John C. Sutton, Terry J. Gillespie, and Paul D. Hildebrand
University of Guelph, Ontario, Canada

Monitoring Weather Factor

Innovations in weather instrumentation of the past 10–15 years have profoundly enlarged our capabilities in monitoring microclimates of crops and have introduced intriguing possibilities for exploring weather dynamics in relation to plant disease. As recently as 5 years ago, plant pathologists depended almost entirely on mechanical instruments, such as hygrothermographs, hemp-string wetness meters, funnel-type rain gauges, and sunshine recorders, for measuring microclimate. Although continuing to have useful applications, mechanical instruments may measure environmental variables roughly or infrequently and record data inconveniently as ink traces on chart paper. In recent years, a wide range of sensors with electrical outputs easily recorded by data loggers has been developed. Many electrical sensors are now sufficiently durable for continuous use in crop canopies.

Electrical sensors have immensely improved the scope and accuracy of microclimate monitoring. Rain, irradiance, and low as well as high wind speeds may be measured continuously. Relative humidities near saturation can be monitored more precisely than before. Leaf wetness, a variable of unique importance in plant pathology, can now be monitored with much improved accuracy in many types of crops. Several electrical sensors are sufficiently small to permit monitoring weather variables at point locations among plants or, in some instances, on plant surfaces. Often, sensors can be positioned at different locations in the crop and connected in series or parallel to provide spatially averaged or maximum values for the weather variable. A few sensors, notably the thermistor, have applications in the soil environment.

Electrical sensors in conjunction with microprocessor-based data loggers enormously facilitate epidemiologic studies of weather in relation to disease and show increasing promise for application in disease management on the farm. Because of improved efficiency of weather monitoring, holistic studies of epidemics have become more feasible and more widely applied. Continuous observations of weather, crop, pathogen, and disease during weeks or months of epidemics are indispensable for identifying and measuring key relationships among these variables. Rapid response of the sensors and frequent recording of data allow examination of abrupt changes in weather in relation to sporulation, spore release, and other biological events of short duration. Data of holistic studies contribute substantially to models of epidemics, which may have predictive value in timing fungicides and other disease management practices or in forecasting yield losses (7). Comparatively simple monitoring systems utilizing two or three weather sensors are of particular value for validating, verifying, and implementing disease models on the farm.

The main task in monitoring crop microclimate is to acquire valid data. Vast quantities of data that turn out to be invalid are deceptively easy to collect. In general, plant pathologists would do well to consult with agrometeorologists to obtain a basic appreciation of the functioning, calibration, protection, and limitations of instruments as well as the requirements for maintaining sensors and data loggers in the field. Disease management scouts also need adequate hands-on instruction with weather instrumentation.

To acquire valid data, investigators must be aware of several sources of error. Sensors may have inherent error or systematic error attributable to poor calibration (4). The manufacturer's error specifications are useful guides but should be verified in the laboratory if possible. Errors may arise when radiation, evaporation, conduction, or other variables interfere with sensor readings, and many sensors require protection from direct sunlight, moisture, or debris. Induction in the wires leading from sensors and inadequacies in data loggers can also result in errors.

In this discussion of the instrumentation we consider useful for monitoring microclimate in studies of plant disease, we emphasize practical considerations and share some pitfalls, frustrations, and successes we have encountered.

Temperature

Temperatures are measured almost universally in epidemiologic studies, and various kinds of thermometers are used. Among the most versatile and dependable are thermistors adapted for monitoring

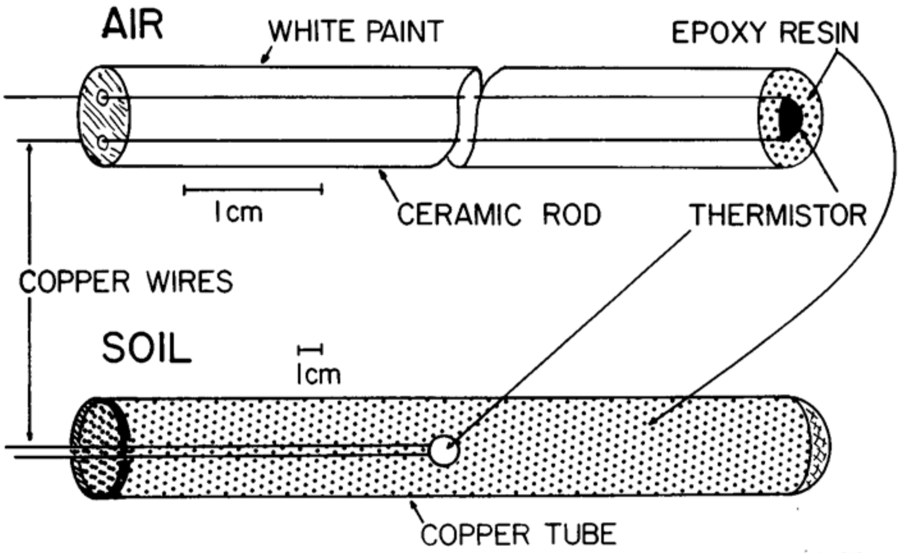

Fig. 1. Thermistor probes for monitoring air and soil temperatures. The ceramic rod of the air thermistor minimizes thermal conduction to the thermistor sensor. Copper tubing in the soil thermistor provides high thermal conductivity from the soil to the sensor.

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n Relation to Plant Disease

air and soil temperatures in crops. Thermistors are semiconductors that show a strong inverse exponential relationship of resistance and temperature (4). Because resistance decreases about 5% when the temperature increases one degree Celsius, high resolution of temperature is possible (eg, ±0.1 C). Ready-calibrated thermistors are manufactured in sizes ranging upward from about 0.02 mm and in such shapes as rods, disks, and beads. The calibration is often good for many years but should be checked every few months. Thermistors for the aerial environment are commonly mounted in rods or probes (Fig. 1) and require occasional cleaning. The soil thermistor shown in Figure 1 is a robust, homemade design for obtaining spatially averaged temperature measurements; epoxy resin is injected into the copper tube to protect the sensor from moisture.

Thermocouples, another type of electrical thermometer, are constructed by soldering or welding two wires of dissimilar metals, often copper and constantan. They are easily made in a variety of sizes, from <0.02 to >1 mm, at little cost. A disadvantage is the very small electrical signal produced (microvolts) that requires a sensitive data logger (eg, Model CR-7, Campbell Scientific Inc., Logan, UT 84321) for accurate detection.

When deployed in the aerial environment, thermometers should be shielded from radiation and wetness. A thermometer measures its own temperature, which rises above that of the ambient air in response to irradiance and falls below that of the ambient air when water evaporates from the thermometer surface. Louvered instrument shelters offer suitable protection, but a simple, easily made nonventilated shield (Fig. 2) allows more precise positioning of the sensor in the crop foliage and reduces the temperature difference of sensor and air to 0.5–1 C in full sun. More elaborate shields are available that protect the sensor from radiation arising from soil and plants as well as direct solar radiation. These shields reduce radiation errors to <0.1 C but are artificially ventilated by means of fans that require an electrical source.

The hygrothermograph is a popular instrument that continuously records air temperature and relative humidity as separate traces on a 7-day, clock-driven chart (Fig. 3). Hygrothermograph records of temperature and humidity must be digitized for application in computer analyses, a tedious task greatly facilitated by use of a graphics digitizer. Computer programs are available that digitize heights and areas of chart records and correct for a fast or slow clock (1,13).

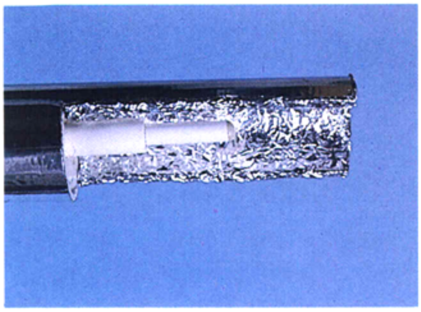


Fig. 2. Thermistor probe protected by a simple shield. In the field, the shield is oriented with the open end facing north to prevent solar radiation impinging on the sensor.

Fig. 3. Hygrothermograph for monitoring air temperature and relative humidity, positioned in an instrument shelter.

The temperature sensor of a hygrothermograph is commonly a coiled bimetallic strip that bends in response to temperature changes, and this response is amplified through mechanical linkages to a pen arm. In the field, the hygrothermograph must be housed in an instrument shelter to protect the sensing elements and other components from solar radiation or rain. The temperature reading should be calibrated against an accurate (±0.5 C) mercury-in-glass thermometer every week at a time when the temperature is stable.

Relative Humidity

Functioning as a hygrometer, the hygrothermograph depends on expansion and contraction of human hair in response to relative humidity (RH) changes (12). Response time is about 5 minutes. Should RH increase from 0 to 100%, the hair would lengthen only by 2.5%. This small, nonlinear response is amplified, then recorded as an ink trace. When high humidity is of special interest, as in epidemiologic studies, the hair element is calibrated at or near saturation. Because the element slowly loses calibration under dry conditions, recalibration about every 2 weeks is advisable. An instrument in a shelter can be calibrated by misting deionized water repeatedly onto the hair sensor for half an hour, then adjusting the recording arm to read 95% RH. Alternatively, the instrument can be adjusted against an Assmann-type psychrometer, preferably when RH is stable.

Highly accurate measurements of RH may be obtained with a ventilated psychrometer, but this instrument needs frequent attention as well as an electrical source. A psychrometer consists of a dry thermometer for measuring air temperature and a continuously moist thermometer cooled by evaporation of water. RH is calculated as a function of the difference in temperature readings of the wet and dry sensors. Thermistors are appropriate thermometers for use in continuously recording psychrometers and function in the same manner as the familiar wet- and dry-bulb mercury-in-glass psychrometers.

For a ventilated psychrometer suitable for field-plot use (Fig. 4), two thermistors matched according to temperature response are mounted inside separate tubes that are double-walled and covered with Mylar-coated reflective aluminum foil to minimize radiation errors. The "wet" thermistor is kept moist by a tightly woven cotton wick extending into a reservoir of deionized water. Wicks are best cleaned before use by boiling in soap solution and then in deionized water. Wicks in use should be checked once or twice a day to make sure they are moist and to wash off any particulate matter. A fan draws air continuously over the thermistors at a speed needed to achieve maximum dew-point depression (>3 m sec^{-1}) (4).

The rationale for calculating RH from

Fig. 4. Portion of a ventilated psychrometer for monitoring relative humidity.

the wet- and dry-bulb psychrometer readings is as follows:

$$RH = 100\ (e/e_{STDB}),$$

where e and e_{STDB} are, respectively, the actual and the saturated vapor pressures at the dry bulb temperature.

$$e = e_{STWB} - \alpha\ (T_{DB} - T_{WB}),$$

where e_{STWB} is the saturated vapor pressure at the wet bulb temperature, α is the psychrometric constant, and T_{DB} and T_{WB} are the respective temperatures (C) of the dry and wet bulbs.

$$\alpha = (1.01)\ (\text{barometric pressure, mbar})/(0.622\ \lambda),$$

where λ is the latent heat of vaporization of water (in J g^{-1}), which decreases almost linearly with increase in temperature according to the equation:

$$\lambda = -2.3619\ (C) + 2{,}500.$$

Using the average seasonal value for barometric pressure at a specific location results in only minor errors.

$$e_{STDB} = 6.1078 \exp\left[17.269\ T_{DB}/(237.3 + T_{DB})\right],$$

where exp [x] is 2.71828^x. The same formula may be used for e_{STWB} by replacing T_{DB} with T_{WB}. The above equations may be written into functions for converting temperature data to RH values in the computer.

Another type of humidity sensor of practical value to plant pathologists exploits the effects of moisture adsorption and desorption on the electrical conductivity of a sulfonated polystyrene (SP) plate (about 1 × 20 × 40 mm) to which two electrodes are bonded (Fig. 5). Resistance of the SP sensor varies logarithmically with RH. The sensor responds substantially in about 3 seconds but may take many minutes to attain complete equilibrium. Elements with an operational calibration not exceeding ±5% are available (Phys-Chemical Research Corp., New York, NY 10011). The SP sensor does not function well in a dirty environment and must be shielded from rain; an ordinary weather shelter provides suitable protection. Forced ventilation is not needed provided the temperature of the sensor is monitored, eg, with a thermistor. Ambient RH is then found from:

$$RH = RH_{SP}\ (e_{STSP}/e_{STDB}),$$

where RH_{SP} is the RH at the SP sensor and e_{STSP} and e_{STDB} are the saturated vapor pressures at the temperatures of the SP sensor and ambient air, respectively.

Leaf Wetness

Leaf-surface wetness normally refers to dew or rain on aerial plant surfaces. The duration of wetness is of chief interest in epidemiology, although the amount and form (eg, films, droplets) of free water may also be important (14). Wetness duration varies considerably not only with weather conditions but also with the type and developmental stage of the crop; the position, angle, and geometry of the leaves; and the specific location on the individual leaf. Therein lies a challenge for the epidemiologist attempting to monitor wet periods!

Instruments for monitoring leaf wetness utilize either a string-type sensor or an electrical-resistance sensor. Wet periods also can be estimated roughly from the duration of RH ⩾90% on hygrothermograph charts. The string-type sensors constrict when moistened and slacken as they dry. The deWit instrument, first introduced some 35 years ago, records the response of degreased hemp string as an ink trace on a circular chart (Fig. 6). In our experience, deWit recorders estimate dew periods with reasonable accuracy (error <1 hour) in carrot, apple, and potato foliage but not in onions, in which wetness is substantially overestimated or underestimated depending on growth stage of the crop (Fig. 7). The slope of the ink trace after dew onset provides a rough but useful indication of the rate of wetting of leaves. The leaf wetness indicator of MacHardy and Sondej (8) utilizes a sensor made from cotton chalk line, of the type used by carpenters, linked to a contact plate that makes or breaks an electrical circuit when the sensor contracts or slackens. A pen arm records wetness as an ink trace, but the device could be adapted for use with data loggers.

Various kinds of electrical wetness sensors either clip onto the foliage or are placed among the leaves where they provide an artificial leaf surface for simulating foliar wetting and drying. In both forms, rain or dew provides the electrical pathway between two pairs of electrodes. Alternating current is used to avoid electrolysis. Small clip sensors mount on leaves without additional support. For onion leaves, however, we use nickel-wire (0.25 mm) electrodes mounted on the two halves of plastic clothespins clamped to a metal support. The electrodes are bent to gently clasp the leaf without damaging the epidermis even on windy days (Fig. 8). Several clips connected in a parallel circuit and mounted at various heights in the canopy provide good estimates of wetness periods under various weather conditions. Because clips respond to high RH before dew deposition, calibration against sensible dew is important. Clips require daily checking for foliar attachment and thus are not well suited for disease management purposes on the farm.

Artificial leaves for monitoring wetness are made in various shapes from electronic circuit board, plastic, or cloth on which electrodes are mounted (5). Two types of sensors we have found useful in a variety of crops are flat plates with electrodes printed in the form of interlocking fingers and acrylic or polyvinyl chloride cylinders on which the electrode wires are wound in shallow grooves cut as parallel spirals (Fig. 9). The sensor is coated with white latex paint, slightly darkened with black or green pigment, to serve as a moisture-absorbing medium and to increase sensitivity to initial dew. Drying of dew on the sensor can be matched to that on a particular crop by adjusting the shade of paint. Some latex paints contain undesirable surfactants that absorb moisture at humidities below saturation, but these often may be removed by steaming the sensor after it is painted. Although rate of drying is a stronger function of reflectivity than of size, the sensor is best made roughly the size of the leaf. Angle of exposure markedly affects rate of drying of the plate sensor but not of the cylinder sensor, which is normally positioned horizontally among the leaves. Large water drops that form on the lower side of cylinder sensor tend to dry simultaneously with the largest (and last) drops on the plant.

Rain

Rain has a diversity of attributes of potential importance in epidemics, but only certain of these are readily monitored in the field. Spatial distribution of rain is of particular interest in farm-scale or regional epidemiologic work. Temporal attributes of rain, mainly time, frequency, and duration, often are critical for disease progress. Rain intensity (amount/unit time) is a collective function of the number, size, and velocity of droplets, each of which may affect disease in different ways. The tipping-bucket rain gauge (Fig. 10) is valuable for measuring both the temporal features and the overall intensity of rain. Funnel-type gauges measure only total rain for chosen intervals between readings but are sufficiently inexpensive for multisite applications. We are not aware of any instrument suitable for monitoring the number, size distribution, or velocity of raindrops in field plots.

The tipping-bucket gauge operates by directing rain from a collecting funnel into a two-chambered, V-shaped vessel that tips backward and forward in response to each 0.25 or 2.5 mm of rain. Each time the vessel tips, an electrical pulse is initiated by means of a photocell, magnetic reed switch, or other device. Errors arise during heavy downpours if the apparatus becomes "quenched." In periods of drizzle or light rain, significant timing errors may result from water remaining on the funnel and from rain carrying over from one shower to the next in a partially filled chamber of the tipping vessel. Tipping-bucket gauges usually require little maintenance except for occasional cleaning. Some types tend to become plugged with bird excrement unless modified to discourage roosting (Fig. 10). Rain collected from gauges may be useful for enumerating fungal spores washed from the air.

Wind

Complexities of wind in and above crop canopies are encountered as variable speeds and directions often associated with gusts, eddies, and other turbulence phenomena (6). Wind, often in conjunction with rain or soil, directs spread of pathogens and may injure plants directly or through mutual abrasion or violent movement of plant parts. Such injuries are infection sites of many pathogens. Many turbulence phenomena in crops are difficult or impractical to measure, but we can monitor overall wind speed and direction. Instruments suitable for field use include cup and thermal anemometers for measuring wind speed and vanes for indicating wind direction (4,6,11).

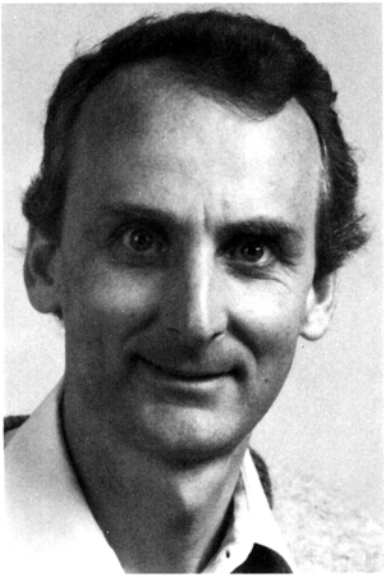
The simplicity of the familiar cup anemometer makes it the sensor of choice for continuous monitoring. Mean wind speeds in crops usually are low but increase logarithmically with height above crops (3,10). Accordingly, anemometers with low starting thresholds (wind <0.4 m sec^{-1}) are advantageous. As sensitivity increases, however, ruggedness to sustain severe weather usually declines. Sensitive anemometers utilize a cup-assembly spindle, at the lower end of which is a slotted cylinder. At each rotation, the cylinder interrupts a light beam to a photoconductive cell, thereby generating electrical pulses as a function of wind speed. Cup anemometers start slowly because of inertia and, as a result of "overrun" associated with momentum, overestimate when wind speed drops sharply. Thus, unlike thermal anemometers, they do not respond well to turbulence.

Thermal anemometers are useful for monitoring turbulent winds of relatively low speeds at point locations in the crop. The sensors of thermal anemometers are fine wires, films, thermocouples, or thermistors that are maintained electronically to a constant temperature or a constant current (4,11). Electrical resistance of the sensors changes when they are cooled by wind. Thermal anemometers tend to be fragile and easily contaminated and thus are most suitable for short-term applications.

Wind vanes appear to be used in few epidemiologic studies, yet they are

John C. Sutton

Dr. Sutton is a professor of plant pathology in the Department of Environmental Biology at the University of Guelph, Ontario, Canada. His research interests include epidemiology and management of foliar diseases affecting cereals, onions, carrots, and strawberries. He teaches courses in plant disease epidemiology, plant pathology techniques, and diagnostic mycology. He received a B.Sc. in agricultural botany from the University of Nottingham in 1965 and a Ph.D. in plant pathology from the University of Wisconsin in 1969.



Terry J. Gillespie

Dr. Gillespie is a professor in the agrometeorology section of the Department of Land Resource Science at the University of Guelph, Ontario, Canada. He teaches courses in meteorology and climatology. His research interests focus on weather instrumentation and relationships of weather to insects and diseases. He received a B.Sc. from the University of British Columbia, an M.A. from the University of Toronto, and a Ph.D. from the University of Guelph.

Paul D. Hildebrand

Dr. Hildebrand is a research scientist at the Agriculture Canada Research Station at Kentville, Nova Scotia, Canada. He received a Ph.D. in plant pathology from the University of Guelph in 1983. His research interests center on epidemiology and management of plant diseases. He is now initiating a research program on diseases of small fruits.

valuable tools for studying pathogen dispersal and disease spread. Vane direction is commonly monitored by means of a low-torque potentiometer connected to the vane shaft.

Irradiance

Solar energy arrives at our atmosphere and either impinges directly on our crops as shortwave radiation (0.3–3 μm) or is converted to long-wave radiation (4–50 μm) in the atmosphere. Crops also receive long-wave radiation emitted or reflected by soil, plant materials, and other terrestrial objects. Total incoming shortwave energy per unit time is the radiant flux, and the flux per unit area is called the radiant flux density, or irradiance, usually quoted in Wm^{-2} (3,10). Instruments to measure irradiance are called pyranometers ("fire measurers").

Thermopile pyranometers measure radiant energy as heat to accuracies within ±5% (Fig. 11). Solar radiation first passes through a glass hemisphere that filters out long-wave radiation and protects a black-and-white sensing disk from cooling by wind and moisture. The radiant energy differentially warms the black and white portions, which are, respectively, the hot and cold junctions of a thermopile. Newer models have a black sensing disk and an internal cold junction. Output of the thermopile is typically 15 mV for full sunlight of 1,000 Wm^{-2} and is linearly related to shortwave irradiance. A simpler pyranometer utilizes a silicon photocell sensitive to irradiance at about 0.4–1.1 μm wavelengths (Fig. 12). Commercial sensors (LI-COR, Inc., Lincoln, NE 68504) correct for additional solar radiation at 1.1–3 μm and thus respond according to total solar irradiance. The correction factor is not valid, however, when the radiation deviates substantially from the direct solar spectrum. Consequently, this pyranometer sensor is not suitable for measuring irradiance inside crop canopies, under artificial shading, from reflected sunlight, or from artificial lamps or light tubes. Thermopile pyranometers are appropriate for these applications, and a quantum sensor is available (LI-COR, Inc.) for measuring light quanta (as opposed to light energy) in the photosynthetically active portion of the spectrum (0.4–0.7 μm).

Logging Weather Data in Research Plots

Systems for monitoring weather factors in crops involve weather sensors and data-logging devices (Fig. 13). Such systems preferably should have low power requirements for extended operation on batteries. Important features of data loggers include acceptance of DC analog inputs over the range of voltages appropriate to the chosen sensors and provision of DC excitation voltage for thermistors. Wetness sensors and electronic RH sensors require AC excitation to avoid polarization of water, so the data logger should feature channels that rectify AC inputs. Pulsed outputs of rain gauges or anemometers need digital input channels that count rapidly enough to accommodate the rate of sensor output. Circuit diagrams for connecting sensors to data loggers usually are provided by manufacturers. It is

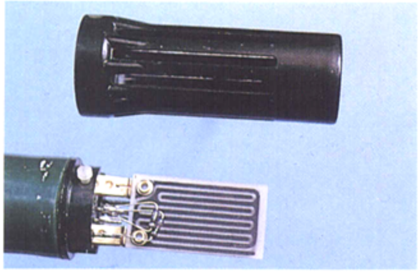


Fig. 5. (Bottom) Humidity sensor constructed from a sulfonated polystyrene plate to which two electrodes are bonded, and (top) a protective cover (Phys-Chemical Corp.).

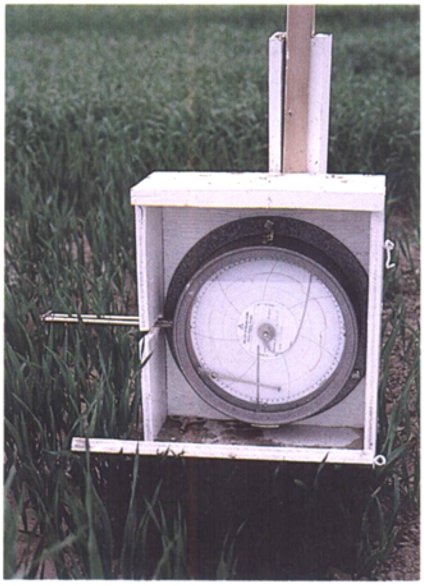


Fig. 6. The deWit leaf wetness recorder monitoring wet periods in wheat.

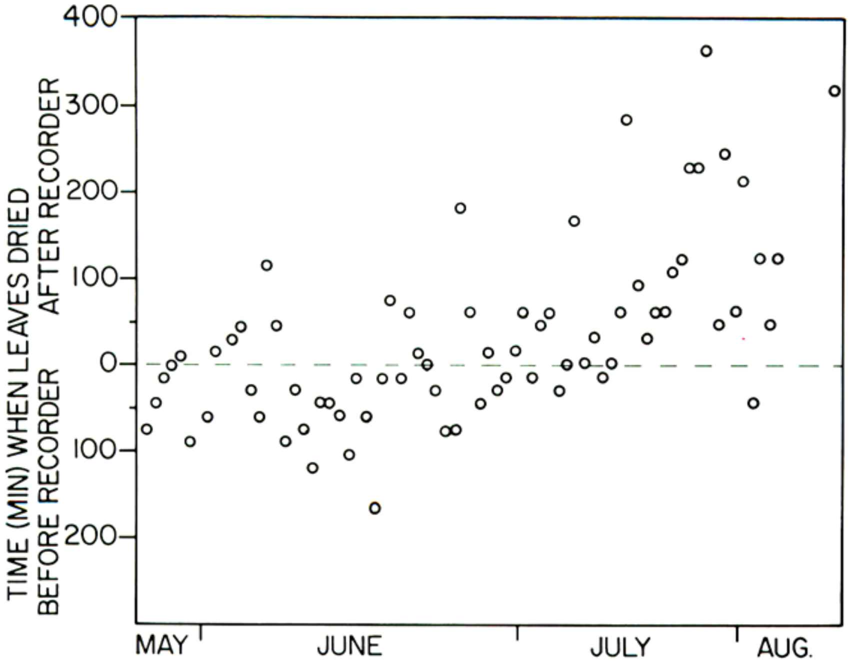


Fig. 7. Time of drying of onion foliage measured by electrodes clipped on the leaves relative to that measured by a deWit recorder on various days in the growing season. The leaves usually dried before the hemp-string sensor of the recorder early in the season but after the hemp-string sensor late in the season.

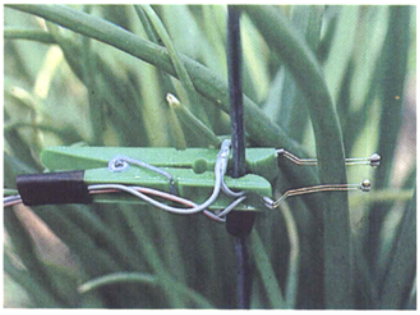


Fig. 8. Electrical wetness sensors clipped onto a green onion leaf.

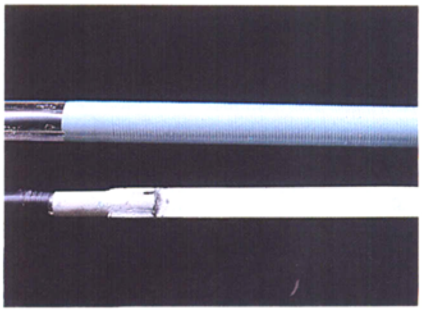


Fig. 9. Artificial leaves for monitoring leaf wetness duration.

imperative that electrical shields on signal wires are connected to ground only at the data logger and that sensors in contact with soil are electrically insulated to prevent ground loops.

Power surges associated with lightning strikes are a great hazard to electronic monitoring equipment. Spark gaps incorporated into circuits may help prevent damage to sensors and memory chips in data loggers when lightning strikes nearby, but distant strikes may result in surges in the main power supply. Surge protectors should always be used whenever monitoring systems are connected to the main power supply, not only to protect instruments but to provide peace of mind during thunderstorms!

Data loggers usually scan sensor outputs at frequent (⩽1 minute) intervals but may be programmed to average the readings over longer periods. Averaging intervals of 15 minutes to 1 hour are often useful in epidemiologic studies. Calibration equations to convert millivolt, resistance, or pulse outputs of sensors into desired units of measurement for the weather variables may be keyed directly into modern data loggers. Immediate conversion to appropriate units greatly facilitates troubleshooting. Data may be read on a digital display but are usually transmitted to a cassette tape recorder or a printer. Highly reliable read-only memories (EPROMS) may shortly replace cassette tape recorders in many data loggers.

In our laboratory, data are transferred from tapes or EPROMS to a microcomputer via an RS 232 communications interface. These numbers are viewed on a video screen to detect and, when possible, correct for any "noise" that appears as slashes or other symbols in place of numbers. Noise from cassette data often is associated with an incorrect volume or head setting on the recorder or with imperfections in the magnetic surfaces of the tapes. Data in the computer may be processed in several languages, including BASIC, FORTRAN, or PASCAL. For APL, the code is first manipulated as character vectors, then converted to numeric vectors before introducing additional functions, such as those for calculating RH from psychrometer readings. Data are then organized into a separate matrix for each weather variable from which plotting or further analyses may be done.

Data Analysis

In analyzing epidemics, the investigator is confronted with numerous possible relationships among the dependent and independent biological and meteorologic variables. Biological variables typically include quantitative estimates of the host, the pathogen, and the disease. Usually, only certain pairs or groups of dependent and independent variables justify detailed examination or statistical analyses. Probable associations between variables are more easily recognized when all the variables are plotted against time, either by hand or with a computer plotter. For instance, large peaks of airborne spores may coincide with the onset of rain showers, or disease may fail to progress when temperatures are low or wet periods short. Such associations are easily detected because the measured biological response is synchronous with fluctuations in the weather factors. Recognizing associations becomes more difficult when measuring the culmination of biological processes that may have been affected by weather during several hours or days. Spores of fungal pathogens commonly mature after dawn, but the sporulation process may have been affected by the weather of the previous night, the preceding day, or longer. Similarly, lesion populations are related to weather conditions affecting infection and latent development of the pathogen during several days. Stage of the epidemic is a further confounding factor, because quantitative responses of pathogens and disease to

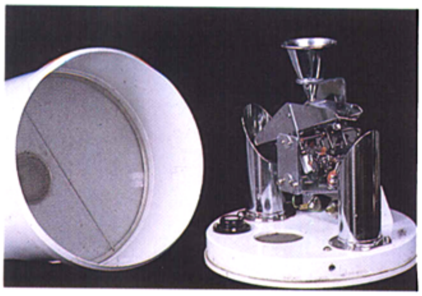


Fig. 10. Tipping-bucket rain gauges manufactured by (top) Weathertronics Inc., Sacramento, CA 95841, and (bottom) Edmund Scientific Co., Barrington, NJ 08007; wires have been added to discourage birds from roosting on the gauge.

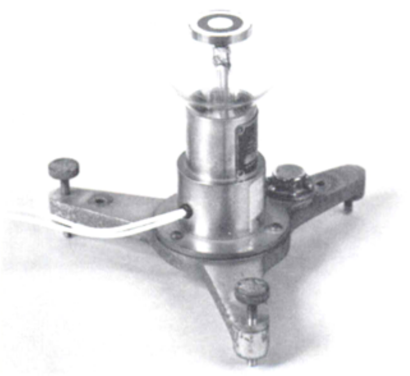


Fig. 11. Thermopile pyranometer for measuring irradiance in crops (Eppley Laboratory, Inc., Newport, RI 02840).

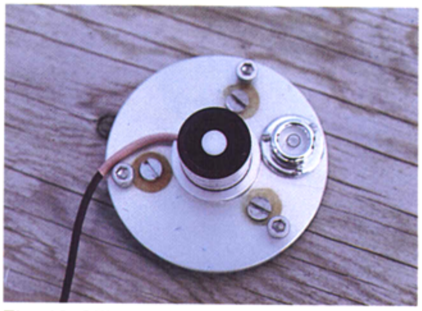


Fig. 12. Silicon photocell pyranometer for measuring irradiance (LiCor Ltd.).

Fig. 13. Weather sensors and data-logging devices in an onion field. (Bottom) Data logger with nine input channels (Model CR-21, Campbell Scientific Inc.), positioned in a weather shelter.

weather generally become stronger as the epidemic progresses. This problem may be overcome by dividing the epidemic into portions for analysis. In general, the investigator draws on a great deal of biological knowledge and intuition in selecting variables for statistical treatments. Inductive reasoning ranks prominently in these kinds of studies.

Statistical frequencies, correlations, and regressions are effective means for examining the biological and weather data. Frequency of association of a biological phenomenon, such as spore release or survival, with specific weather conditions is a simple but useful approach that lends itself to presentation as easily interpreted bar graphs or frequency tables. Calculation of the correlation coefficient gives a measure of the relationship between the biological variable and the weather variable. Epidemiologists, however, often wish to determine the amount of change in the biological variable associated with a unit change in the weather variable and therefore use simple or multiple regressions.

Many precautions are called for in regression analyses but are often forgotten. For instance, successive observations on the biological variable should be independent, but those such as daily spore counts may not be and grouping or other treatment of the observations may be necessary. A second precaution is that the distributions of the biological variable at various levels of the weather variable (the conditional distribution) should be normal and have the same variance. Butt and Royle (2) provided excellent insights into the practicalities and pitfalls of using regressions in epidemiologic analyses. When drawing conclusions we should remember that correlations and regressions do not prove causal relationships but do reveal consistent associations that we may use predictively. Causal relationships call for studies in controlled environment. Data of the field and growth cabinet form the basis for disease models (7).

Weather Monitoring in the Grower's Field

Implementation of models for timing disease management practices, such as fungicide applications, usually requires monitoring of temperature and wetness duration or relative humidity and sometimes of rainfall in the crop. Weather instruments are used mainly to determine, in retrospect, whether conditions were favorable for sporulation or for infection. Several models, such as BLITECAST for potato late blight (9), use cumulative weather data as an indirect means for monitoring early stages of epidemics when disease is otherwise difficult and costly to quantify.

Instruments for commercial disease management should be low in cost and maintenance and easy to use and calibrate, as well as durable, reliable, and accurate. Although hemp-string recorders and hygrothermographs are widely used, considerable time is required to digitize the data and compute such variables as mean temperature of the wet period. Mechanical difficulties often arise with pen inking, clock function, and chart changes, and good-quality instruments tend to be costly. The weather monitoring systems of MacHardy and Sondej (8) have overcome several objections to mechanical instrumentation. A practical alternative is to use thermistors, electrical impedance sensors (artificial leaves), sulfonated polystyrene sensors, and, perhaps, tipping-bucket rain gauges in conjunction with microprocessor-based data loggers. We have successfully deployed two-channel data loggers (Fig. 14), each with a thermistor and wetness sensor, for field validation of BOTCAST, a model for Botrytis leaf blight in onions. Several electronic recording devices automatically integrate wetness and temperature data in terms of severity of infection periods or the like. Relatively simple data loggers of this kind appear to have wide application in disease management.

Fig. 14. Programmable data logger with two input channels and data printout (Crop Technologies Inc., Waterloo, Ontario, Canada N2J 3X2).

Future Directions

Many applications and adaptations of weather instrumentation in plant disease studies remain to be explored and exploited. Thus far, leaf wetness has been measured in terms of green foliage, yet many pathogens are affected by wetness of necrotic leaves, with quite different wetting phenomena. Applications of microwave beams for remote sensing of leaf wetness and internal plant moisture may be worth investigating. Imaginative studies are needed to explore effects of sunlight on pathogens and disease independently of changes in temperature and humidity. Surface electrical phenomena represent hitherto unexplored variables that may have implications in plant disease epidemiology. Data loggers are now used year-round in cold climates and even on mountain peaks, so weather monitoring in relation to low-temperature pathogens should be well within our grasp. In-crop monitoring on the farm will likely expand substantially, and the possibility exists for linking the monitoring devices directly to personal computers by means of radio signals. Integrated work involving astute biological observations, environmental physics, and electronics offers much to advance the science and practice of plant disease epidemiology.

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