ABSTRACT

THAYER, CHARLES L. Plant Disease Forecasting and Model Validation: Classic and Modern Approaches. (Under the direction of Turner B. Sutton.)

Alternaria blotch of apples emerged in the late 1980s in North Carolina threatening the nations seventh largest apple producing state. Alternaria blotch, causal agent *Alternaria mali*, has since spread throughout the entire Southeast apple growing region. Alternaria blotch proved to be difficult to control with the management programs in place at the time. Filajdic et al developed a weather-based disease-forecasting model to aid in the timing of fungicide applications to manage the disease. However, this model was based on the use of iprodione (Rovral), which never became fully registered for use on apples. The purpose of this project is to improve the prediction of the onset and progression of Alternaria blotch to aid in the timing of fungicide applications. The ability of four Alternaria models for predicting the occurrence of Alternaria blotch was examined over three growing seasons. Five sites across the apple production area of Henderson County, North Carolina were established to track disease progress and collect weather information. The data collected on-site were compared to the output of the disease models generated from on-site weather data as well as geospatial satellite based weather data. The initial results of the project show that none of the examined models exhibit a strong correlation with either the onset or the progression of the disease. However, examining the individual disease model attributes revealed key information about the disease progression. The detailed model analysis suggests that the initial inoculum level, in addition to the increasing susceptibility of the host, most readily influences the progression of the disease over the course of a growing season.

The traditional approach of plant disease model validations is usually limited in scope to counties, states, or regions. With the possible threat of bio-terrorist attacks on our nation's agricultural system, the ability to create and validate models on a national scale is of paramount importance in protecting America's immense agro-economic infrastructure. The nearly non-existent national disease incidence and severity data sets for foliar fungal pathogens are a serious limitation for the accurate validation of risk prediction models such as The North Carolina State University / Animal and Plant Health Inspection Service Plant Pathogen Forecasting System (NAPPFAST). The future of rapid disease model validations is dependent on the existence of research tools to give researchers the ability to accurately predict the potential establishment of exotic diseases. NAPPFAST is a template based modeling tool that uses daily 10-km^2 geospatial weather input to create empirical infection models. An adequate validation of NAPPFAST models requires a data set of disease observations with national coverage for multiple years, pathogens and crops. The object of this project was to investigate the potential suitability of meta-analysis techniques to validate the NAPPFAST infection model using disease observation data from fungicide trials available in Fungicide and Nematicide Tests reports. Data on the incidence of apple scab, caused by *Venturia inaequalis*, were obtained for 10 years for six locations and 25-years for one location. There was a poor correlation between the output from the NAPPFAST model and the observed incidence of apple scab for the locations and years examined. The model appears to be missing variables such as inoculum density or phenological data that may play a key role in apple scab forecasting.

PLANT DISEASE FORECASTING AND MODEL VALIDATION: CLASSIC AND MODERN APPROACHES

by
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BIOGRAPHY

Charles Lucas Thayer was born December 16, 1975 in the renowned arts community of Northampton Massachusetts. In 1998, while attending the University of Massachusetts at Amherst, Charles began his work in Integrated Pest Management with the Massachusetts state IPM coordinator Dr. Bill Coli and the vegetable IPM coordinator Ruth Hazzard. Charles graduated from the University of Massachusetts in 1999 with a Bachelor of Science degree in Environmental Science and a minor in Biology. In 2000, Charles began working as the Southern Appalachian Apple Integrated Pest Management Coordinator at the North Carolina State University Mountain Crops Research and Extension Center, located at Fletcher North Carolina. Charles managed apple IPM activities on over 80 orchards for 23 different growers. In 2003 Charles was accepted into the North Carolina State University department of Plant Pathology graduate program to study decision support systems. He is married to Rebecca Elizabeth Thayer and has two children: Isabella Elizabeth Thayer and Lucas Robert Thayer.

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Plant Disease Model Forecasting and Validation: Alternaria Blotch of Apples

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ABSTRACT

Thayer, C.L., Sutton, T.B., and Magarey, R.D. 2005. Disease model forecasting and validation: Alternaria blotch of apples

Alternaria blotch of apples, caused by *Alternaria mali,* emerged as a serious disease in the late 1980s in North Carolina and has since spread throughout the southeastern United States. Filajdic (7) developed a weather-based disease-forecasting model, analogous to a model used in Korea, to aid in the timing of fungicide applications to manage the disease. However, the Filajdic model was based on the use of iprodione (Rovral), which never became fully registered on apples. The objective of this study was to improve the prediction of the onset and progression of Alternaria blotch to aid in the management of the disease. The ability of four models used to predict diseases caused by *Alternaria* spp. was examined for their ability to predict the occurrence of Alternaria blotch. Sites were established across the apple production area of Henderson County, North Carolina to track disease progress and monitor weather variables for three consecutive growing seasons. The data collected on-site were compared to the output of the disease models generated from on-site weather data as well as geospatial ZedX weather data. None of the models examined accurately predicted either the onset or progression of the disease. However, when examined separately the individual disease model attributes revealed that the inoculum level, in addition to the

susceptibility of the host, most readily influenced the progression of the disease over the course of a growing season. A decision matrix to aid growers in managing the disease is proposed based on grower risk preference, an estimate of orchard inoculum level and cultivar.

INTRODUCTION

North Carolina is the nations' seventh largest apple producing state with over a million apple trees in production in 2001 (16). The small mountain community of Henderson County, North Carolina accounts for 65-70% of the entire North Carolina apple production. The unique geographic location and topographic features of Henderson County work together to create a premier apple growing area. However, these superlative apple-growing conditions create an environment ideal for a great diversity of plant pathogens for the growers of this area to manage (22). The ability for growers to accurately and precisely make management decisions in such a complicated cropping environment is highly desirable (16). Most apple growers have little time to decipher new and emerging technologies for possible inclusion into their bustling management schedule. Additionally, analytically testing a decision support system for single pathogens is beyond the scope of most growers. Apple growers would greatly benefit from a simplified management decision support system that would reduce the number or strengthen the accuracy of the management decisions that they make within a single apple-growing season (4, 12, 20, 21, 22).

Alternaria blotch of apples emerged in North Carolina in the late 1980s as a serious disease that quickly proved to be difficult to control (4), thus threatening one of the major industries of western North Carolina (16). First described in 1924 by Roberts (18), Alternaria blotch of apples is a polycyclic disease that primarily affects leaves and potentially causes devastating defoliation (8, 9, 15, 18). The causal agent of Alternaria blotch of apple is *Alternaria mali* (*Alternaria alternata* apple pathotype) which produces the host specific toxin AM1 (18). While *A. mali* is specific to apples, it is most aggressive to those apple cultivars with a parental lineage of Delicious (2). Small dark raised pimple-like lesions typify fruit infections and generally appear on or near lenticels. Infected leaves are characteristically distributed uniformly on foliage throughout the canopy, though they may be more severely affected in the lower 1/3 of the tree canopy where the foliage remains moist during wetting periods (22). Additionally, elevated mite populations act synergistically with Alternaria blotch infections to cause increased defoliation (4, 22). The incidence of Alternaria early in the apple-growing season is directly correlated with the observed severity of Alternaria at the end of the season (2, 7).

Following the outbreak of Alternaria blotch in the 1980s throughout the southeastern U.S., tools were developed and tested for timing fungicide applications. Filajdic (5) modified a disease model that was developed for use in Korea where Alternaria blotch had been a problem since the 1960s. The Kim model (13) was designed to predict the onset or initial occurrence of Alternaria blotch. In 1994 Filajdic (7) released a modified version of the Kim model, the Alt-Buster computer assisted model, for determining when to initiate fungicide sprays for the control of Alternaria blotch. The Alt-Buster model, developed for apple orchards with a high to moderate intensity of Alternaria blotch, is an empirical model that predicts the final percent defoliation of apple trees based on disease incidence early in the season. The Kim and Alt-Buster models both use a degree-day (DD) base; the model developed in Korea used a base of 10°C whereas Alt-Buster uses a base of 0°C. The Alt-

Buster model is based on DD accumulated beginning from 15 April, which corresponds to the phenophase tight cluster to pink bud during most seasons in NC. The Filajdic model threshold initiates fungicide sprays when at least 400 DD have accumulated along with 300 hours of leaf wetness from precipitation and dew combined. The Kim model begins accumulating DD on 20 April (approximately phenophase bloom) and the first symptoms of disease are predicted to occur when at least 160 DD have accumulated followed by four rain events.

The Alt-Buster model was developed specifically for use with the fungicide iprodione (Rovral), which was registered for use on apples in NC at the time of the Filajdic study under a Section 18 Emergency Exemption. Iprodione provided excellent control and was able to arrest an epidemic once it began (5, 7). After the Section 18 expired, iprodione was never granted full registration for use on apples and until the QoI (strobilurin) fungicides were registered on apples in 1999/2000, there were no effective fungicides available for growers to use. The QoI fungicides however, are generally not as effective at controlling Alternaria blotch as iprodione; consequently, an empirically derived threshold of 20% incidence of was established for the first fungicide application. However, resistance has recently been reported to the QoI fungicides in *A. mali*, necessitating the need to conserve their use (14). Models, if available, could assist in timing applications of QoI fungicides as a resistance management strategy (5, 7, 15, 22).

In addition to the Alt-buster and Kim models developed specifically for Alternaria blotch of apples, there are other models used for Alternaria diseases, which are widely employed and have been found to be robust. TOM-CAST is a simple model that predicts the likelihood of the development of late blight on tomato (caused by *A. solani*). TOM-CAST is based on Disease Severity Values (DSV), which are calculated daily, based upon the hours of leaf wetness and the average temperature during the leaf wetness period. Daily DSVs are summed to produce an accumulated DSV value and the accumulated value serves as a threshold to trigger the next fungicide application (17).

ALTER-RATER is a weather-based point system designed to assist in the timing of fungicide applications for the control of Alternaria brown spot on citrus (caused by *A. citri*). Rainfall is an important factor affecting disease incidence, but the amount of rainfall is not critical as long as it is more than a trace. To use the system, points are assigned to each day based on the rainfall, leaf wetness and average daily temperature. The daily point scores are totaled and a fungicide application is made when the selected threshold value is reached. Threshold values vary with the susceptibility of the cultivars and the disease history in each grove. When using this system, citrus growers apply the first fungicide spray when the spring flush reaches 5 to 7 cm in length. Thereafter, all sprays are weather based and are determined by the accumulation of the point score. Each time a spray is applied the score returns to zero (1).

The objective of this study is to investigate the ability Alt-Buster, the Kim model, TOMCAST, and ALTER-RATER to predict the progress of Alternaria blotch for use as a management aid for controlling Alternaria blotch. Additionally, the fundamental variables driving the epidemic during the period of rapid disease increase of the Alternaria epidemic were identified.

MATERIALS AND METHODS

Data collection. In all years, on-site weather stations were established during May in orchards with strains of Delicious apples in Henderson County, North Carolina. The sites included in the 2002 study were designated as Staton Packhouse (82.3757 longitude, 35.313 latitude, and altitude 656.8 meters), Barnwell Ranch (82.3614 longitude, 35.3632 latitude, and altitude 642 meters), Barnwell Lancaster (82.4227 longitude, 35.376 latitude, and altitude 648.5 meters), and the Mountain Horticultural Research Station (MHCRS) (82.5669 longitude, 35.43 latitude, and altitude 656.8 meters). The relative locations of each site are shown in Fig. 1. Data were collected from the same sites in 2003 with the addition of a fifth location designated as Joel Reed (82.3101 longitude, 35.3802 latitude, altitude 815.1 meters).

During 2003 GIS/GPS was used to capture geospatial information pertaining to the data collection sites. Each orchard block was mapped and plotted as an ellipsoid by a handheld Teletype 3108 GPS receiver equipped iPaq 3650 running Microsoft 2002 Pocket and ESRI ArcPad software. The locations of each weather station were captured as points into the GIS as shape files. The captured shape files were transferred to a Desktop PC running Windows 2000 and ESRII ArcPad to be integrated with Geo-referenced world files displaying topographic and/or satellite ground imagery. In 2004 two blocks of Golden Delicious were added to the study to examine the effect of cultivar differences on the accuracy of the model output. The two Golden Delicious orchards were Dalton Spicer Cove and Coston-Apple Valley. In 2004 two of the orchards initially used in the study were removed and GIS/GPS was used to find suitable replacement sites for these orchards. The entire Barnwell-Lancaster orchard was removed by the growers and the proximal replacement site was determined to be Coston-Apple Valley (Fig. 1). Additionally, the Reed orchard was not used in 2004 and the ideal proximal location in the Sugarloaf Mountain area was determined to be the orchard designated as Dalton-Spicer Cove (35.376775 longitude, 82.26723 latitude). Lastly, the Red Delicious trees at Barnwell-Ranch were removed at the end of 2003 and the most proximal replacement site was the site designated as the Nix-Mystery Orchard (35.36636 longitude, 82.34349 latitude).

Monitoring sites and weather data. Weather data at each location were collected using Spectrum Technologies Watchdog model 450s. The Watchdogs loggers have built-in sensors for recording temperature and humidity. External sensors monitored leaf wetness and rainfall. Data were downloaded from the on-site weather stations on 2-week intervals.

Site data (including longitude, latitude and elevation for each location) were used by ZedX, Inc. (369 Rolling Ridge Drive, Bellefonte, PA 16823) to establish each data set, and the parameters and date ranges for the models. The parameters for each model output were provided as follows: Alt-Buster included DD, accumulated DD, wet hours, and accumulated wet hours; Kim model included DD accumulated DD, and daily precipitation; TOM-CAST included DSV accumulated DSV, wet hours, and accumulated wet hours; ALTER-RATER included daily score, and accumulated score. In addition to model output, daily weather parameters for each location were provided, and includied daily average temperature, daily precipitation, and daily wet hours.

Climatological data. A 30-year climatology for Henderson County was calculated from the daily average temperature and rainfall collected over a 30-year period from data provided by the State Climate Office of North Carolina (SCONC). The Henderson County SCONC data set included temperature and rainfall data from 1974-200 for each of the three sites maintained by the SCONC in Henderson County. They included; Asheville WSO AP

Asheville, latitude 35.43°, longitude 82.55°, elevation 652.7 m.; Fletcher 3 W Fletcher, latitude 35.43°, longitude 82.57°, elevation 631.4 m; Hendersonville 1 NE Hendersonville, latitude 35.33°, longitude 82.45°, elevation 658.8 m. The State Climate Office of North Carolina site locations are shown in Fig. 1.

The 30-year climatology data set consisted of weather variables recorded from 1974 through 2003. Data for each variable were examined for the same period as used for evaluating the Alternaria models: 28 April (derived from the 14-year average of bloom recorded at the MHCRS) through 31 July; 31 July is 95 days from 28 April. The 30-year climatology was constructed to create a baseline to use as a comparison of the years' data that were collected in the project (2002, 2003, 2004), as well as to classify the normalcy of each of the years' data used in the study. In addition, the climate data were used as a check when the data collection devices used in the project generated suspected errors. The three co-op weather station data sites from the NCSCO coordinates were entered into a GIS layer along with the coordinates of the project sites. ESRII Arc GIS was used to determine the most proximal NCSCO Weather Station from each of our sites.

Collection of disease severity data. Plots in each orchard in this study were established in each orchard in 2002, 2003, and 2004 following the guidelines established by Filajdic (6). In each orchard site, four trees (Delicious) were arbitrarily selected centered in the vicinity of the WatchDog Model 450 weather station. Each selected tree was visually divided into four distinct quadrants using a compass. Each quadrant corresponded to the direction it faced, designated as the following: 1 (north), 2 (east), 3 (south), and 4 (west). Additionally, each quadrant contained two flagged shoots, marked to indicate the tree, quadrant, and terminal number. The tagged terminals were assessed for Alternaria blotch incidence and severity throughout the season; the two terminals in each quadrant were counted on each assessment. Two shoots per quadrant for each of the four trees per site were assessed for the remainder of the season to minimize the potential loss of data during summer pruning and storms. Tags on some shoots blew off during the season and subsequent data were recorded as missing. In 2004, Golden Delicious trees were monitored for Alternaria blotch in two orchard sites with the protocol above.

Assessments of the severity of Alternaria blotch were based on a modified Horsfall/Barratt scale with a disease severity rating scale from 0 to 5 representing the percentage of leaf area affected: 0=0%, 1=3%, 2=4-6%, 3=7-12%, 4=13-25%, 5=26-50% (9). The modified Horsfall/Barratt scale used in this project is limited to 50% severity because leaves with over 50% of the surface covered with lesions abscise. Data on disease incidence were obtained from the number of leaves that exhibited symptoms of Alternaria blotch over the number of symptom-free leaves. Assessments were conducted on 17 and 29 May, 5, 11, and 19 June, 9, 16, and 31 July, 7 August, 2002, 8 and 22 May, 5 and 18 June, 5 and 26 July, 29 August, 2003, 12 April, 14 May, 1 and 20 June, 5 and 25 July, 2004. The disease data collected for all years and all locations were used for comparison to the model output.

Symptoms of Alternaria blotch closely resemble those of frogeye leaf spot (caused by *Botryosphaeria obtusa*) as well as injury from applications of the fungicide captan. Consequently, when first symptoms of Alternaria blotch were observed symptomatic leaves found nearby tagged terminals were placed in plastic bags, and stored in an incubator at 4°C until they could be processed. The leaves were surface disinfested in 10% chlorox for 5 s and sections of the lesions were placed on one-half strength acidified potato dextrose agar (PDA) medium (19.5 grams of PDA, 10 grams of agar, 15 drops of 50% lactic acid and 1L of water). The dishes were incubated at 28°C until sporulating colonies formed. Conidia from each colony were examined at 200X and compared to published descriptions confirm the presence of *A. mali* (18). Additionally, Koch's postulates were performed on a subset of isolates to further confirm that the isolates were *A. mali*.

Models evaluated. The models investigated in this study were: the Alt-Buster model for Alternaria blotch of apples (7); the Kim model for Alternaria blotch of apples developed in Korea (13); the TOM-CAST model (TOMato disease foreCASTing) for late blight of Tomato (17); and the ALTER-RATER model for Alternaria on lemons (1). The on-site weather stations and ZedX provided data to run the individual models. The model output (accumulated TOM-CAST DSVs, accumulated ALTER-RATER daily assigned points, accumulated Alt-buster degree-days and leafwetness hours, and accumulated Kim Model CDPs) was compared to the observed incidence. In addition to the models accumulated hours of leaf wetness and day of the year were also evaluated as a predictor of Alternaria blotch incidence. All models were initiated on 28 April which coincides with the average petal fall date at the study sites. The parameters for each model were computed as described below.

TOM-CAST. TOM-CAST is derived from the original F.A.S.T. (Forecasting *Alternaria solani* on Tomatoes) model developed by Madden, Pennypacker, and MacNab at Pennsylvania State University (PSU) (17) (Table 1). DSVs were accumulated based on average temperature during leaf wet hours and hours of leaf wetness per day (17). The DSVs range from 0 to 4 where 0 reflects unfavorable conditions and 4 reflects very favorable conditions for disease development.

ALTER-RATER. ALTER-RATER is based on the accumulation of assigned daily points. Daily points were accumulated when rainfall, leaf wetness and average daily temperature requirements were met as described in Table 2 (1).

Kim model. The Kim model is based on the accumulation of cumulative degree portions (CDP), calculated as CDP = $\Sigma(T_d\text{-}10)$, when T_d is daily average temperature over 10°C. This model was developed to predict the time of initial disease occurrence. According to the model, initial disease occurrence takes place after approximately 160 CDP have accumulated and then followed by at least four occurrences of rain (13).

Alt-Buster. The Filajdic Alt-Buster model was designed to predict the time of 65% disease incidence (7). In order to examine this model, the accumulated product of the DD and leaf wetness as well as only the DD accumulation was utilized. Degree-days (base 0°C) were accumulated as the daily average temperature greater than 0°C.

Data analyses. Disease progress curves were constructed for each location and year, for all locations across years and for Golden Delicious (2004 only). Each model was examined using regression analyses to determine the relationship between the observed disease incidence and the model output for each site and year, for each site across all years and for all sites across all years. Additionally, disease incidence was compared to the output of each model across all sites and years for orchards classified as high to moderate risk sites only. Regressions were also run between disease incidence and the actual day of the year (21).

RESULTS

Thirty-year climatology. Rainfall for the period 28 April through 31 July in 2003 and 2004 were above the 30-year average (Table 3). 2003 was the wettest year of the study with rainfall almost double that of the 30-year average. Temperatures during the 3 years of the study were each within the range of the 30-year normal.

Alternaria blotch incidence. The incidence of Alternaria blotch averaged over all locations was greatest in 2002 (Fig. 2). However, according to the 30-year average, 2002 was comparatively dry, whereas 2004 and 2003 were average and considerably wetter, respectively, than normal (Table 3). In 2002 disease increased more rapidly earlier in the season than in 2003 or 2004 (Fig. 2). The final disease incidence in 2002, 2003, and 2004 was 84%, 55% and 66% respectively. The first symptoms of Alternaria blotch were observed by most locations in mid to late May (days 130 – 150) (Fig. 3a). However, it is likely first symptoms occurred at Ranch/Nix prior to day 130 because 20% of the leaves were affected in day 137, the first sample date (Fig. 3d).

The incidence of Alternaria blotch was least at Dalton/Reed in all years (Fig. 3a). The final disease incidence was >70% all other sites and all years except for MHCRS in 2002 and 2003 when the final incidence was between 50 and 60% (Fig. 3b). When data from the orchards with Red Delicious and Golden Delicious were examined separately the disease progressed more rapidly in orchards with the cultivar Delicious than Golden Delicious in 2004 (Fig. 2b).

Model Output. None of the models satisfactorily predicted the incidence of Alternaria blotch through the season (Figs. 4-8). Also, each model tended to over-predict the incidence of the disease at the onset of the epidemic. Coefficients of determination for regression of the observed incidence and the output of the various models using on-site data for 2002-2004 ranged from 0.42 for TOM-CAST and Kim models to 0.52 for Filajdic DD (Table 4). Interestingly the R^2 for the regression of the observed incidence and day of the year was as high as that of any of the models. When data from ZedX were used in the analyses, all R^2s were lower and ranged from 0.26 for Filajdic to 0.41 for Kim and ALTERATER models (Table 4). Accumulated wet hours were the poorest predictors of Alternaria blotch incidence with R^2= 0.22. When only sites with moderate to high infection were included in the regression analyses the R^2 of all models except the Filajdic model improved, however they still accounted for <63% of the variation in the data (Table 5). The observed incidence and severity as well as both the on-site weather data used to calculate the model output and a summary of the model output derived from the ZedX weather data are found in Appendix 1.

DISCUSSION

None of the models examined satisfactorily predicted the onset of progression or Alternaria blotch. Most models accounted <60% of the variation in the data. Because none of the models examined accurately predicted either the onset or progression of the disease through the growing season, other variables such as the inoculum density or the susceptibility of the cultivar grown maybe more important in determining the progress of Alternaria blotch epidemics.

Kim et al (13) found a positive relationship between wetness periods and disease development. This is not surprising since Alternaria requires free moisture for spore release and germination (19). In the Southern Appalachian region free moisture is continually available, especially in the morning mists that are commonplace (22). When the parameter of leaf wetness hours and the degree-day accumulations were factored together to examine the Alt-Buster model (as the product of the two parameters), the model did not fit as well (Table 4). Additionally, hours of leaf wetness alone was a poor predictor of the incidence of infection (Table 4). It appears that the typically abundant free moisture in the form of dew and fog in the mornings of Henderson County during the epidemic provides the necessary leaf wetness since infection can occur in as few as 5.1 hr at 20.3 C with an incubation period of only 24 hr (18). Therefore measurable wetness does not appear to be a limiting factor for the progression of the disease as far as a model parameter is concerned. Light dew and fog, as a factor of leaf wetness, could possibly explain why such little Alternaria blotch was observed at the higher elevation orchards, primarily Reed/Dalton (Fig. 1) where fewer hours of leaf wetness were recorded (C. Thayer unpublished). This could also explain why day of the year was as good a predictor of the disease incidence as the output of any of the models.

A specific disease incidence or severity threshold for initiating a control program for Alternaria blotch has not been firmly established. However, the pioneering work done by Filidjic (6), suggests that the first application should be applied before 35% disease incidence is exceeded. To maintain the disease incidence at or below this level, it is necessary to keep the initial inoculum as low as possible. Filajdic (3) found that *A. mali* over-wintered in leaves on the orchard floor and buds in the tree, but the leaves were identified as the most important over-wintering site. Filajdic et. al., (9) found that only a small amount of over-wintering inoculum is needed to initiate an epidemic. The abundance and viability of over-wintering inoculum did not greatly differ among the three orchards he studied, each with distinctly different environments and different disease histories (3). Nonetheless shredding over-wintering leaves with a flail mower or fall urea treatments can reduce leaf litter in orchards and may be useful for reducing the inoculum level of *A. mali* (10).

Because of the poor performance of any of the models and the significant investment needed to run a disease decision support model, we developed two decision matrix tables for managing Alternaria blotch. A decision matrix is a simple heuristic decision support system that is based on examining the individual requirements for the probable infection of *A. mali* on apple by identifying the relevant attributes of the orchard of interest. The two decision matrix tables are determined by the grower's attitude on risk: the first table (Table 6) is intended for a risk averse grower who is less likely to employ a disease model in his or her management plan; the second table (Table 7) is devised for a risk neutral grower who would be more likely to employ a disease model in their management plan. The key ingredients of the matrices for managing Alternaria blotch are orchard risk of *A. mali* and the relative susceptibility of the cultivar.

The orchard risk can be estimated for an orchard based on the previous year's Alternaria blotch incidence as well as the current years incidence in relation to the time of year. Filajdic (2) showed a strong correlation between the disease incidence observed mid-June and the subsequent amount of defoliation observed at the end of the season. Furthermore, he noted that the disease tended to increase more rapidly in mid-June than at any other time during the season. Finally, if incidence exceeded 35% in mid-June then final incidence would likely exceed 70%, resulting in extensive defoliation. Therefore, he concluded that mid-June would be an ideal time for determining how to manage the disease for the remainder of the season (8). Consequently, we established three risk levels: low, moderate, and high. An orchard of slightly susceptible cultivars with a history of minimal Alternaria blotch, defined by an incidence of 35% or less in early to mid-June, would be classified as low risk. Conversely, an orchard comprised of a highly susceptible cultivar which has a history of Alternaria blotch that reaches the 35% threshold incidence by the second week in June can be considered as high risk for Alternaria blotch and defoliation.

Classifying moderate risk level is not as clearly definable or concise as the description of low and high-risk orchards, given that the resistance and/or susceptibility of apple cultivars to *A. mali* is within a continuum and not distinct graduations. For the purpose of our decision matrix, we define moderate risk as an orchard that contains moderately susceptible cultivars and has Alternaria blotch from year to year but it is not consistently at or above threshold of 35% by second week in June.

Filajdic published two papers on the relative susceptibility of cultivars (6, 10). We selected one of these and arbitrarily divided the cultivar list into three sections (Table 8): the cultivars with a mean disease severity >1 are considered to be highly susceptible to Alternaria blotch and include strains of Delicious and cultivars with Delicious parentage, cultivars with a mean disease severity <1 but >0.3 are considered to be moderately susceptible; and the cultivars with a mean disease severity < 0.3 are considered to be slightly susceptible.

Action items within the matrix are: no additional management needed, scouting, and calendar spray. No additional management needed means that fungicides specifically targeted to Alternaria blotch aren't needed prophylactically. Scouting should be used in orchards where the disease is sporadic, and fungicides should be applied only if the disease incidence exceeds 35%. Calendar sprays refer to the need to use sprays targeted to Alternaria blotch on a preventative basis, beginning when the incidence exceeds 20%. A threshold of 20% was selected because the QoI fungicides, which are conventionally used, are generally not as effective as iprodione (T.B. Sutton personal communication). By using these matrices growers should be able to avoid unnecessary sprays in orchards where the disease isn't a problem and optimize the application of fungicides in orchards where the disease is a chronic problem.

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Table 1. Parameters used by TOM-CAST[a] to calculate Daily Severity Values (DSV) [a]

Average Temperature During Leaf Wet Hours degree C	Hours of Leaf Wetness per Day				
13-17	0-6	7-15	16-20	21+	
18-20	0-3	4-8	9-15	16-22	23+
21-25	0-2	3-5	6-12	13-20	21+
26-29	0-3	4-8	9-15	16-22	23+
Daily DSV =	0	1	2	3	4

[a] Poysa, V., Brammall, R.A., Pitblado, R.E. 1993.

Table 2. Parameters used by the ALTER-RATER model to assign daily scores[a]

Daily Points Assigned				
Rainfall (>0.01 inch)	Leaf Wetness (> 10 hr)	Ave. daily temp. (°F)	Ave. daily temp. (°C)	Assigned score
+	+	68-83	19.98	11
+	+	>83	>28.31	8
+	+	<68	<19.98	6
+	-	68-83	19.98-28.31	6
+	-	>83	>28.31	4
+	-	<68	<19.98	3
-	+	68-83	19.98-28.31	6
-	+	>83	>28.31	6
-	+	<68	<19.98	4
-	-	68-83	19.98-28.31	3
-	-	>83	>28.31	0
-	-	<68	<19.98	0

[a] Bhatia, A., Roberts P.D., and Timmer, L.W. 2003

Table 3. Average daily rainfall and temperature for Henderson County NC for the period 28 April – 31 July 2002-2004 compared to the 30-year average (1974-2004).

	Rainfall (cm)		Temperature (°C)	
Year	30-year Average	Observed	30-year Average	Observed
2002	34.67	29.74	20.95	20.54
2003	34.67	67.46	20.95	20.17
2004	34.67	42.37	20.95	20.67

Table 4. Regression analysis of observed disease incidence versus model output for all locations and all years (2002, 2003, 2004).

Model[a]	**Data Source**	**n**	**R^2**
Day of Year			0.52
Filadjic DD	observed	87	0.52
Filadjic	observed	87	0.41
Kim	observed	87	0.51
ALTER-RATER	observed	87	0.51
TOM-CAST	observed	87	0.42
Acc Wet Hours	observed	87	0.41
Filadjic DD	ZedX	87	0.37
Filadjic	ZedX	87	0.22
Kim	ZedX	87	0.41
ALTER-RATER	ZedX	87	0.41
TOM-CAST	ZedX	87	0.26
Acc Wet Hours	ZedX	87	0.22

[a]See text for description of models. Day of year is actual calendar day of year. Acc Wet Hours is the accumulated hours of leaf wetness.

Table 5. Regression analysis of observed disease incidence versus model output for high to moderate risk sites for all years (2002, 2003, 2004).

Model[a]	**Data Source**	**n**	**R^2**
Day of Year			0.63
Filadjic DD	observed	77	0.54
Filadjic	observed	77	0.41
Kim	observed	77	0.63
ALTER-RATER	observed	77	0.63
TOM-CAST	observed	77	0.58
Acc Wet Hours	observed	77	0.53
Filadjic DD	ZedX	77	0.45
Filadjic	ZedX	77	0.35
Kim	ZedX	77	0.48
ALTER-RATER	ZedX	77	0.54
TOM-CAST	ZedX	77	0.38
Acc Wet Hours	ZedX	77	0.37

[a]See text for description of models. Day of year is actual calendar day of year. Acc Wet Hours is the accumulated hours of leaf wetness.

Table 6. Risk Averse Decision Matrix for managing Alternaria blotch.

Orchard Risk	Susceptibility of Apple Cultivar		
	High	Moderate	Slight
Low	Scouting	No additional management needed	No additional management needed
Moderate	**Scouting/ Calendar spray**	**Scouting/ Calendar Spray**	No additional management needed
High	Calendar spray	**Scouting/ Calendar spray**	**Scouting/ Calendar spray**

Table 7. Risk neutral Decision Matrix for managing Alternaria blotch.

Orchard Risk	Susceptibility of Apple Cultivar		
	High	Moderate	Slight
Low	Scouting	No additional management needed	No additional management needed
Moderate	Scouting	No additional management needed	No additional management needed
High	Scouting	Scouting	Scouting

Table 8. Susceptibilities of cultivars and selections to Alternaria blotch based on mean severity ratings by Filadjic and Sutton (6).

Cultivar or selection	Mean Disease Severity	Susceptibility
Ace Spur	1.50	High
Red Delicious	1.36	High
Red Chief	1.26	High
Early Red One	1.23	High
Red Delicious	1.22	High
Oregon Spur	1.21	High
Top Spur	1.15	High
Nured Spur	1.15	High
Silver Spur	1.11	High
Ultrared	1.07	High
Scarlet Spur	1.07	High
Dixiered	1.07	High
Empire	0.78	Moderate
Stark Spur	0.78	Moderate
McSpur Green	0.74	Moderate
Golden Supreme	0.70	Moderate
Lurared	0.63	Moderate
Red Yorking	0.52	Moderate
New Red McIntosh	0.50	Moderate
Red Gala	0.47	Moderate
Commander York	0.46	Moderate
Firmgold	0.44	Moderate
Jon-A-Red	0.38	Moderate
Red Fuji	0.31	Moderate
Mutsu	0.26	Slight
Fulford Gala	0.25	Slight
Law Spur	0.24	Slight
Lorigold	0.22	Slight
Akane	0.20	Slight
Braeburn	0.20	Slight
Nittany	0.19	Slight
Golden Delicious	0.19	Slight
Summer Treat	0.19	Slight
Stayman	0.18	Slight
Nu Red Rome	0.18	Slight
Ginger Gold	0.17	Slight
Starkspur Winesap	0.14	Slight
Yellow Delicious	0.13	Slight
Smoothee	0.12	Slight
Winesap	0.11	Slight
Ozark Golden	0.11	Slight
Royal Gala	0.11	Slight
Ultragold	0.07	Slight
Grandspur	0.06	Slight
Granny Smith	0.06	Slight
Jonagold	0.06	Slight
Lysgolden	0.05	Slight

FIGURE LEGENDS

Figure 1. Map of Henderson County, North Carolina and surrounding area. The State Climate Office of North Carolina data site locations are shown in the map, indicated by triangles. Circles indicate the locations of the observed data sites and on-site weather stations. Squares represent the locations used in 2004 as replacement data collection sites for the orchards that became unavailable for use.

Figure 2. The disease progress of Alternaria blotch through the growing season, 2002-2004. A.) All locations, B.) Golden vs. Red locations 2004 only.

Figure 3. The disease progress of Alternaria blotch in study orchards, 2002-2004. A) Dalton-Reed, B) MHCRS, C) Staton, D) Coston-Lancaster.

Figure 4. Regression of observed incidence of Alternaria blotch versus TOMCAST model output from on-site data. A) 2002, B) 2003, C) 2004.

Figures 5. Regression of observed incidence of Alternaria blotch averaged over all locations versus ALTER-RATER output from on-site data. A) 2002, B) 2003, C) 2004.

Figure 6. Regression of observed incidence of Alternaria blotch averaged over all locations versus Kim Model output from on-site data. A) 2002, B) 2003, C) 2004.

Figure 7. Regression of observed incidence of Alternaria blotch averaged over all locations versus Alt-Buster DD output from on-site data. A) 2002, B) 2003, C) 2004.

Figure 8. Regression of observed incidence of Alternaria blotch averaged over all locations versus the accumulation of wet hours from on-site data. A) 2002, B) 2003, C) 2004.

Figure 1. Map of Henderson County, North Carolina and surrounding area. The State Climate Office of North Carolina data site locations are shown in the map, indicated by triangles. Circles indicate the locations of the observed data sites and on-site weather stations. Squares represent the locations used in 2004 as replacement data collection sites for the orchards that became unavailable for use.

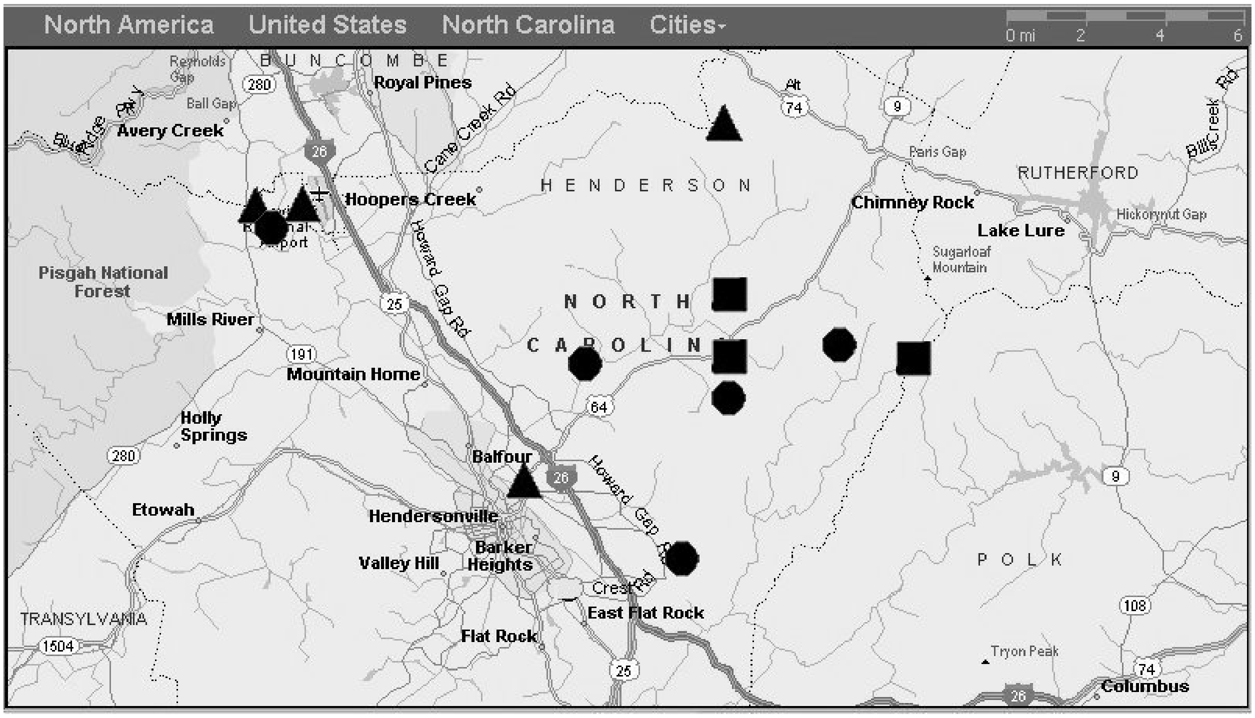


Figure 2. The disease progress of Alternaria blotch through the growing season, 2002-2004. A.) All locations, B.) Golden vs. Red locations 2004 only.

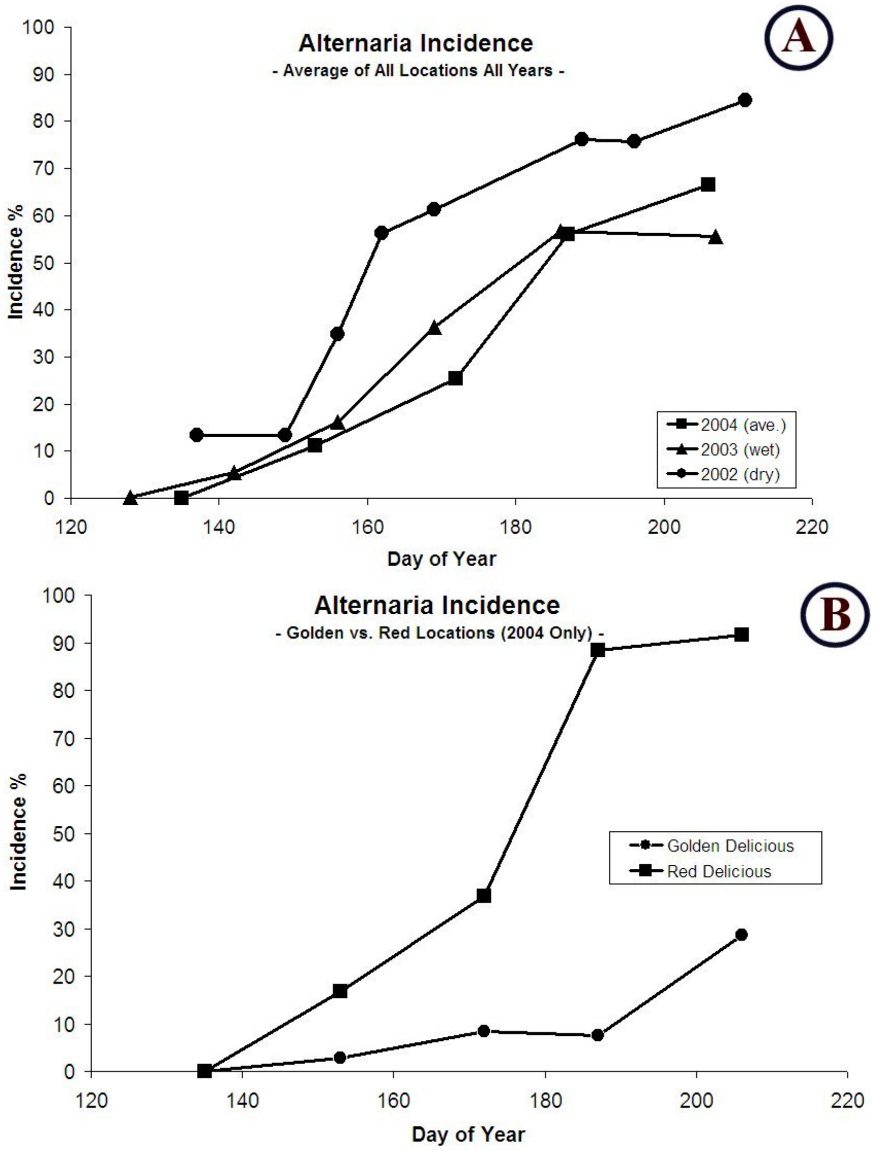


Figure 3. The disease progress of Alternaria blotch in study orchards, 2002-2004. A) Dalton-Reed, B) MHCRS, C) Staton, D) Coston-Lancaster.

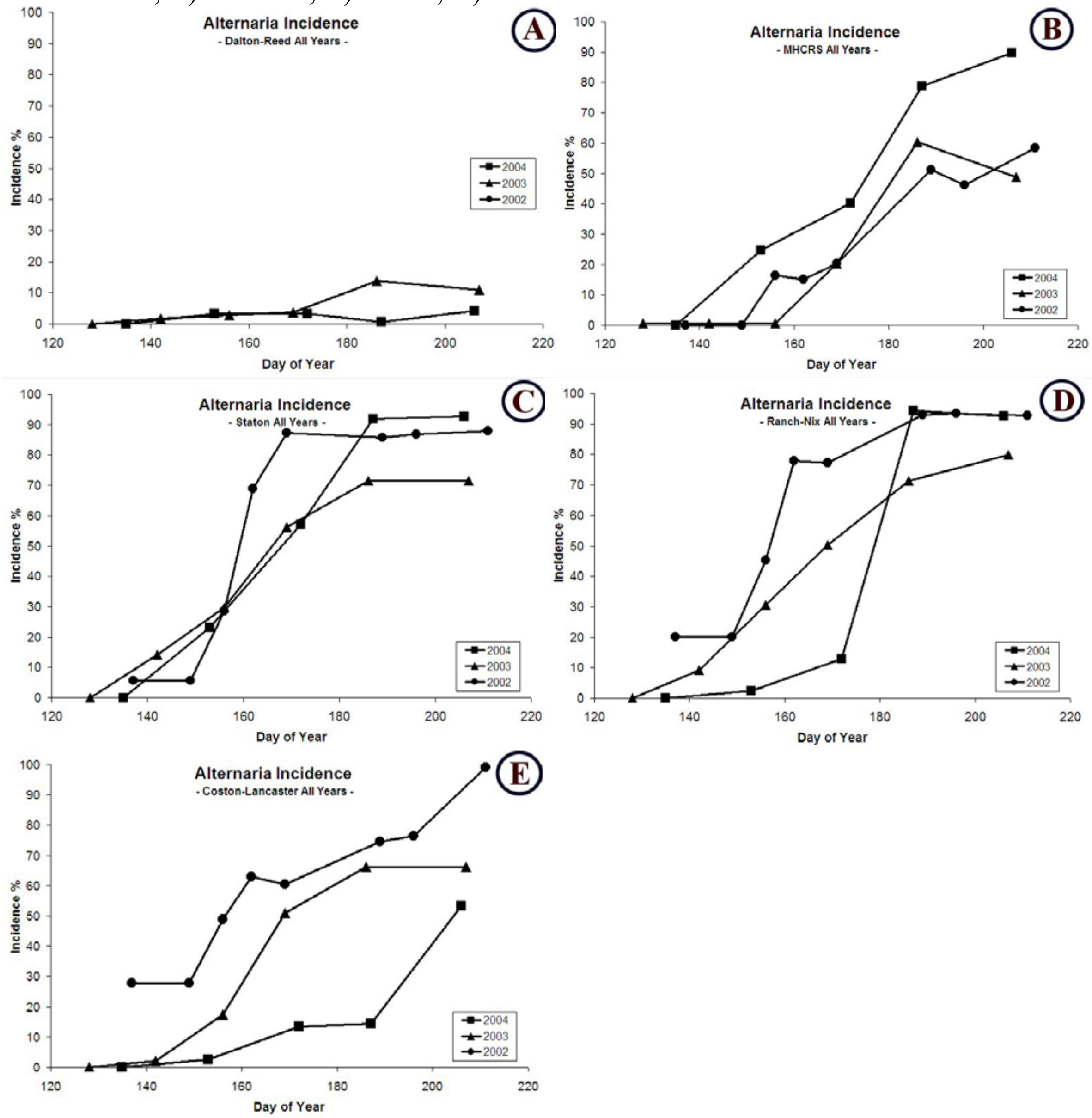


Figure 4. Regression of observed incidence of Alternaria blotch versus TOMCAST model output from on-site data. A) 2002, B) 2003, C) 2004.

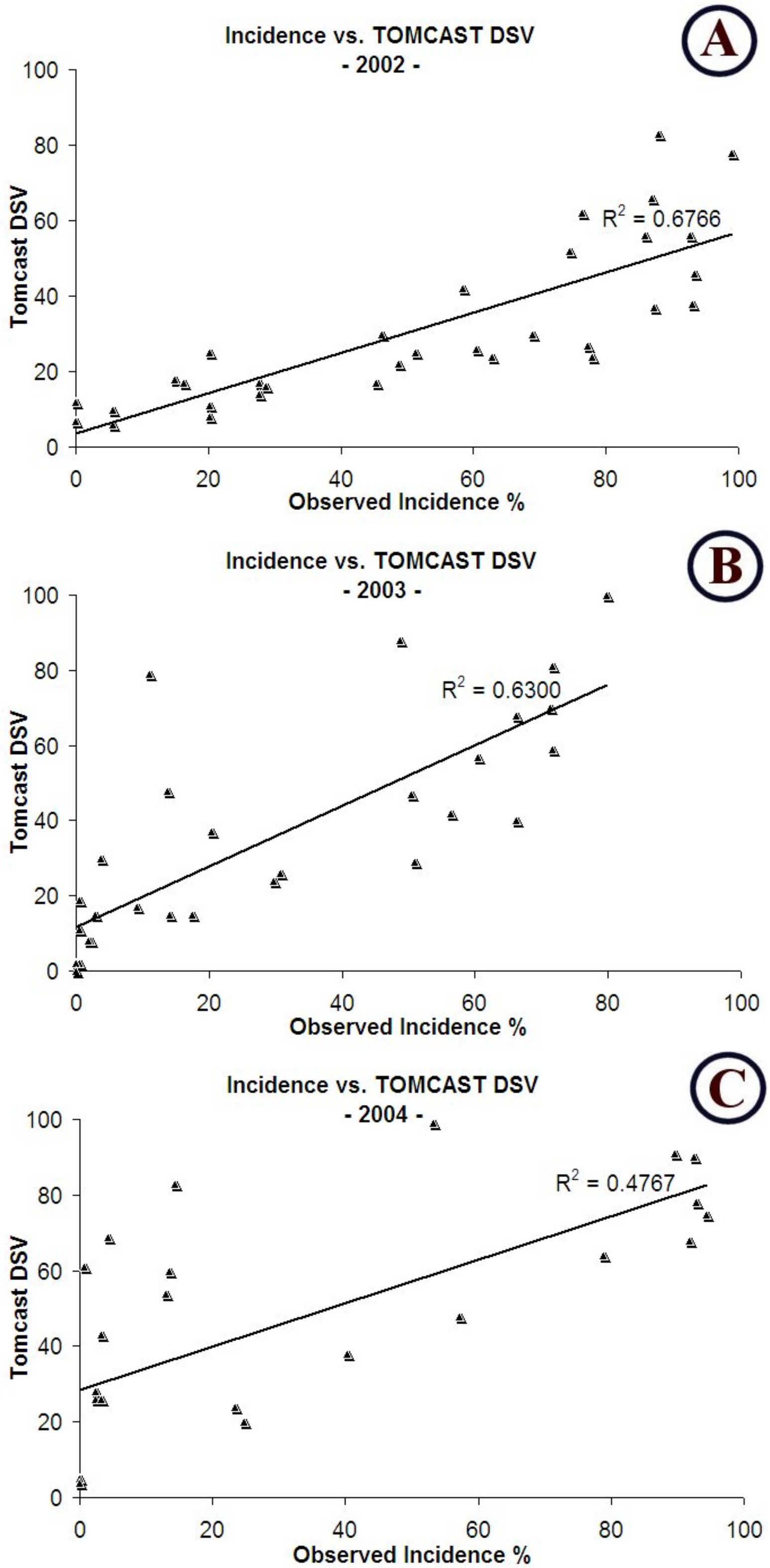


Figure 5. Regression of observed incidence of Alternaria blotch averaged over all locations versus ALTER-RATER output from on-site data. A) 2002, B) 2003, C) 2004.

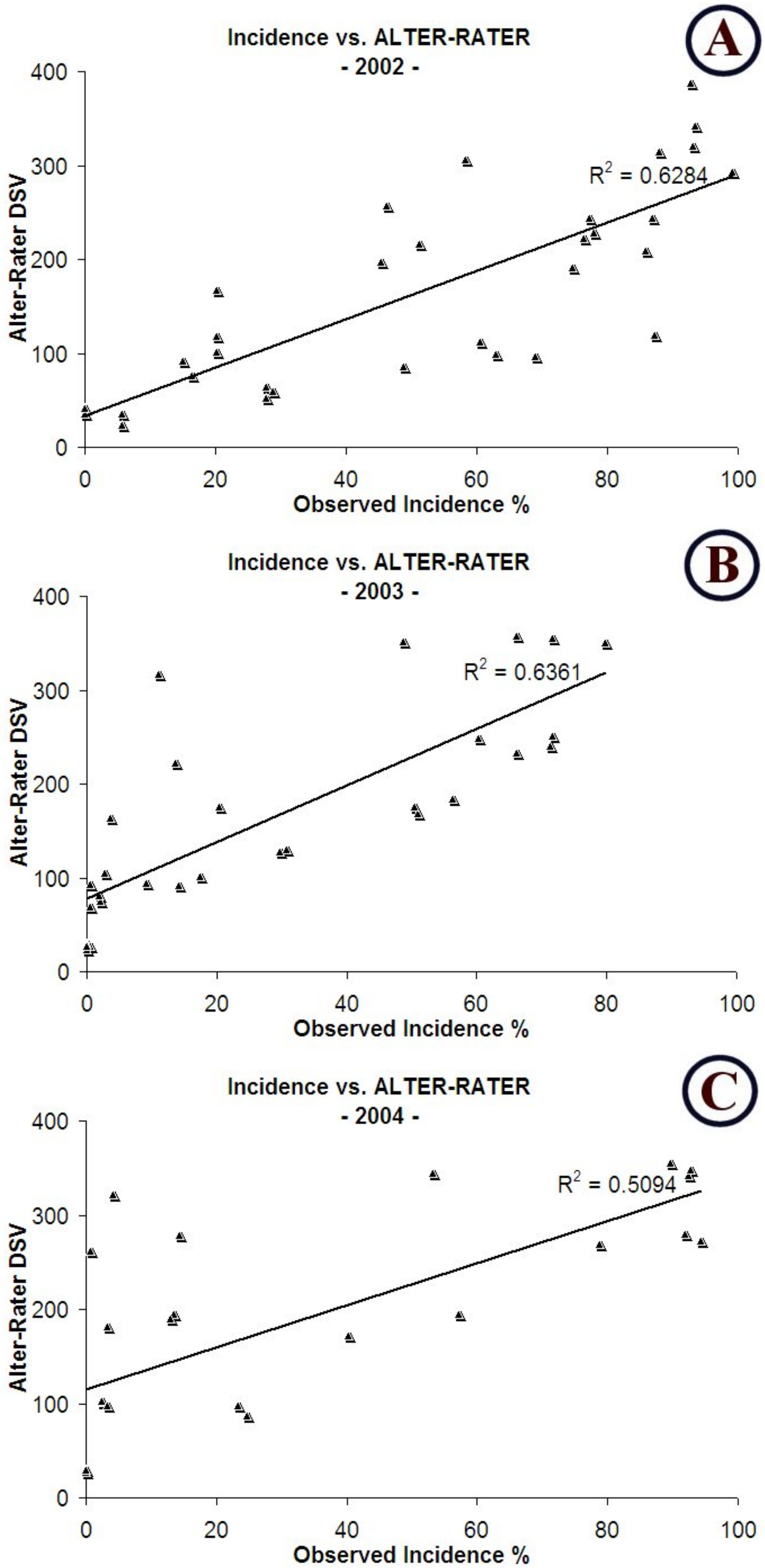


Figure 6. Regression of observed incidence of Alternaria blotch averaged over all locations versus Kim Model output from on-site data. A) 2002, B) 2003, C) 2004.

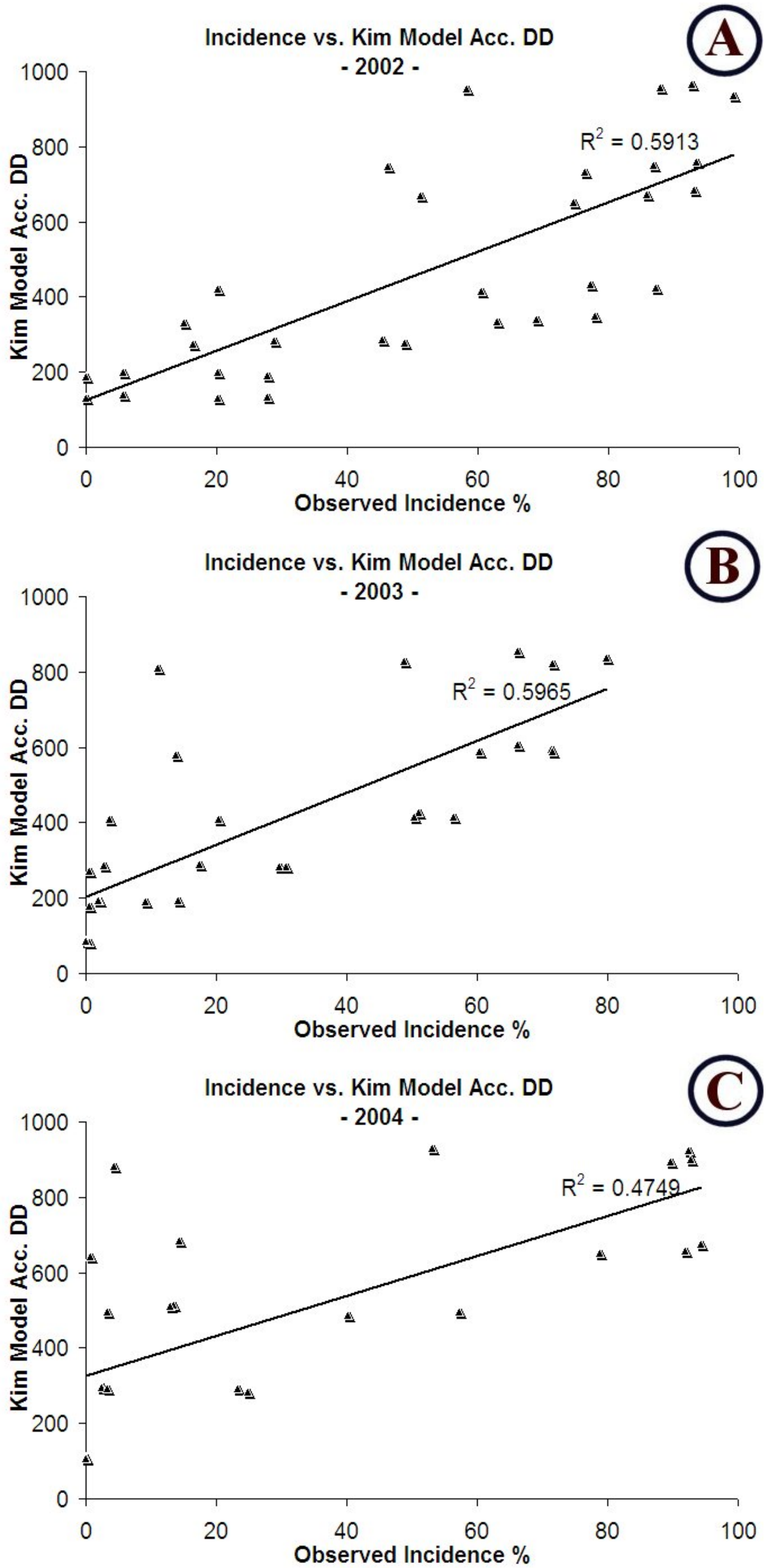


Figure 7. Regression of observed incidence of Alternaria blotch averaged over all locations versus Alt-Buster DD output from on-site data. A) 2002, B) 2003, C) 2004.

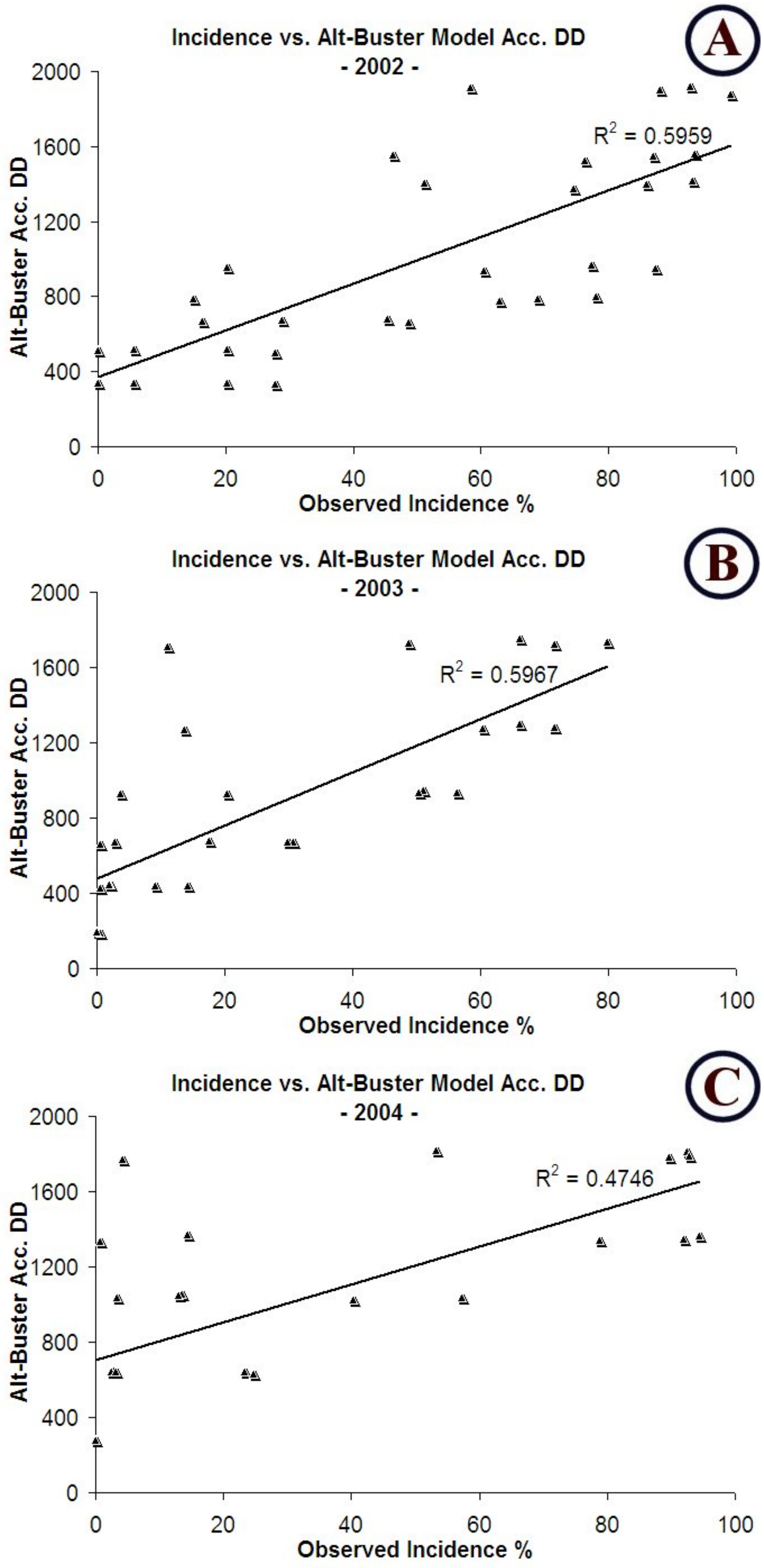
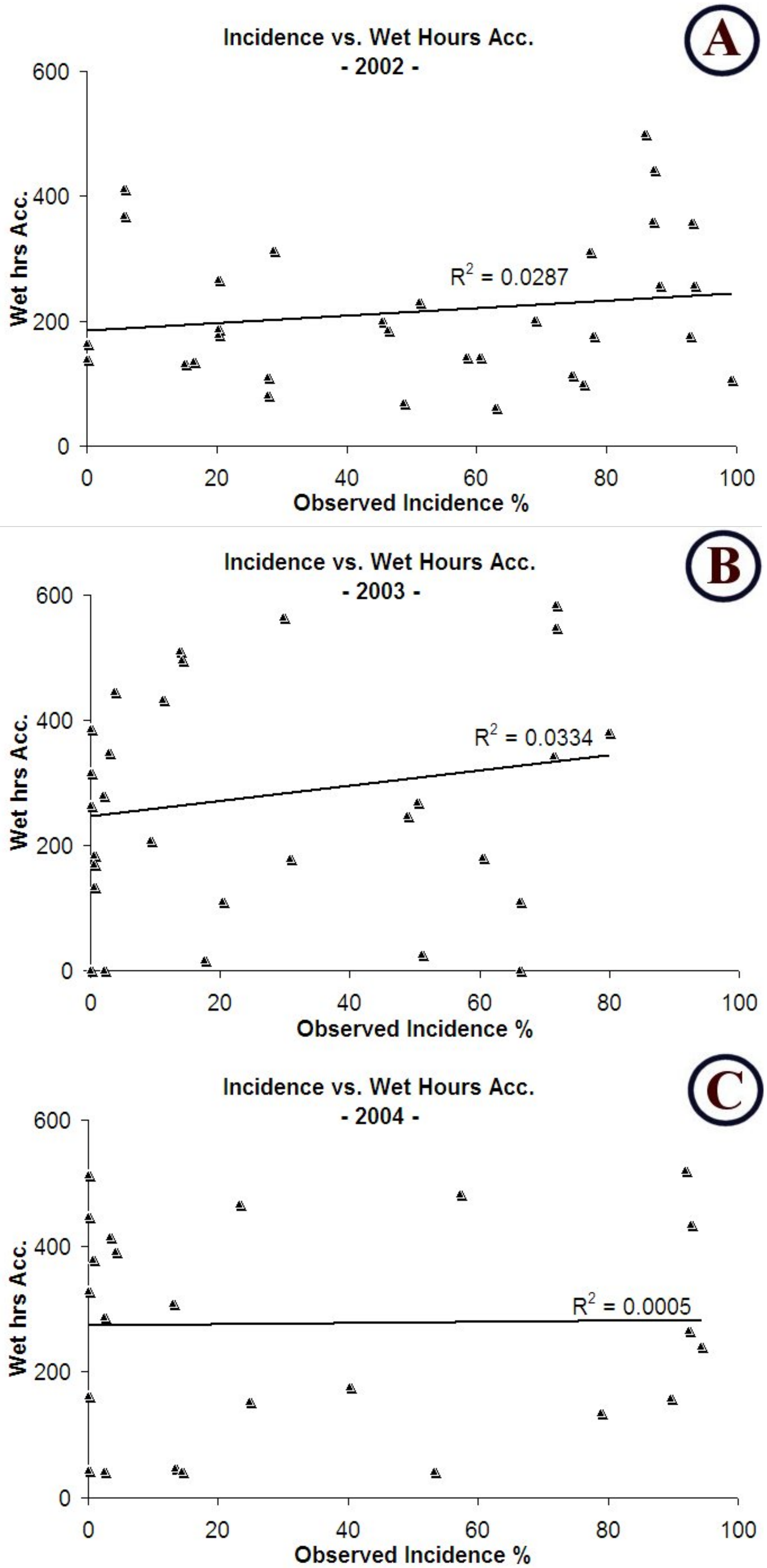


Figure 8. Regression of observed incidence of Alternaria blotch averaged over all locations versus the accumulation of wet hours from on-site data. A) 2002, B) 2003, C) 2004.



APPENDIX 1

Coston/Lancaster Observed Alternaria blotch and On-Site Model Output.

		Alternaria blotch		On-Site Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	278	108	5	27
06/01/04	153	2.43	0.02	649	299	26	102
06/20/04	172	13.40	0.13	1056	516	60	195
07/05/04	187	14.36	0.17	1376	686	83	279
07/25/04	206	53.16	0.53	1821	931	99	345
05/08/03	128	0.00	0.00	198	88	0	24
05/22/03	142	2.13	0.02	446	196	8	75
06/05/03	156	17.47	0.19	682	292	15	102
06/18/03	169	51.01	0.65	949	429	29	169
07/05/03	186	66.21	0.86	1299	609	40	234
07/26/03	207	66.21	0.86	1757	857	68	358
05/17/02	137	27.74	0.31	335	135	14	53
05/29/02	149	27.74	0.31	506	191	17	65
06/05/02	156	48.75	0.70	664	279	22	86
06/11/02	162	62.87	0.88	779	334	24	100
06/19/02	169	60.49	1.01	940	415	26	112
07/09/02	189	74.59	1.63	1377	653	52	192
07/16/02	196	76.34	1.71	1527	732	62	223
07/31/02	211	99.07	2.55	1883	938	78	293

Staton Observed Alternaria blotch and On-Site Model Output.

		Alternaria blotch		On-Site Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	279	109	4	30
06/01/04	153	23.30	0.26	642	292	24	98
06/20/04	172	57.21	0.97	1036	496	48	195
07/05/04	187	91.86	1.75	1348	658	68	280
07/25/04	206	92.79	0.00	1791	901	78	348
05/08/03	128	0.00	0.00	197	87	0	27
05/22/03	142	14.13	0.14	443	193	15	92
06/05/03	156	29.74	0.30	674	284	24	128
06/18/03	169	56.34	0.68	936	416	42	184
07/05/03	186	71.64	0.83	1281	591	59	251
07/26/03	207	71.64	0.75	1724	824	81	356
05/17/02	137	5.63	0.06	342	142	6	24
05/29/02	149	5.63	0.06	519	199	10	36
06/05/02	156	28.75	0.37	674	285	16	60
06/11/02	162	68.97	0.78	792	342	30	97
06/19/02	169	87.29	1.25	953	424	37	120
07/09/02	189	85.86	1.69	1402	673	56	209
07/16/02	196	86.98	1.98	1549	750	66	244
07/31/02	211	88.02	1.98	1907	957	83	315

Nix/Ranch Observed Alternaria blotch and On-Site Model Output.

		Alternaria blotch		On-Site Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	282	112	5	30
06/01/04	153	2.43	0.02	647	297	28	103
06/20/04	172	12.91	0.13	1051	511	54	190
07/05/04	187	94.33	2.43	1366	676	75	273
07/25/04	206	92.46	0.00	1816	926	90	342
05/08/03	128	0.00	0.00	197	87	2	30
05/22/03	142	9.15	0.09	443	193	17	95
06/05/03	156	30.66	0.31	673	283	26	131
06/18/03	169	50.42	0.60	936	416	47	176
07/05/03	186	71.36	1.01	1285	595	70	241
07/26/03	207	79.78	1.11	1738	838	100	351
05/17/02	137	20.24	0.28	339	131	8	102
05/29/02	149	20.24	0.28	524	199	11	168
06/05/02	156	45.34	0.68	682	288	17	198
06/11/02	162	77.97	1.13	803	349	24	229
06/19/02	169	77.33	1.62	968	434	27	244
07/09/02	189	93.09	2.59	1421	687	38	321
07/16/02	196	93.43	2.70	1563	759	46	343
07/31/02	211	92.72	2.39	1923	968	56	388

MHCRS Observed Alternaria blotch and On-Site Model Output.

		Alternaria blotch		On-Site Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	279	109	4	30
06/01/04	153	24.76	0.27	635	285	20	87
06/20/04	172	40.24	0.57	1029	489	38	172
07/05/04	187	78.83	1.29	1341	651	64	270
07/25/04	206	89.63	1.63	1786	896	91	356
05/08/03	128	0.57	0.01	193	83	2	27
05/22/03	142	0.57	0.01	429	179	11	69
06/05/03	156	0.57	0.01	664	274	19	93
06/18/03	169	20.37	0.19	929	409	37	176
07/05/03	186	60.36	0.57	1279	589	57	249
07/26/03	207	48.71	0.79	1729	829	88	352
05/17/02	137	0.00	0.00	344	133	7	36
05/29/02	149	0.00	0.00	517	189	12	42
06/05/02	156	16.36	0.18	673	275	17	77
06/11/02	162	15.00	0.18	791	333	18	92
06/19/02	169	20.25	0.27	961	423	25	118
07/09/02	189	51.19	0.72	1407	670	25	217
07/16/02	196	46.20	0.70	1556	748	30	258
07/31/02	211	58.33	0.92	1914	956	42	306

Dalton/Reed Observed Alternaria blotch and On-Site Model Output.

		Alternaria blotch		On-Site Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	279	109	4	30
06/01/04	153	3.22	0.03	644	294	26	98
06/20/04	172	3.32	0.03	1036	496	43	182
07/05/04	187	0.74	0.01	1335	645	61	262
07/25/04	206	4.23	0.04	1774	884	69	322
05/08/03	128	0.00	0.00	198	88	0	24
05/22/03	142	1.85	0.05	446	196	8	81
06/05/03	156	2.81	0.03	677	287	15	105
06/18/03	169	3.66	0.05	931	411	30	164
07/05/03	186	13.73	0.15	1271	581	48	223
07/26/03	207	11.05	0.16	1711	811	79	317

Coston/Lancaster Observed Alternaria blotch and ZedX Model Output

		Alternaria blotch		ZedX Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	296	126	26	73
06/01/04	153	2.43	0.02	573	223	48	135
06/20/04	172	13.40	0.13	944	404	97	245
07/05/04	187	14.36	0.17	1256	566	132	329
07/25/04	206	53.16	0.53	1696	806	197	504
05/08/03	128	0.00	0.00	184	74	20	53
05/22/03	142	2.13	0.02	411	161	41	113
06/05/03	156	17.47	0.19	640	250	53	147
06/18/03	169	51.01	0.65	903	383	91	230
07/05/03	186	66.21	0.86	1256	566	132	329
07/26/03	207	66.21	0.86	1696	806	197	504
05/17/02	137	27.74	0.31	329	131	25	77
05/29/02	149	27.74	0.31	506	192	30	99
06/05/02	156	48.75	0.70	669	286	40	137
06/11/02	162	62.87	0.88	794	351	47	160
06/19/02	169	60.49	1.01	959	436	51	186
07/09/02	189	74.59	1.63	1429	706	88	327
07/16/02	196	76.34	1.71	1580	787	105	368
07/31/02	211	99.07	2.55	1953	1009	127	454

Staton Observed Alternaria blotch and ZedX Model Output.

		Alternaria blotch		ZedX Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	12	2	5	42
06/01/04	153	23.30	0.26	19	9	32	118
06/20/04	172	57.21	0.97	18	8	82	260
07/05/04	187	91.86	1.75	23	13	126	379
07/25/04	206	92.79	0.00	24	14	190	561
05/08/03	128	0.00	0.00	184	74	18	50
05/22/03	142	14.13	0.14	408	158	36	102
06/05/03	156	29.74	0.30	638	248	48	139
06/18/03	169	56.34	0.68	901	381	85	222
07/05/03	186	71.64	0.83	1256	566	124	321
07/26/03	207	71.64	0.75	1694	804	188	483
05/17/02	137	5.63	0.06	329	132	20	71
05/29/02	149	5.63	0.06	508	195	24	96
06/05/02	156	28.75	0.37	672	288	32	128
06/11/02	162	68.97	0.78	796	353	38	151
06/19/02	169	87.29	1.25	963	440	39	172
07/09/02	189	85.86	1.69	1434	711	72	303
07/16/02	196	86.98	1.98	1585	791	89	354
07/31/02	211	88.02	1.98	1960	1017	106	434

Nix/Ranch Observed Alternaria blotch and ZedX Model Output.

		Alternaria blotch		ZedX Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	291	122	22	64
06/01/04	153	2.43	0.02	669	320	72	208
06/20/04	172	12.91	0.13	1074	536	124	353
07/05/04	187	94.33	2.43	1393	704	175	493
07/25/04	206	92.46	0.00	1855	967	221	645
05/08/03	128	0.00	0.00	186	76	19	52
05/22/03	142	9.15	0.09	412	162	37	104
06/05/03	156	30.66	0.31	645	255	48	138
06/18/03	169	50.42	0.60	910	390	86	221
07/05/03	186	71.36	1.01	1267	577	126	320
07/26/03	207	79.78	1.11	1708	818	190	487
05/17/02	137	20.24	0.28	333	136	21	71
05/29/02	149	20.24	0.28	515	200	25	96
06/05/02	156	45.34	0.68	679	294	33	131
06/11/02	162	77.97	1.13	804	360	38	154
06/19/02	169	77.33	1.62	972	448	40	175
07/09/02	189	93.09	2.59	1445	721	73	306
07/16/02	196	93.43	2.70	1597	802	90	357
07/31/02	211	92.72	2.39	1974	1029	107	437

MHCRS Observed Alternaria blotch and ZedX Model Output.

		Alternaria blotch		ZedX Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	286	119	22	59
06/01/04	153	24.76	0.27	661	314	73	209
06/20/04	172	40.24	0.57	1063	525	129	367
07/05/04	187	78.83	1.29	1378	690	181	512
07/25/04	206	89.63	1.63	1832	945	229	664
05/08/03	128	0.57	0.01	183	73	19	53
05/22/03	142	0.57	0.01	409	159	40	110
06/05/03	156	0.57	0.01	636	246	53	148
06/18/03	169	20.37	0.19	899	379	88	236
07/05/03	186	60.36	0.57	1250	560	129	335
07/26/03	207	48.71	0.79	1688	798	194	510
05/17/02	137	0.00	0.00	326	129	23	77
05/29/02	149	0.00	0.00	502	189	28	99
06/05/02	156	16.36	0.18	665	282	38	137
06/11/02	162	15.00	0.18	790	347	45	160
06/19/02	169	20.25	0.27	954	431	49	186
07/09/02	189	51.19	0.72	1423	700	86	327
07/16/02	196	46.20	0.70	1573	780	103	365
07/31/02	211	58.33	0.92	1944	1002	126	451

Dalton/Reed Observed Alternaria blotch and ZedX Model Output.

		Alternaria blotch		ZedX Weather Output			
Date	Day of year	Observed Incidence	Observed Severity	Filidjic	Kim	Tomcast	Alter-Rater
05/14/04	135	0.00	0.00	268	103	21	56
06/01/04	153	3.22	0.03	615	271	70	181
06/20/04	172	3.32	0.03	986	452	123	329
07/05/04	187	0.74	0.01	1281	597	170	450
07/25/04	206	4.23	0.04	1711	826	215	587
05/08/03	128	0.00	0.00	171	62	17	49
05/22/03	142	1.85	0.05	376	128	32	98
06/05/03	156	2.81	0.03	584	196	44	132
06/18/03	169	3.66	0.05	832	314	79	210
07/05/03	186	13.73	0.15	1167	479	118	296
07/26/03	207	11.05	0.16	1585	697	177	450

Preliminary Meta-Analysis of Apple Scab Modeling Using National Fungicide Trial Data and Geospatial Weather Data

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ABSTRACT

Thayer, C.L., Sutton, T.B., Magarey, R.D. 2005. Preliminary meta-analysis of apple scab modeling using national data sets and geospatial weather data

The traditional methods of plant disease model validation are usually limited in scope to counties, states, or regions. With the possible threat of bio-terrorist attacks on our nation's agricultural system, the ability to create and validate models on a national scale is of paramount importance in protecting America's immense agro-economic infrastructure. A lack of national disease incidence and severity data sets for foliar fungal pathogens is a serious limitation for the accurate validation of risk prediction models such as The North Carolina State University / Animal and Plant Health Inspection Service Plant Pathogen Forecasting System (NAPPFAST). The future of rapid disease model validations is dependent on the existence of research tools to give researchers the ability to accurately predict the potential establishment of exotic diseases. NAPPFAST is a template based modeling tool that uses daily 10-km^2 geospatial weather input to create empirical infection models. An adequate validation of NAPPFAST models requires a data set of disease observations with national coverage for multiple years, pathogens and crops. The object of this project was to investigate the potential suitability of meta-analysis techniques to validate

the NAPPFAST infection model using disease observation data from fungicide trials available in Fungicide and Nematicide Tests reports published by the American Phytopathological Society. Data on the incidence of apple scab, caused by *Venturia inaequalis,* were obtained for 10 years for six locations and 25years for one location. There was a poor correlation between the output from the NAPPFAST model and the observed incidence of apple scab for the locations and years examined. The model appears to be missing variables such as inoculum density or phenological data that may play a key role in apple scab forecasting. Additionally, the way NAPPFAST assigns severity values based on calendar days may be flawed for diseases such as apple scab. Integrating crop phenology modeling into NAPPFAST has the potential to improve the viability of the system as a major research tool in the future.

INTRODUCTION

Traditional methods of plant-disease model validations are difficult to conduct rapidly on a county, state, regional or national scale (9). The current threat of bioterrorist attacks on our nation's agricultural system requires the creation of national scale disease models to help protect America's immense agro-economic infrastructure (8). With the wide spread adoption of the Internet beginning in the mid 90s, plant pathologists were given a potentially potent tool to collect and disperse pertinent information in a rapid and broad manner (6, 7). However, datasets of national disease incidence and severity of foliar fungal pathogens are nearly nonexistent. This is a major limitation for the accurate validation of risk prediction models used in rapid response systems such as the North Carolina State University / Animal and Plant Health Inspection Service Plant Pathogen Forecasting System (NAPPFAST) (8, 9).

NAPPFAST is a novel Internet based research tool used to predict the potential establishment of exotic pathogens and pests (1). The primary purpose for the design of the system is to support the predictive pest mapping needs of the Cooperative Agricultural Pest Survey (CAPS) program. By doing a simple literature search environmental values can be obtained that correspond to the requirements of the casual organism on a specific host (10). For instance, apple scab, caused by *Venturia inaequalis* (Cke.) Wint., requires a known number of wet hours at a specific temperature threshold to fulfill the environmental requirements for infection to occur (2, 5). Based on similar literature searches, models have been constructed for other plant pathogens and arthropod pests (8, 9, 10). NAPPFAST can be used as a tool for historical analysis by allowing users to run models for past seasons or time periods and for specific weather stations. A large database of disease observations is available through Fungicide and Nematicide Test reports (FNT) published by the American Phytopathological Society Press (APS Press St. Paul, MN) and may be useful for validating models. The validation relies upon a comparison of the disease observations with model output using historical weather information for the same time period and location. Rosenburg et al. (10) recently demonstrated how meta-analysis could be used for synthesizing research results from FNT.

Meta-analysis is a method for synthesizing research results through statistical procedures using data derived from previously conducted studies. Meta-analysis provides a useful technique to compare treatments in studies over different years and locations. For example, disease incidence in a treatment can be compared to an unsprayed control. Because the FNT often take place at a specific location repeated over many years they become an ideal source of information when conducting a meta-analysis (10).

Venturia inaequalis is an ideal pathogen to use for evaluating NAPPFAST because a large number of reports are available for the same sites over a broad geographic area and multiple years. *V. inaequalis* is a polycyclic pathogen and criteria for infection are well documented and readily contribute to the objective of this study (2, 4, 13). The purpose of this study is to determine if data on apple scab incidence from FNT can be used to validate NAPPFAST epidemiological models using a meta-analysis.

MATERIALS AND METHODS

Disease observations. The locations chosen for the studies were sites where apple scab data had been collected for over 10 years with data sets including an unsprayed control plot. The locations selected for study were in New York, Pennsylvania, Virginia, North Carolina, Michigan, Oregon, and Ohio (Table 1). The period 1994-2003 was selected because data were published for the same sites for most years continuously in FNT (Table 1) and missing data were obtainable from researchers in those states. Data were also collected from the site in North Carolina for a 25-year period (1979-2003) were also used in the study.

NAPPFAST. The NAPPFAST system uses databases of weather, climatological, geographical, crop distribution, and digital orthoquads to model pest outbreaks. The NAPPFAST system uses a graphical user interface (GUI) to link meteorological and geographic databases with templates for biological modeling and risk assessment. The GUI is comprised of sections for historical, climatic, or forecast weather data with output in the form of maps, tables or graphs. The biological templates include a generic tool kit for empirical or logical models, a generic infection model based on a temperature response function for plant pathogens, and a degree-day model for insect pests. The infection model for plant pathogens used in this analysis is based on a temperature response function (9).

NAPPFAST assigns potential infection ratings to a single calendar day, from hour 0 to hour 24; thus potential infection ratings do not extend across multiple days. Daily potential infection ratings can be accumulated over selected time periods through the NAPPFAST system. NAPPFAST maps are generated using a proprietary interpolation procedure based on the Barnes interpolation technique (1, 8, 9). The Barnes interpolation technique was used instead of inverse distance weighting because it uses a higher degree of smoothing in the analysis and suppresses small-scale irregularities (11).

Model parameters. The cardinal values used in the apple scab model within NAPPFAST were as follows: minimum temperature = 1°C, optimum temperature = 20°C, maximum temperature = 35°C, minimum wetness duration = 6 hours, maximum wetness duration = 40 hours (2, 3, 9). To run the apple scab model in NAPPFAST it was necessary to establish the time to initiate the model at each location. Recently emerged leaves are the most susceptible (2), but data on the date of the phenophase green tip were not available for each site. Therefore, models were initiated two weeks before the pink bud phenophase. They were then run for a 60, 75 or 90 day period, coinciding with the approximate date incidence data were taken at each location (Table 2). The accumulated mean days of potential infection was calculated by counting the number of days with potential infection during the 60-day period beginning from green tip. The 10-year NAPPFAST data were output as a color ramped map. Because of the limitations in discernable color separation a range of seven increments was used. Thus NAPPFAST model output was represented as the mean accumulated days of potential infection and therefore the color ramp is based on the number of days out of the 60, 75 or 90-day time period examined for each location that was favorable for the development of apple scab. The ranges used were 0, 0.1-10, 10-20, 20-30, 30-40, and 40-50. The North Carolina 25-yr NAPPFAST data were output in graphical form as daily increments because of the high quality and depth of available weather data directly adjacent to the test site.

Meta-analysis. In this analysis, accumulated mean days of potential infection, as generated by NAPPFAST, was compared to observed incidence reported in FNT for each location. Data were entered in a comprehensive spreadsheet (Microsoft Excel) with columns defined as location, year, assessment date, observed incidence, and accumulated infection level from NAPPFAST. A correlation analysis was run between the observed disease incidence and the accumulated mean days of potential infection for each location (13).

RESULTS

NAPPFAST maps, generated for each year and location, provided the accumulated mean days of potential infection (Table 3). Representative NAPPFAST output of accumulated mean days of potential infection for the 10-yr data from Pennsylvania are found in Appendix 1.

The accumulated mean days of potential infection as predicted by NAPPFAST for each location for the 10-year period examined did not vary greatly. For most sites and years the accumulated mean days of potential infection as predicted by NAPPFAST ranged from 35 to 45 (Table 3). In contrast, the observed disease incidence varied greatly. For example, in Virginia the observed incidence was as high as 55% in 2003 and as low as 2% in 2002 but the mean accumulated potential days of infection only varied from 35 to 45. Consequently the correlation between the observed incidence and the NAPPFAST output for Virginia was low ($r = 0.41$). Correlations for other sites were lower and in three cases negative. The correlation between the observed incidence and the NAPPFAST output did not improve when 25 years of data from North Carolina were examined (r=0.06) (Table 6). When the data were examined by year across the seven locations, correlations were generally higher (Table 5). Highest correlations were found in 1996 (r =0.68) and 2001 (r =0.65) and were lowest in 1994 (r =0.00). Because of the results of the correlation analysis were poor, additional meta-analyses were not performed.

DISCUSSION

The NAPPFAST accumulated mean days of potential infection neither accurately nor consistently predicted the incidence of apple scab at the locations or years tested. The failure to accurately predict the incidence of apple scab is most likely due to a missing model parameter, such as phenology data and/or information on the initial inoculum at each site each year and/or because of the way NAPPFAST assigns severity values.

Gadoury et al. (4) showed a high correlation between the severity of infection and the area of exposed tissue, host susceptibility, and the dose of airborne inoculum with apple phenology. Once the minimum criteria for infection are met or exceeded, phenology is more important than additional wetting in determining severity of infection (4). In this study we assumed that a 60-day period beginning 2 weeks before the pink budstage would span the period that the leaves were most susceptible, which matched fairly well with the time that data on scab incidence and severity were collected in North Carolina, and Virginia. However data at other sites were taken beyond this 60-day period and the model was run for a 75 or 90-day period in order to match with the average assessment date. If our assumption on the susceptibility of the leaves is correct, then model runs during the time leaves are most susceptible (0-60 days) would be included with those occurring later (61-90) when leaves are not as susceptible for some sites (Table 2). As a consequence the correlation between observed disease incidence and NAPPFAST accumulated mean days of potential infection would not necessarily be linear. Additionally there was difference in the cultivars assessed among locations (Table 1). McIntosh is generally considered more susceptible than the other varieties. However all cultivars assessed are considered all highly susceptible to apple scab. The addition of crop phenology modeling into NAPPFAST may improve its ability to predict the severity of disease and strengthen its utility as a research tool.

Another factor that was not taken into consideration is the latent period for *V. inaequalis*, which typically is 9 to 17 days (5). Consequently the amount of disease recorded on the assessment date potentially underestimates the actual amount of infection, depending on the number of infection periods that occurred in the 9 to 17-day period prior to assessment (5, 6). This may not be a factor for the assessments that occurred at 75 and 90 days because leaves would have become more resistant, but could be a factor for the 60-day assessments.

The correlation between the amount of disease and the inoculum density (dose) has been investigated in numerous studies (5), which indicate that there is a linear relationship between the airborne ascospore concentrations of *V. inaequalis* and the incidence of disease. Thus the disease severities recorded at the various locations each year may be more closely related to the initial inoculum density (dose) than the occurrence of infection periods (5). At present, there is no method to account for high initial inoculum levels in NAPPFAST.

Another factor affecting the NAPPFAST output is that the generic infection model does not take into account other processes in the polycycle, including dispersal, sporulation and the incubation period (12). Consequently, the model may do a poor job of estimating the rate of epidemic development. Modeling these processes effectively may greatly increase the complexity of the model, including the number of input parameters. This may make the model unsuitable for use with exotic fungal pathogens for which there is often little known about their epidemiology.

An additional concern with the NAPPFAST infection model is the way it assigns severity ratings to a single calendar day, from 0 h to 24 h, causes individual infection periods that span two or more days to be split. Thus in the current version of the infection model in NAPPFAST it is not possible to distinguish between infection periods terminated by dry periods and those terminated at 24 hours. The best solution is to use hourly input data instead of daily averages and totals. Another alternative is to develop a rule set based on relative humidity for deciding if consecutive daily wetness events are additive into an infection period. For example, a rule set may look something like this: if wetness on both days was greater than 4 hours and relative humidity was at least 90% then add wetness from consecutive days. Furthermore, NAPPFAST considers all wetting periods, not those just associated with rain when ascospores would be released. Consequently infection periods would likely be overestimated in years with infrequent rainfall.

In summary, several design changes may be necessary to the generic infection template in order for NAPPFAST to be able to successfully predict apple scab (and by inference other fungal diseases) in site-specific forecasts. These modifications include: i) adding a rainfall requirement to the infection period; ii) switching from daily to hourly data or implementing a rule set for adding wetness periods in consecutive days; and iii) adding a relative risk of infection index. Each of these three criteria can be estimated quantitatively and weighted between zero and one. Area of host tissue and susceptibility can be estimated from a phenological model driven by day degrees. Inoculum dose can be estimated from disease in the previous season and an ascospore maturity model run by day degrees. Using these three criteria it would be possible to calculate a daily relative risk of infection index based on the product of the three indices. The relative risk of infection could be added to an infection model to calculate a more refined disease forecast. Such modifications need to be made carefully since too many input parameters may make the model difficult to implement.

This study is an initial step designed to investigate the potential suitability of meta-analysis techniques in conjunction with fungicide trial data for the purpose of validating NAPPFAST or other national forecasting systems. The variation in the accumulated mean days of potential infection among years shows that the intent of NAPPFAST as a source for showing national risk is functioning properly. Currently, NAPPFAST is not accurate enough to base a growers disease management spray program. However, the variation among years shows that the intent of NAPPFAST as a source for showing national risk is functioning properly. Further studies of this nature are warranted for additional pathogens and locations to determine if the results of this study are not only unique to the apple scab pathogen but to NAPPFAST as well.

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TABLES AND GRAPHS

Table 1. The American Phytopathological Society Fungicide and Nematicide Trials used in the analyses.

Year	Volume	Pages
2003	Volume 59	PF003, PF006, PF027, PF017
2002	Volume 58	PF003, PF017, PF34, PF019
2001	Volume 57	PF09, PF07, PF41, PF15
2000	Volume 56	PF09, PF07, PF41, PF15
1999	Volume 55	55:16, 55:31, 55:32, 55:33, 55:8, 55:46, 55:28
1998	Volume 54	1-2, 5-7, 9-12, 14, 17, 20-21, 23-27.
1997	Volume 53	2, 8-11, 15-17, 19-20, 23, 25, 28-33, 35, 37.
1996	Volume 52	4, 8, 10-17, 19, 21, 25-26, 29-33, 335.
1995	Volume 51	3, 7-13, 15, 18-19, 21-23, 26, 28-29, 327-328.
1994	Volume 50	3-4, 8, 11-14, 16-18, 20-22, 26-28, 30-37, 40-42.

Data for missing years were provided by Drs, J. Scheidt (Oregon), M. Ellis (Ohio), and T. Sutton (North Carolina).

Table 2. Extended model accumulation dates based on average reported assessment date for each location.

Location	Model Begin Date	Model End Date	Average Assessment Date	Model Accumulation Interval
Michigan	14-Apr	13-Jul	14-Jun	90 Days
New York	13-Apr	12-Jul	20-Jun	90 Days
Pennsylvania	6-Apr	5-Jul	15-Jul	90 Days
Virginia	9-Apr	8-Jun	16-Jul	60 Days
Oregon	28-Mar	11-Jun	23-Jun	75 Days
Ohio	30-Mar	28-Jun	18-Jul	90 Days
North Carolina	1-Apr	31-May	31-May	60 Days

Table 3. NAPPFAST extended accumulated potential days of infection versus observed incidence separated by year and location.

Year	location	Terminal leaf %	Mean days of infection	Year	location	Terminal leaf %	Mean days of infection
2003	Virginia	55.00	35.00	1998	Virginia	41.10	35.00
2002	Virginia	2.00	25.00	1997	Virginia	16.10	25.00
2001	Virginia	11.00	35.00	1996	Virginia	26.30	25.00
2000	Virginia	19.70	35.00	1995	Virginia	20.00	25.00
1999	Virginia	29.00	25.00	1994	Virginia	26.00	25.00
2003	Pennsylvania	38.00	65.00	1998	Pennsylvania	30.40	65.00
2002	Pennsylvania	2.60	55.00	1997	Pennsylvania	22.70	45.00
2001	Pennsylvania	24.80	55.00	1996	Pennsylvania	83.00	55.00
2000	Pennsylvania	37.00	65.00	1995	Pennsylvania	69.10	55.00
1999	Pennsylvania	27.90	55.00	1994	Pennsylvania	48.30	45.00
2003	Oregon	32.20	65.00	1998	Oregon	45.70	35.00
2002	Oregon	67.00	45.00	1997	Oregon	44.80	45.00
2001	Oregon	51.20	55.00	1996	Oregon	46.60	35.00
2000	Oregon	51.60	55.00	1995	Oregon	31.90	35.00
1999	Oregon	13.30	45.00	1994	Oregon	26.70	35.00
2003	Ohio	100.00	55.00	1998	Ohio	100.00	55.00
2002	Ohio	90.50	55.00	1997	Ohio	100.00	45.00
2001	Ohio	100.00	55.00	1996	Ohio	100.00	45.00
2000	Ohio	86.00	55.00	1995	Ohio	100.00	45.00
1999	Ohio	100.00	45.00	1994	Ohio	97.60	35.00
2003	North Carolina	9.40	45.00	1998	North Carolina	30.70	45.00
2002	North Carolina	0.00	35.00	1997	North Carolina	53.30	35.00
2001	North Carolina	0.10	35.00	1996	North Carolina	45.50	35.00
2000	North Carolina	3.70	35.00	1995	North Carolina	1.00	35.00
1999	North Carolina	19.20	35.00	1994	North Carolina	5.00	35.00
2003	New York	80.10	65.00	1998	New York	59.50	65.00
2002	New York	64.20	55.00	1997	New York	74.80	45.00
2001	New York	28.90	55.00	1996	New York	63.80	55.00
2000	New York	39.40	65.00	1995	New York	7.30	55.00
1999	New York	65.20	55.00	1994	New York	14.70	55.00
2003	Michigan	58.20	55.00	1998	Michigan	26.70	55.00
2002	Michigan	61.70	45.00	1997	Michigan	72.50	45.00
2001	Michigan	68.40	55.00	1996	Michigan	39.20	45.00
2000	Michigan	75.90	55.00	1995	Michigan	75.50	45.00
1999	Michigan	69.40	45.00	1994	Michigan	71.60	45.00

Table 4. Locations of FNT, years of trials, varieties tested and correlations between the observed incidence and the NAPPFAST generated output.

NAPPFAST generated output.	**Year**	**Variety**	**r**
Michigan	1994-2003	Golden Delicious/Red/McIntosh	-0.24
New York	1994-2003	JerseyMac/MacIntosh	0.03
Pennsylvania	1994-2003	Rome	-0.03
Virginia	1994-2003	Golden Delicious	0.41
Oregon	1994-2003	Breaburn/Rome	0.22
Ohio	1994-2003	McIntosh	-0.34
North Carolina	1994-2003	Rome Beauty	0.09
North Carolina 25-yr	1979-2003	Rome Beauty	0.06
All	1994-2003	All	0.36

Table 5. 25-year NAPPFAST accumulated potential days of infection versus observed incidence

Year	Location	Terminal leaf %	Days of infection
1979	North Carolina	26.20	42.00
1980	North Carolina	37.50	28.00
1981	North Carolina	0.50	48.00
1982	North Carolina	0.10	47.00
1983	North Carolina	0.10	41.00
1984	North Carolina	18.20	43.00
1985	North Carolina	35.20	44.00
1986	North Carolina	0.00	28.00
1987	North Carolina	0.10	40.00
1988	North Carolina	0.00	32.00
1989	North Carolina	0.30	33.00
1990	North Carolina	1.10	38.00
1991	North Carolina	57.60	50.00
1992	North Carolina	66.10	41.00
1993	North Carolina	63.50	38.00
1994	North Carolina	5.00	40.00
1995	North Carolina	1.00	43.00
1996	North Carolina	45.50	32.00
1997	North Carolina	53.30	32.00
1998	North Carolina	30.70	50.00
1999	North Carolina	19.20	42.00
2000	North Carolina	3.70	41.00
2001	North Carolina	0.10	26.00
2002	North Carolina	0.00	42.00
2003	North Carolina	9.40	42.00

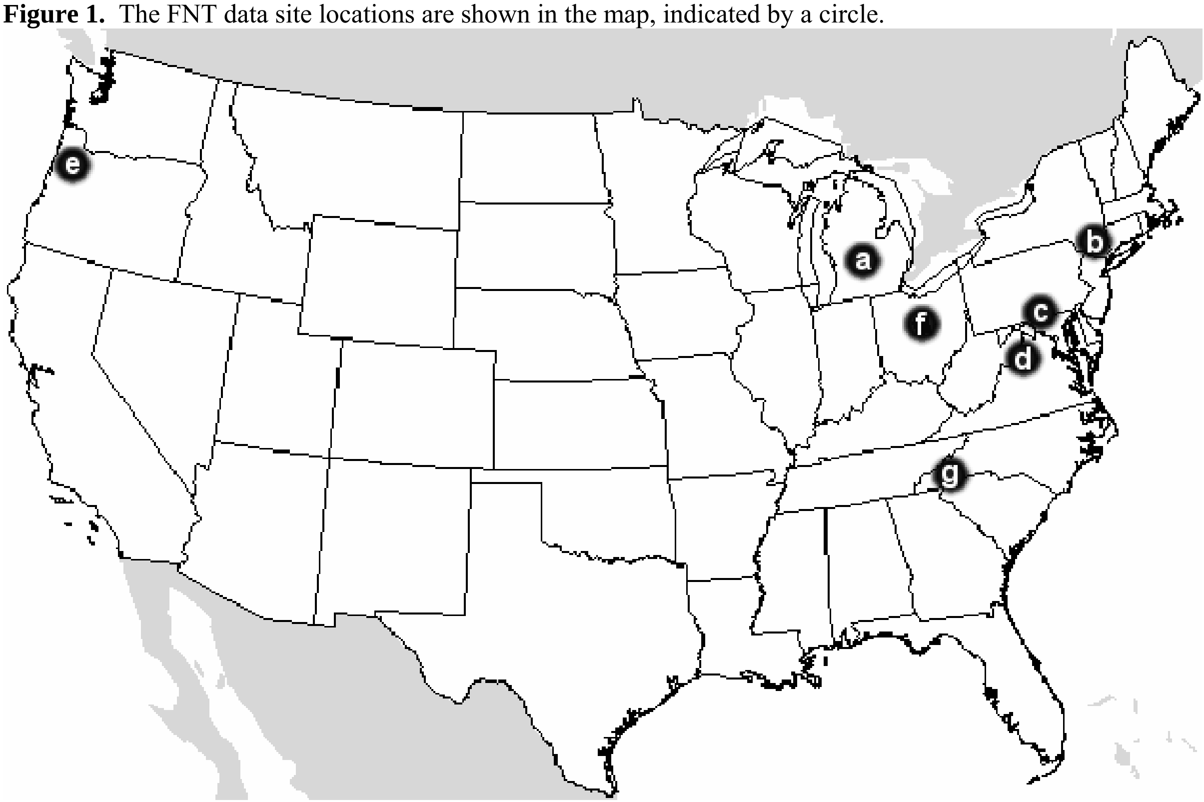
Table 6. Results of the correlation analysis for the extended NAPPFAST accumulated potential days of infection.

Year	r
2003	0.36
2002	0.46
2001	0.65
2000	0.50
1999	0.44
1998	0.15
1997	0.56
1996	0.68
1995	0.36
1994	0.00

FIGURE LEGENDS

Figure 1. The FNT data site locations are shown in the map, indicated by a blue circle. The locations are: a. Lansing, MI 48815; b. Geneva, NY 12528; c. Biglerville, PA 17307; d. Winchester, VA 22602; e. Corvalis, OR 97331; f. Wooster, OH 44691; g. Fletcher, NC 28732.

Figure 1. The FNT data site locations are shown in the map, indicated by a circle.



APPENDIX 2

NAPPFAST Example of Accumulated Infection Maps