a	18.75 a	6.82 a	0.83 a
7	20.86 a	6.54 a	0.00 a	19.52 a	7.61 a	0.71 a
C	18.63 a	5.66 a	0.01 a	17.82 a	8.70 a	0.56 a
B	18.83 a	6.71 a	0.00 a	17.34 a	7.40 a	0.79 a
A	19.43 a	5.92 a	0.00 a	15.42 a	8.01 a	1.03 a
Control	17.00 a	5.01 a	0.01 a	15.28 a	7.63 a	1.08 a

^y Treatments A, B, and C have FAST-determined applications and intervals, and treatments 5 and 7 have set 5-day and 7-day spray intervals.

^z Yields in tons/acre values in same column followed by the same letter are not statistically different at the 0.05 level of significance as tested by Duncan's New Multiple Range Test (19).

TABLE 7. Correlation coefficients of environmental parameters and early blight disease occurrence during 1983.^a

	DEWHRS	RH90	RAIN	SPORES	DISEASE
DEWHRS ^b		.608	.230	.437	.406
RH90 ^c	.608		.332		
RAIN ^d	.230	.332			-.181
SPORES ^e	.437				.310
DEWMAX ^f	.650	.281		.462	.382
DEWMIN ^g		.247		.331	
DEWAVE ^h	.477	.271		.436	.235
TEMPMIN ^j	.207	.263		.334	
TEMPAVE ^k				.271	

^a Only values below the 0.05 level of significance were included, as determined by the Correlation (CORR) procedure of SAS82 (59).

^b DEWHRS = Number of daily hours of leaf-wetting period.

^c RH90 = Number of daily hours relative humidity $\geq 90\%$.

^d RAIN = Daily rainfall (inches).

^e SPORES = Number of spores trapped per day.

^f DEWMAX = Maximum daily temperature during leaf-wetting period.

^g DEWMIN = Minimum daily temperature during leaf-wetting period.

^h DEWAVE = Average daily temperature during leaf-wetting period.

^j TEMPMIN = Minimum daily temperature.

^k TEMPAVE = Average daily temperature.

^l DISEASE = Disease proportion data from control plots.

TABLE 8. Correlation coefficients of environmental parameters and early blight disease occurrence during 1980.^a

	DEWHRS	RH90	RAIN	DISEASE
DEWHRS ^b		.828	.355	.245
RH90 ^c	.828		.378	.225
RAIN ^d	.355	.378		
DEWMAX ^e	.411			-.306
DEWMIN ^f				-.583
DEWAVE ^g	.240			-.447
TEMPMAX ^h	-.282	-.227		-.551
TEMPMIN ^j				-.574
TEMPAVE ^k				-.593

^a Only values below the 0.05 level of significance were included, as determined by the Correlation (CORR) procedure of SAS82 (59).

^b DEWHRS = Number of daily hours of leaf-wetting period.

^c RH90 = Number of daily hours relative humidity $\geq 90\%$.

^d RAIN = Daily rainfall (inches).

^e DEWMAX = Maximum daily temperature during leaf-wetting period.

^f DEWMIN = Minimum daily temperature during leaf-wetting period.

^g DEWAVE = Average daily temperature during leaf-wetting period.

^h TEMPMAX = Maximum daily temperature.

^j TEMPMIN = Minimum daily temperature.

^k TEMPAVE = Average daily temperature.

^l DISEASE = Disease proportion data from control plots.

correlation than between the former and daily rainfall. The wetting of foliage by rainfall usually lasted for less time than the typical leaf wetness period caused by high relative humidity and dew formation. During 1980 the rainfall did not have a significant correlation with disease production, and in 1983 the correlation coefficient was negative. These observations suggest that high relative humidity may be more important than rainfall for foliar wetting, and hence for disease production. The reason the 90% level of relative humidity was chosen was because it was the average of the levels described as necessary for germination and penetration by Hodossy (27), Rotem (62), and Waggoner and Horsfall (84).

For the production of disease prediction equations, the partial regression coefficients for the disease-influencing environmental parameters were determined by multiple regression analysis of the parameters on disease occurrence in the control plots.

In 1980 the prediction equations utilizing significant parameters without parameter interactions accounted for 67.0% of the variability of disease. When parameter interactions were included the disease predicting ability rose to 76.4% (Table 9).

In 1983 the daily spore count was significantly correlated with disease occurrence, but was not as important as other variables in the formation of the best prediction equation. Without the use of the spore count variable, the disease predicting ability reached 71.6% when parameter interactions were added (Table 10).

TABLE 9. Partial regression coefficients for early blight prediction equations ^a determined by multiple regression ^b of individual environmental parameters and parameter interactions ^c on disease occurrence during 1980.

Coefficients included in equation after submitting all parameters, including all parameter interactions:

$$\begin{aligned} \text{DISEASE} = & (.030) \text{ RH90} + (.013) \text{ DEWMAX} + (.114) \text{ DEWHRS} \\ & + (-.016) \text{ DEWHRS} * \text{RH90} + (-.001) \text{ DEWHRS} * \text{RAIN} \\ & + (.027) \text{ RH90} * \text{RAIN} + (-.028) \text{ DEWMAX} * \text{DEWHRS} \end{aligned}$$

$$R^2 \times 100 = 76.4\%$$

Coefficients included in equation after submitting all parameters, but without any parameter interactions:

$$\text{DISEASE} = (.022) \text{ RH90} + (-.101) \text{ RAIN}$$

$$R^2 \times 100 = 67.0\%$$

^a Equation of form: $\text{DISEASE} = \text{LN} (x/1-x) = b_1 X_1 + b_2 X_2 + \dots + b_n X_n$

and when interactions included add: $b_{n+1} X_1 X_2 + b_{n+2} X_2 X_3 + \dots + b_{n+m} X_{n-1} X_n$

^b Multiple regression analysis for disease prediction within control plots by Stepwise procedure of SAS82 (59).

^c Only variables below the 0.05 level of significance were included;
* designates interaction between two variables.

DEWHRS = Number of daily hours of leaf-wetting period.

RH90 = Number of daily hours relative humidity $\geq 90\%$.

RAIN = Daily rainfall (inches).

DEWMAX = Maximum daily temperature during leaf-wetting period.

TABLE 10. Partial regression coefficients for early blight prediction equations ^a determined by multiple regression ^b of individual environmental parameters and parameter interactions ^c on disease occurrence during 1983.

Coefficients included in equation after submitting SPORES variable, but without any parameter interactions:

$$\begin{aligned} \text{DISEASE} = & (-.031) \text{ RH90} + (-.288) \text{ RAIN} + (.042) \text{ DEWHRS} \\ & + (-.036) \text{ TEMPAVE} + (.029) \text{ TEMPMAX} + (.001) \text{ SPORES} \\ & + (.005) \text{ DEWMAX} \end{aligned}$$

$$R^2 \times 100 = 70.8\%$$

Coefficients included in equation after submitting SPORES variable and all parameter interactions:

$$\begin{aligned} \text{DISEASE} = & (.025) \text{ DEWHRS} + (.001) \text{ DEWHRS*SPORES} \\ & + (.039) \text{ DEWHRS*RAIN} + (-.070) \text{ RH90*RAIN} \end{aligned}$$

$$R^2 \times 100 = 68.9\%$$

Coefficients included in equation after not submitting SPORES variable or any of its interactions, but with all other parameter interactions:

$$\begin{aligned} \text{DISEASE} = & (-.147) \text{ RH90} + (-.026) \text{ RH90*RAIN} + (.025) \text{ TEMPMAX} \\ & + (.013) \text{ TEMPMIN} + (.008) \text{ DEWHRS*RH90} + (.041) \text{ DEWHRS} \end{aligned}$$

$$R^2 \times 100 = 71.6\%$$

^a Equation of form: $\text{DISEASE} = \text{LN} (x/1-x) = b_1X_1 + b_2X_2 + \dots + b_nX_n$

and when interactions included add: $b_{n+1}X_1X_2 + b_{n+2}X_2X_3 + \dots + b_{n+m}X_{n-1}X_n$

^b Multiple regression analysis for disease prediction within control plots by Stepwise procedure of SAS82 (59).

^c Only variables below the 0.05 level of significance were included; * designates interaction between two variables.

DEWHRS = Number of daily hours of leaf-wetting period.

RH90 = Number of daily hours relative humidity $\geq 90\%$.

RAIN = Daily rainfall (inches). SPORES = Daily spore count.

DEWMAX = Maximum daily temperature during leaf-wetting period.

TEMPMAX = Max. daily temperature. TEMPMIN = Min. daily temperature.

TEMPAVE = Average daily temperature.

Revision of Early Blight Forecast Models

Madden and co-workers (49) state that the disease severity value (S) model is based on conditions that favor conidiophore and conidia formation (Table 1). Adjustments were made in the number of hours of the leaf wetness period and in the temperature during that period to better correspond to values found in the literature (Table 11). Waggoner and Horsfall (84) found that the optimum temperature for sporulation is between 19 and 23C. The optimum temperature for conidiophore formation is 22-24C (84). Douglas (18) observed the most sporulation at 20C, and at 25C spore production is halted.

The disease severity rating (R) model, also developed by Madden and co-workers (49), is based on the observations that early blight disease severity increases with increases in rainfall, relative humidity, and temperature (Table 2). Slightly different conditions are required for disease development during the prefruit-set phase of the tomato plant growth than during the postfruit-set phase. Before fruit set occurs and the plants become stressed, the parts of the *Alternaria solani* life cycle that must be examined are the germination, penetration, and latent infection (incubation) periods (Table 12). Lesion development and subsequent sporulation normally occur after the fruit set period of plant growth.

Pound (57) found that temperatures between 17 and 25C promote a higher infection rate than below 17C, and that the optimum temperature for mycelial growth is 28C. Following penetration the daily temperature becomes the most important environmental factor, as the leaves contain

TABLE 11. Revised early blight disease severity values (S) based on leaf wetness hours and average air temperature during leaf wetness period.

Mean Temp (C)	Daily Disease Severity Values ^z				
	0	1	2	3	4
----Leaf Wetness Period (hrs)----					
13-15	0-6	7-15	16-20	21-24	
16-18	0-3	4-8	9-15	16-22	23-24
19-24	0-2	3-5	6-12	13-20	21-24
25-29	0-6	7-15	16-20	21-24	

^z The range of disease severity values (S) are from 0 (unfavorable weather conditions for *Alternaria solani* spore development) to 4 (highly favorable conditions).

Table data revised from Madden and co-workers (49).

TABLE 12. Revised early blight forecast model: prefruit-set disease severity ratings (R) as determined by number of hours of relative humidity greater than 90%, average daily temperature, and total rainfall.

Average Temp (C) ^a	Hours RH>90% ^b	Total Rainfall ^c	R ^d
<17	<60	<0.5	0
>17	<60	<0.5	1
<17	<60	>0.5	2
<17	>60	<0.5	2
<17	>60	>0.5	3
>17	<60	>0.5	3
>17	>60	<0.5	4
>17	>60	>0.5	5

^a Average daily temperature during last 5 days (C).

^b Hours of Relative humidity greater than 90% during last 5 days.

^c Total rainfall during last 5 days (inches).

^d The range of disease severity ratings (R) are from 0 (unfavorable weather conditions for *Alternaria solani* spore development and infection) to 5 (highly favorable conditions).

Table data revised from Madden and co-workers (49).

adequate moisture. Symptom development begins after the foliar hexose level drops due to fruit set; subsequently temperatures below 16C were found to quicken lesion production (57) (Table 13). Troiano and Butterfield (78) determined that rainfall at the rate of 1 cm/hr can remove 55% of foliar chlorothalonil residues after 1 hour. Therefore the rainfall critical value in both revised disease severity rating (R) models was reduced to 0.5 inches.

An additional modification to the disease severity rating (R) models was to reduce the interval of time for the rainfall to the last 5 days. During both 1980 and 1983 it was noted that the leaf wetness and subsequent raised relative humidity levels after a rain were negated within 5 days.

The R values derived from the various combinations of temperature, relative humidity and rainfall in both models were expanded to increase the precision of the models (Tables 12 and 13).

The early blight disease control spray schedule (Table 3) was modified by making the disease severity rating (R) model the more important factor for determining whether to spray or not. The disease severity value (S) model was changed to designate a 5-day or 7-day spray interval. The reason for this alteration was because conditions favorable for penetration, infection and lesion development should be more important than conditions favorable for spore production (Table 14).

A second modification to this schedule was to eliminate the cumulative disease severity rating (CR). The R values are based on the temperature, relative humidities, and total rainfall for the past 5

TABLE 13. Revised early blight forecast model: postfruit-set disease severity ratings (R) as determined by number of hours of relative humidity greater than 90%, average daily temperature, and total rainfall.

Average Temp (C) ^a	Hours RH>90% ^b	Total Rainfall ^c	R ^d
<17	<60	<0.5	2
>17	<60	<0.5	2
<17	<60	>0.5	4
<17	>60	<0.5	4
>17	<60	>0.5	4
<17	>60	>0.5	5
>17	>60	<0.5	5
>17	>60	>0.5	6

^a Average daily temperature during last 5 days (C).

^b Hours of Relative humidity greater than 90% during last 5 days.

^c Total rainfall during last 5 days (inches).

^d The range of disease severity ratings (R) are from 0 (unfavorable weather conditions for *Alternaria solani* spore development and infection) to 6 (highly favorable conditions).

Table data revised from Madden and co-workers (49).

TABLE 14. Revised early blight disease control spray schedules as determined by recommendations for Tennessee and by cumulative disease severity values (CS) and disease severity ratings (CR).

Treatment ^x	Critical Limit	Spray Interval
5	None	5-day
7	None	7-day
A	R $\geq$ 5	7-day
	R $\geq$ 5 and CS $\geq$ 13 ^y	5-day
B	R $\geq$ 4	7-day
	R $\geq$ 4 and CS $\geq$ 11	5-day
C	R $\geq$ 3	7-day
	R $\geq$ 3 and CS $\geq$ 9	5-day
K	None	None

^x Treatments A, B, and C have FAST-determined applications and intervals, and treatments 5 and 7 have set 5-day and 7-day spray intervals.

^y CS represents the 5-day cumulative disease severity value (S).
Table data revised from Madden and co-workers (49).

days, therefore the CR value includes weather data up to 9 days old. Since the life cycle of *Alternaria solani* can be completed in 5 days (27, 58, 84), this was dropped.

Chapter V

CONCLUSIONS

During 1980 the FAST-generated spray regimens C, B, and A (17, 12, and 5 sprays, respectively) were not able to control early blight as well as the more frequently sprayed 5-day spray interval method (26 sprays). However, there was no difference between the disease controlling ability of the recommended 7-day spray in interval method (18 sprays) and two of the FAST-generated spray regimens (17 and 5 sprays, respectively).

During 1983 the most frequently sprayed FAST-generated spray regimen (18 sprays) achieved the best control of early blight. This was followed by the 5-day (22 sprays) and the 7-day (19 sprays) spray interval methods, and a second FAST-generated spray regimen (15 sprays).

With the modification of environmental requirements which designate when and how often to spray, better disease control is possible. To obtain better control also requires that the timing of the initial spray application precedes the initial primary infections. Since infections often remain latent until fruit set, it can be difficult to ascertain when infections actually begin. The monitoring of quantities of air-borne conidia can be helpful for this timing, but subsequent monitoring of quantities cannot be used to determine later spray times. Due to the rapid ability of the conidia to germinate and to penetrate the tomato foliage when accompanied by favorable conditions the initial counts must be made daily.

Yields appear to be less sensitive than do levels of defoliation to the frequency of fungicide applications. Although, when the disease outbreak occurs late in the season additional spray applications cannot give any significant increase in yield, and the amount of early blight fruit rot is lessened.

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