Integrated Method of Organizing, Computing, and Deploying Weather-Based Disease Advisories for Selected Peanut Diseases

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ABSTRACT

Epidemiological information can be used with weather data to anticipate disease onset. These disease advisories can be applied to reduce the unnecessary use and improve the timing of fungicide sprays. Delivery of weather-based disease advisories to peanut growers in North Carolina was expedited by streamlining programming and information deployment procedures. This approach utilized a standard method of organization of weather data collection and analysis for all diseases, and daily reports were posted to the web. A standardized method of analysis is described which is flexible, and it allows information from epidemiological studies and practical experiences to be integrated to create a specific model for individual diseases. Included is a description of the research and extension activities over a 17-yr period during which weather-monitoring hardware and disease advisories were developed, tested, and utilized for advisories in peanuts at the farm level. Advantages and limitations to this approach with reference to its use in other crops are discussed.

Key Words: Algorithms, forecasting, models, pesticides.

Epidemiological information can be used to anticipate the onset of disease and to warn farmers of the likelihood of disease occurrence. Weather-based disease advisories can help to minimize the unnecessary use and improve the timing of fungicide sprays. A successful advisory system includes (a) reliable and affordable weather-monitoring hardware, (b) personnel who can develop advisory models from basic epidemiological information, (c) an easily maintained user interface (software), (d) educational programs to address risk aversion and skepticism of growers, (e) application to diseases which can be controlled after the onset of disease-favorable weather, and (f) applied research programs to demonstrate that models are realistic and robust enough to work on the farm.

Public and private groups have made important improvements in developing and deploying weather-based advisories for peanut disease management (Bailey *et al.*, 1974; Lee *et al.*, 1990; Davis *et al.*, 1991; Phipps, 1993; Parvin *et al.*, 1994; Phipps *et al.*, 1997). A peanut leaf spot advisory program was deployed statewide in Virginia in 1981 (Phipps *et al.*, 1997) and starting in a single county in North Carolina in 1983. Both states now have widespread acceptance of timing sprays according to weather-based advisories. While additional models have been developed for peanut insects and diseases (Davis *et al.*, 1991; Mack *et al.*, 1993; Phipps *et al.*, 1997), only a small portion of the U.S. peanut production areas are using weather-based advisories to time pesticide applications. An important reason for this is the difficulty associated with integrating the separate components that comprise a weather-based advisory development and deployment system.

Weather-based advisories have been used to manage peanut early leaf spot (*Cercospora arachidicola* Hori) by North Carolina growers since 1983. Evolution of the peanut early leaf spot spray advisory, its acceptance, and the utility of weather forecasts for predicting conditions conducive to disease has been described (Bailey *et al.*, 1994). The need to develop better decision support for additional diseases led to the development and the deployment of multiple advisories to North Carolina growers. Efforts to simplify and streamline the process of model development and deployment resulted in the creation of several electronic weather-monitoring device designs and a simplified method of creating software (Bailey and Campbell, 1996). The purpose of this paper is to discuss weather-monitoring hardware and programming techniques useful in the development and deployment of weather-based disease advisories.

Materials and Methods

Hygrothermographs. In 1983, hygrothermographs were used by volunteers at five sites in Northhampton county to collect data required by the peanut leaf spot spray advisory (Bailey *et al.*, 1994). Hours of relative humidity (RH) > 95% and minimum night-time temperatures were the cardinal daily weather values used to compute the spray advisory (Parvin *et al.*, 1974). Recommended fungicides were applied when favorable conditions occurred and 14 or more days had transpired since the last spray. County extension personnel evaluated the data and recorded the advisories on a telephone message for growers.

Electronic Weather Monitors. Electronic weather stations were developed to simplify data collection and analysis for early leaf spot advisories. In 1982, a microprocessor-based device was constructed which measured temperature and RH, computed the advisory, and displayed the results on a panel. Lights on the panel flashed next to statements displayed on the panel face indicating the need to spray and the reasons for the spray recommendation (Fig. 1A). A lithium chloride RH sensor was used to monitor air moisture. In 1983, a new device was built which included a unique method of measuring dew point (Fig. 1B). This sensor utilized a leaf wetness grid to which a thermal electric cooler had been glued. The grid was cooled until water condensed (causing water droplets to form) which conducted current across two electrodes indicating a "wet"

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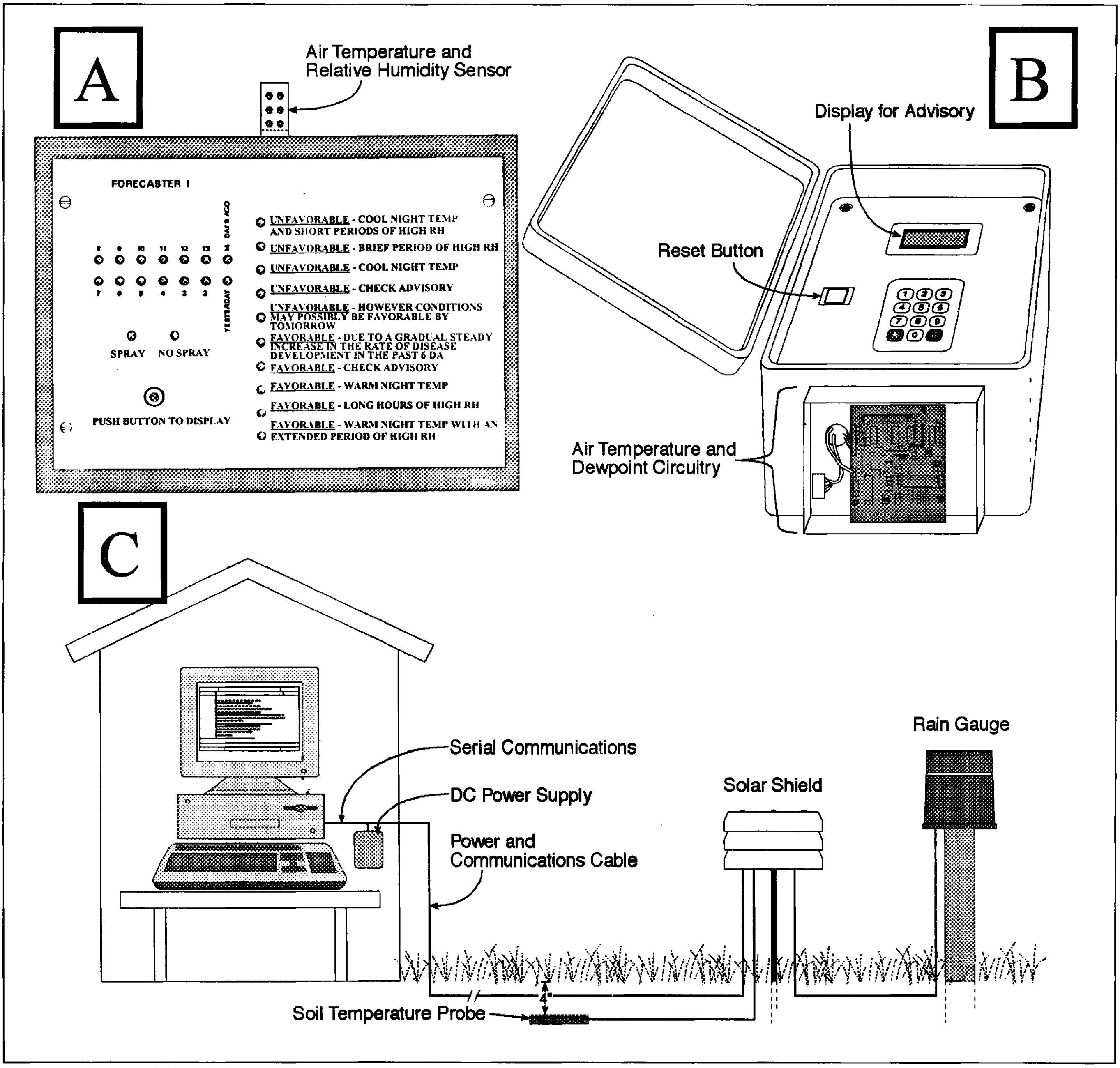

Fig. 1. Different electronic weather monitor configurations used throughout this study. (A) First electronic device (weather station) developed to deploy the peanut leaf spot advisories (1982). Face plate is divided into three sets of lights which displayed information on a) days in which favorable advisories were issued in the last 2 wk (top left of face plate), b) reason for the advisory (right half of face plate), and the spray/no spray lights indicating the recommendation for the current day (left center of face plate). (B) The second version of the weather station (1983) with display, keypad, and leaf wetness grid cooled by a thermal-electric cooler to determine dew point. (C) Current configuration of the weather station. A computer (inside building) is linked to the weather sensors (outside over turf) via a direct cable or radio. The solar shield houses a microprocessor device that monitors air and dew point temperatures (inside solar shield), soil temperatures (4 in. deep), and rainfall. The computer records data every 15 min from the weather sensors, stores the data on disk, and computes and displays the weather-based advisories automatically on the screen.

condition. The temperature was then measured using a temperature sensor mounted to the surface of the grid to determine the dew point temperature. Data were viewed on a liquid crystal display.

By the mid- to late 1980s, relatively inexpensive computer hardware replaced the need for the continued development, construction, and maintenance of data logging and analysis hardware (Fig. 1C). A conventional personal computer was used to collect, analyze, and store weather information. Subsequent improvements to the dew point sensor led to the use of a stainless steel mirror glued to the surface of the cooler and an infrared light-emitting diode and phototransistor (Bailey *et al.*, 1985). The hardware was refined to improve resistance to moisture and lightning effects by Agricultural and Meteorological Systems, Inc., Middlesex, NC. North Carolina State Univ. (NCSU) licensed this technology to the same company which commercialized the product.

Software Development. Before personal computers were used as data loggers, all software was written in assembly language and programmed onto an erasable/programmable memory chip (EPROM). After personal computers were utilized, weather data and disease advisory reports were displayed on the computer screen using a menu-style program. Emphasis was placed on simplicity so that the software, written in C++, would run on virtually any DOS computer. This allowed computers which were outdated for other uses to be used as weather stations. This project was a joint effort between NCSU and engineers from Agricultural and Meteorological Systems, Inc., who licensed this technology from NCSU.

Model Template. A generic algorithm was developed to translate cardinal weather values for disease onset and fungicide needs into an advisory report. A template was designed so the variables for each disease could be utilized by the algorithm to create new disease advisory models (Fig. 2). Weather-based disease advisories were computed automatically when the generic model computed the advisory report using variables from the template. Advisory reports displayed a histogram representing the duration of favorable weather per day and, optionally, a predicted date (threshold) on or after which sprays should have been applied, the "last effective spray date" (Phipps, 1993). To complete a template, the relationship between moisture, temperature, and time, on disease increase must be clearly understood. A common method of describing these factors, in which conditions were described as hours of favorable conditions per day, was established so variables entered into the template had equivalent epidemiological meaning across all diseases.

Moisture required for disease to progress:

Wetness: Rain
- Rain needed for 1 hr of wetness
- Maximum amount of rain to accrue

Wetness: Humidity
- Dew point depression which is wet
- Relative humidity which is wet

Temperature effects on rate of disease progress:
- Temp, location most relevant to disease: Air / soil
- Temp. (F) / Rate of disease progress (%)

Temp. (F)	Rate of disease progress (%)
40	______
45	______
50	______
55	______
60	______
65	______
70	______
75	______
80	______
85	______
90	______
95	______
100	______

Threshold information:
- No. hours (temperature adjusted) of wetness to constitute a favorable day
- No. days (period) in which the favorable days must occur to constitute a spray advisory
- No. favorable days to constitute a spray advisory
- No. days the fungicide spray is effective

Fig. 2. Data entry template to create new disease algorithm.

Wetness. Wetness described the amount of moisture necessary for disease increase, assuming that temperature was not a limiting factor. Wetness occurred when moisture required for disease progress was met. This was defined either as amounts of rain, water availability expressed as dew point depression (DPD), or RH. Rain generally affects soil moisture longer than foliar wetness. Hence, a method for describing wetness duration was developed using a rain register. Rainfall was recorded up to a maximum value defined in the template. For each hour that passed, the rain register was reduced by a set amount defined by a variable in the template. Moisture conditions were considered to be adequate for disease occurrence as long as the rain register was greater than zero. Rain was monitored every 15 min and was added to the register up to the maximum allowable amount. Any rain which fell when the register was full was discarded. DPD or RH could also be used to define when an hour was wet. Leaf wetness was not used in the models described in this manuscript, but could be used instead of a DPD or RH threshold.

The rate of disease progress was a function of wet hours/day and the temperature during each wet hour. Temperature adjustment could use soil or air temperature depending on the area where disease develops. Values from 0% (no development) to 100% (maximum development) showed the degree to which temperature modified the rate of disease progress. Temperature effects were only relevant if the period was wet. When conditions were dry, there was no disease progress regardless of temperature. If the temperature was optimal for disease progress and the hour was wet, the entire hour was counted as favorable. One hour of wetness under temperature conditions that allowed disease to progress at 50% of the optimal rate counted as 0.5 h. Therefore, the number of temperature adjusted hours of disease development was the sum of 24 hourly values where each wet hour was multiplied by a temperature rate factor (0-100%). Consequently, the number of favorable hours in a day could range from 0-24.

The generic algorithm computes all favorable periods and thresholds the same way using variables [defined in the template (Fig. 2)] that were unique for each disease. The basic (and smallest) unit of time used by the models in this system was 1 hr. Days were composed of hours where each hour was an average of four 15-min readings.

A threshold was used to determine when a fungicide should be applied or other action taken, such as scouting for sclerotinia blight to minimize risk of disease loss. The threshold was reported as a date when the action should have been taken. Fungicides applied on or after this date would result in preventing unacceptable disease development. Fungicidal residues on the foliage were assumed to prevent disease development during favorable conditions for the period in which the fungicide was defined as effective. Using these inputs, a "last effective spray date"

(Phipps, 1993) was computed. If a fungicide was applied on or after this date, it should not need to be applied again at this time because the fungicide should have prevented infection.

Results and Discussion

Keys to a successful advisory system were competent, motivated volunteers able to reliably read and maintain equipment; development of a simple method of calculating the spray advisories; and a reliable information delivery system. Advisories worked best in counties with active educational programs and a respected county agent. Use of daily advisories was enhanced by having the county agent augment the reports with other key observations and advice about other commodity production issues in the county. Lapses in delivery of advisory information during periods of personnel turnover or equipment breakdown were particularly damaging to the program.

County agents used a set of rules to guide growers in appropriately using the information. For example, early leaf spot advisory rules were as follows: (a) spray as soon as possible after conditions become favorable, but not within 14 d of the last spray; (b) spray preceding heavy rain; (c) scout fields at least once per week and revert to a 14-d schedule if any part of the field has greater than 20% of the leaflets with one or more spots; (d) spray preventatively at a 14-d schedule if the farm work schedule will prevent spraying within 3 d after the advisory recommends; (e) chlorothalonil should be used on the advisory (at the time it was the most efficacious and broad spectrum material available); (f) revert to a 14-d calendar spray program if web blotch (*Phoma arachidicola* Marasas, G.D. Paver, & Boerema); late leaf spot (*Cercosporidium personatum* Berk. & M.A. Curtis); or severe pepper spot [*Leptoshaerulina crassicae* (Sechet) C.R. Jackson & D.K. Bell] were identified; (g) begin using the disease advisories on 20 June and spray when the first threshold is reached; (h) use disease-resistant cultivars; and (i) rotate with at least 2 yr between peanut crops (Bailey *et al.*, 1994). While growers seldom followed all the rules, the rules made it easy for agents to describe the least risky method of using the advisory. These rules reinforced good crop management practices and gave the county agents more security in promoting the leaf spot advisory.

Weather Monitoring Equipment. Hygrothermographs had several important advantages over most electronic RH and temperature sensors — (a) durability, (b) virtual immunity to lightning damage, (c) moderate cost, and (d) simple to maintain in the field. Disadvantages were moderate to low accuracy, depending in part on the skill of the one interpreting the chart and the need for manual handling of weather data recorded on strip charts.

The first electronic weather stations were developed to simplify the process of monitoring and analyzing weather data. It was predicted that stations would cost less than hygrothermographs. These theoretical improvements were offset by several critical shortcomings common to the use of electronics in agriculture. Development of electronic equipment suitable for outdoor use was difficult given the technology available in the early 1980s. Poor durability and the complexity of building and programming microprocessor-based hardware was a constant challenge. Perhaps the most difficult problem to overcome was the inappropriateness of the lithium chloride humidity sensor, an industry standard, selected for use on these devices. This type of sensor relied on the purity of a salt-impregnated fabric to conduct electrical current, thus converting atmospheric moisture into a resistance value. Contaminants found in the outdoor environment reduced the accuracy of these sensors in a short period of time. It was difficult to know when these devices were becoming inaccurate. These problems made verification of model accuracy extremely difficult. All programming, which included the custom operating system, display and keyboard drivers, and disease algorithm was done in assembly language. This low level programming language was an effective method of minimizing the need for memory chips, which were expensive at the time. However, debugging and changing the software was an arduous task.

A unique aspect of the first electronic device developed (1982) was the type and method of displaying information (Fig. 1A). Three types of information were delivered—a spray/no spray threshold, a 2-wk calendar of lights representing the days on which spray advisories were issued (light on = spray advisory day), and an explanation for the spray advisory. The explanations were keyed to a quadrant defined by conditions being wet/dry and warm/cold as per the logic used by Parvin *et al.* (1994). Pressing the display button turned on the lights beside the relevant information on the display panel. Most users liked the spray/no spray display, but found the 2 wk "calendar" on the upper left hand of the display confusing. Each light represented one of the last 14 d. If the light was "on," that meant that a favorable (i.e., spray) advisory had been issued for that day. Each day the lights shifted down one position and the oldest day was deleted. The purpose was to help growers remember when spray advisories had been issued over the past 2 wk.

What was intended to be simple became complex in practice. For example, growers only needed to spray if 14 d had transpired since the last application. However, most farms were sprayed over a period of two to many days. Growers were encouraged to spray within 3 d of the advisory, but many growers did not keep up with the daily advisories. County agents did not like recording the dates of all the past advisories on the phone messages as it made the message long and difficult to understand. Time became difficult to track between the rules, spray dates, and protection intervals.

Developing a Durable Air Moisture Sensor. A sensor was designed that was inexpensive and tolerant of the air contaminants of the farm environment (Fig. 1B). A Peltier cooler was glued to the bottom and a temperature sensor to the top of a leaf wetness grid. The grid was cooled until condensation triggered the leaf wetness grid to register "wetness". The temperature of the grid was measured to determine the dew point temperature. While the design was durable, it was not extremely accurate, especially at low RH. Empirical testing showed that considerable condensation was needed to complete the circuit causing errors in dew point determination. Air circulation was required to help linearize the error between the "true" and measured dew point temperatures. Miniaturized (ca. 2 × 2 cm) leaf wetness grids were built and tested with limited success. Further tests showed that reflectance of infrared light off a shiny surface adhered to the cooler was a more sensitive method of detecting small amounts of moisture. Similar technology had been used in the construction of relatively expensive chilled mirror dew point hygrometers. Standard curves were developed using an aspirated psychrometer (wet/dry mercury thermometers) to correct the readings. Several redesigns were tested over a 4-yr period to improve weathering, accuracy, and durability issues (Bailey *et al.*, 1985). Design improvements of the hardware/software were similar to and benefited from other similar research (Ellis *et al.*, 1984; Jones *et al.*, 1984).

Use of Personal Computers as Weather Stations. Computer hardware had become inexpensive and widely available by the late 1980s, so custom-designed hardware was no longer necessary or desirable for this project. A weather station was developed which integrated DOS-based personal computers with the chilled mirror dew point hygrometer (Fig. 1C). Ports for soil temperature and rainfall were added to the printed circuit board of the data collector on which the hygrometer was built. Weather data were collected by the computer every 15 min and stored on a disk. Data were analyzed and reports were displayed on the computer monitor. This approach made it easier to deploy multiple models using a standard high level programming language. This allowed the use of a much more abundant (and less expensive) pool of programmers as compared to assembly language programmers who were usually hardware engineers. Software debugging and alternations became easier with standard high level programming. The significant amount of work needed to create an operating system was eliminated also.

Advisory algorithms were programmed for early leaf spot (Parvin *et al.*, 1974), sclerotinia blight (Lee *et al.*, 1990; Phipps, 1995), and lesser corn stalk borer (*Elasmopalpus lignosellus* Zeller) (Mack *et al.*, 1993) which were used in county extension programs. Each model was programmed as a unique set of code and kept separate from the other models. Pest advisory reports plotted daily histograms of the accrued index values for each model and computed the spray thresholds. All advisory reports looked the same, regardless of which pest was involved, making the information easier to create, read, and understand. The reports described daily disease risk as hours of favorable conditions and thresholds as dates when sprays should be applied. Each day, graphs of disease-favorable weather conditions showed how the amount of risk was changing. Displays were produced using familiar words and intuitive displays. Index values utilized by most models were not necessary and were not displayed.

Timing Fungicide Sprays Based on Advisories. The most common use of weather-based advisories is to improve the timing of fungicide sprays. Consequently, these reports were often called spray advisories. Conditions favorable for disease development which fall within the period of residual fungicide protection do not need additional fungicides. While there are models that describe the degradation of fungicides on foliage, it was simple and effective to use the interval known (i.e., information found on the pesticide label, in extension literature, etc.) to control the disease on a standard calendar spray schedule. The threshold was defined as a date on or after which sprays should have been applied. The concept of a last effective spray date was first developed by Phipps (1993). This method is simple for agents to use for an audience that has sprayed on many different dates. For example, a report would recommend: "you should have sprayed since July 20 to be protected from peanut early leaf spot." Growers would have to note when their fields were sprayed to use this information. This also helped simplify reports given on Monday morning to describe conditions during the weekend when the extension service was not issuing spray advisories. Growers who did not call in every day did not miss a change in the threshold as could happen in systems with daily spray/no spray reports.

Factors that influence the successful use of the Last Effective Spray Date included (a) accuracy and applicability of the scientific information used in the model, (b) quality of the weather data, (c) ability of the user to quickly respond to the issuance of an advisory, (d) efficacy of disease control practices, (e) quality of scouting information, and (f) ability to use weather forecasts and common sense to take action before extremely wet and/or conducive weather arrives.

Advisory reports were composed of a histogram of daily hour of favorable weather and the Last Effective Spray Date. The latter can be omitted and the histogram used as the sole source of guidance in cases where the threshold is unknown, there is uncertainty in its accuracy, or where liability concerns are high. Growers like definitive statements about the need for fungicide applications; however, they usually do not follow this advice exactly as it is given unless delivered by a trusted advisor. Consequently, it would be desirable if a relative risk index scale could supply most growers with much of the information they need after experience is gained.

Growers use advisories in their own way. Surveys show that over 80% of growers use the leaf spot advisory (Bailey *et al.*, 1994). Many growers already consider weather conditions when they are determining spray needs without the benefit of a formalized spray advisory. Growers make decisions based on experience, farm logistics, perceived need, and risk aversion. This process would be difficult to incorporate into even the best expert systems. Deployment of histograms, which depict rising and falling risks without establishing specific thresholds, may be an excellent method of delivering information on the risk of disease development. This removes a large amount of liability from those who recommend the use of advisories and should allow more widespread use of generally beneficial information in areas where threshold models may never be developed.

The action threshold, or point at which a grower would take action to control a pest/disease, depends on many factors such as (a) time since the last pesticide application was made, (b) pest history, (c) scouting observations, (d) grower's perception of and willingness to accept risk, (e) effectiveness of cultural practices (i.e., resistant cultivars, rotations) being used, (f) ease of arresting pest/disease development, (g) remaining time to harvest, (h) pesticide label restrictions, (i) safety considerations (i.e., re-entry time), (j) weather forecasts, (k) destructiveness of disease, (l) fungicide price, and (m) current market value of the commodity.

Guidance for pesticide use can be found on their labels which provides a range of spray intervals indicating to spray more often when conditions are "favorable" for disease development. Labels for propiconazole and tebuconazole indicate that the leaf spot advisory can be used as a recommended schedule for Virginia and North Carolina. Growers could be instructed to use these weather advisory graphs to help determine the appropriate spray interval without the use of specific thresholds. This also keeps the risk to a minimum for the grower since pesticide label recommendations are generally well researched over a wide geographic area. Spraying less than the labeled interval remains an option for growers as they learn to interpret the relationship of the weather information in the context of their farm/region. It is assumed that spraying according to the pesticide label will provide satisfactory disease control. While growers can be relied upon to fine tune recommendations based on the advisory, it is most important that they not be misled into allowing a damaging epidemic to occur.

The approach discussed assumes that the pathogen is present or the algorithm is adequate to estimate when control actions need to be implemented and that certain rules such as the importance of phenology, scouting procedures, and resistance levels will be integrated with the weather advisory information. Where necessary, more than one model can be used to describe the epidemic. For example, one model may be used to define conditions for the first spray and another for the rest of the season. If different phenological stages of the plant have unique spray needs, each stage could have its own model. Multiple models could be used to help define the recipe for tank mixes of fungicides.

The same weather equipment was used in both the development and deployment of the advisories. This means that nothing was "lost in the translation" from the experimental plots to the large-scale use due to differences in hardware type and/or placement. New models developed will use the same software format so that dissemination would be a matter of adding a template file to the pre-existing data analysis infrastructure. Output from new models required less explanation because the reports generated are almost identical to the reports for other advisories previously deployed. Education is made easier by the use of help screens. Each new model has a text file for giving specific instructions for use with the advisory. Information added to this file can be displayed when the user types "I" (information) while viewing the model. This text file includes information on disease identification, control, limitations of the report (including a disclaimer), source of information used to create the model, and appropriate information for each user's geographic area.

Multiple advisories offset some of the costs associated with the equipment by maximizing its usefulness. For example, sclerotinia blight advisories (Lee *et al.*, 1990; Phipps, 1995) also are issued with leaf spot advisories. The templates also represent a quick and easy way for cooperators to exchange information or conduct joint research by sending template files via Internet. Currently, equipment has been used for model development in six states on several crops.

While impressive strides have been made in the deployment of disease forecasting systems, they are modest compared to the potential impact if development and deployment of existing information were made easier. The template approach to forecasting describes a method to utilize information in compendia, theses, epidemiological articles, pesticide labels, and expert opinion that ordinarily would not be integrated into advice for the farming community. While the device described in this work has been commercialized, the software and templates are available without cost to prevent algorithmic information from becoming proprietary and to encourage creation, sharing, and testing without the burden of license agreements.

Although great flexibility is possible with this simplistic modeling approach, it does not currently work well for many important diseases. For example, there is currently no method of adding lethal (hot and dry) conditions for downy mildews, or negative/positive relationships with dry, hot weather and activity of *Aspergillus* spp. Further development is currently underway to address issues with multiple diseases.

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