Stella Melugin Coakley
National Center for Atmospheric Research, Boulder, CO, and University of Denver

Describing and Quantifying the Environment

The environment influences the development of plant disease in many ways. An adverse environment may predispose the host to disease or affect the length of a phenological stage when the host plant is susceptible to disease. Subsequent development of disease caused by a biotic pathogen is limited to the period when the environment is simultaneously favorable to host susceptibility, the pathogen, and any necessary vector for a sufficient time. Meteorological conditions greatly influence the development of an epidemic over a growing season and the survival of the pathogen until the next season. Investigations of the incidence, development, and epidemiology of plant disease, therefore, often require researchers to measure climatic and edaphic factors in the plant's environment over a growing season or, in some instances, over an entire year or several years. This article emphasizes measurement of ambient climatic factors, but the principles of measurement also apply to quantification of the soil environment.

Meteorological Data Collection

Micrometeorological data are collected within or very near the plant canopy where the plant affects the environment and usually are tailored to specific investigations. Macrometeorological data, in contrast, are collected above or outside the plant canopy, often at weather stations some distance from the site of interest. Macrometeorological data are often collected by meteorological organizations rather than by the users of the data, although there has been a recent increase in the collection of these data by growers within their fields and orchards. In the United States, most macrometeorological data are recorded by the National Oceanic and Atmospheric Administration (NOAA)–National Weather Service Cooperative Observer Program, primarily as daily maximum and minimum temperatures and precipitation amounts. At 300 weather stations located at airports, data are collected hourly for temperature, wet-bulb temperature, dew point, relative humidity, wind speed and direction, precipitation, and cloud cover. Solar radiation and soil temperature data are not collected routinely; in the continental United States, for example, solar radiation was monitored at only 34 stations in 1979 (1).

In 1981, Dale (1) described the existing meteorological networks (including the relatively new agricultural weather service) and evaluated the adequacy of the network coverage and the quality of the data produced. Users of network data should be aware that stations may be relocated or that equipment type or exposure may be changed. Long-term temperature records have been affected

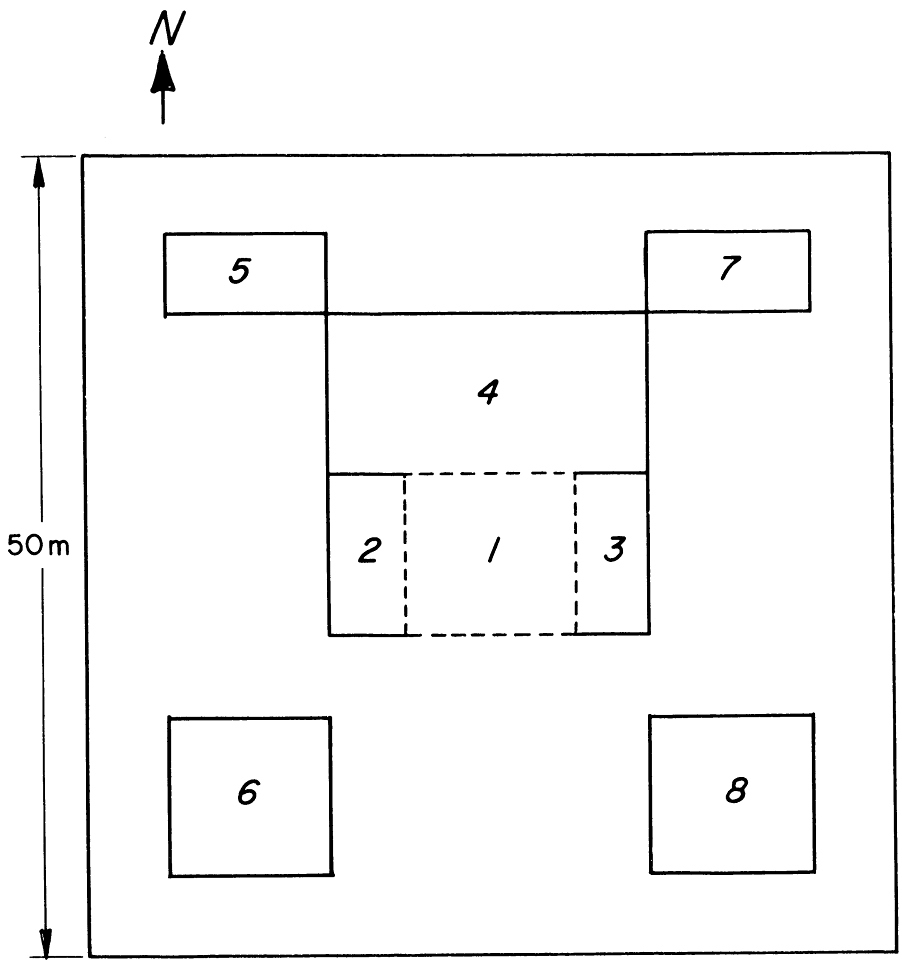


Fig. 1. Design of a reference agrometeorological station as described by Russo (9). Lot 1 (10 × 10 m) contains the basic weather instruments. Lot 2 (5 × 10 m) is for air-quality instruments, lot 3 (5 × 10 m) is for special agrometeorological instrumentation, and lot 4 (20 × 10 m) is for bioassay specimens. Lot 5 (10 × 5 m) and lot 6 (10 × 10 m) are allocated to entomologists for insect light and pheromone traps, respectively. Lot 7 (10 × 5 m) and lot 8 (10 × 10 m) are assigned to plant pathologists for volumetric spore traps and capture mechanisms, respectively.

by changes in observation time. The trend away from late-afternoon or evening observation toward morning observation tends to lower average temperatures and has contributed to a "fictitious" climatic change. The National Weather Service has indicated that even the hourly data may be collected in 10 different ways, which should cause users to consider a station's particular methods and history before analyzing and using its data in research studies. As Dale (1) recommends, we should work toward standardizing a minimum agricultural meteorological network density and the measurement of the variables needed. Instrumentation, exposure, and sampling frequency should be identical for all stations. In addition to the data now being collected, dew intensity and duration, soil temperature, and solar radiation measurements are needed.

Agricultural meteorologists, entomologists, plant pathologists, and agricultural engineers in the northeastern United States are making a collective effort to establish a network of agricultural reference meteorological stations, so that research results in one crop production area can be applied to another area. The unique station design, described by Russo (9), combines meteorological instruments, biological instruments, and bioassay materials into a single unit (Fig. 1). The 50 × 50 m site has short grass cover and defined conditions for the adjacent area. Lot 1 (Fig. 2) is the basic instrumentation area for measuring weather variables. The proposed standard layout of weather instruments is based on international guidelines using standards of the World Meteorological Organization and Food and Agricultural Organization; sensor placement depends on instrument design, supporting apparatus, and shielding or insulating material. Instrument precision and recording accuracy are stated in probabilistic form for a given sampling volume (area of the station) and period, with the uncertainty of a value being estimated for the 95% confidence limit. Individuals may arrange to expose experimental material in lot 4 and request more frequent data collection.

Although we must work toward a goal of standardized data representative of agricultural conditions, we cannot improve historical data. Any historical studies of the influence of the environment on disease occurrence require using data from NOAA network stations, and the meteorological data for a region are usually more complete and extensive than the existing disease data.

Because climatic conditions may vary greatly within the canopy and are not usually the same as those outside the canopy, micrometeorological data are needed by some researchers, for example, to develop plant growth and disease models. Collection of micrometeorological data is not always feasible, and a suitable substitute may be collection of macrometeorological data in the field or orchard, using equipment such as that described by Jones et al (4) designed for a specific predictive system. Such in-field environmental monitoring systems will probably be limited to intensive agricultural systems where high-value crops warrant their use.

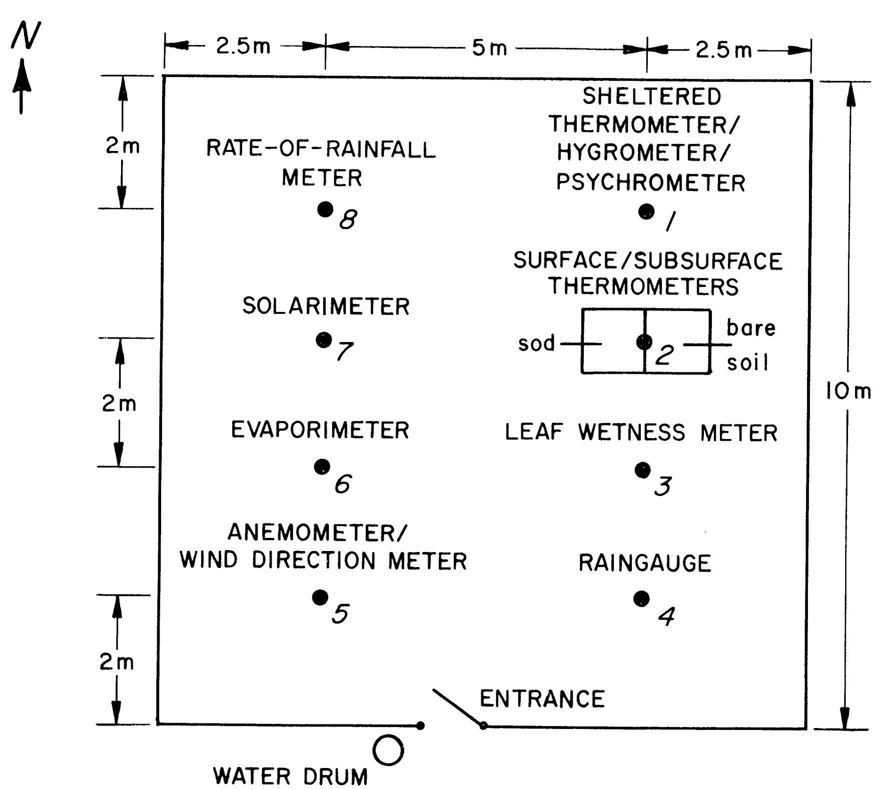


Fig. 2. Standard layout of weather instruments in lot 1 of the reference agrometeorological station described by Russo (9).

Value of Macrometeorological Data in Predicting Conditions

If micrometeorological data cannot be collected directly, can they be predicted from macrometeorological data? Sierchio and Hatfield (10) evaluated the relationship between the microclimates of differentially irrigated crops and the weather data collected at climatic stations with different ground covers. For grain sorghum and soybeans under three irrigation treatments, they compared air temperature in the canopy at heights of 0, 25, 50, 100, and 200 cm with the standard shelter (located 200 m from the experimental area) temperature at 150 cm above the ground. They found that the difference among irrigation treatments was negligible, that the relationship between the sites was closest for maximum temperature, and that the regression describing the relationship could be improved by adding a term for canopy height.

The potential exists for developing analogues for other variables for specific crops that would allow useful predictions of in-canopy conditions from macrometeorological data. Pedro and Gillespie (7) successfully used standard weather station data for estimating dew duration. Hopefully, more studies will follow that will be useful in defining relationships between micrometeorological and macrometeorological conditions for specific crops and management practices and that will facilitate the use of macrometeorological data for disease management.

Planning Data Collection

Regardless of whether one wants to collect data on a macrometeorological or a micrometeorological scale, decisions must be made for use of monetary resources to best advantage. Data collection must be carefully planned because initiating a project with an open mind is often too expensive for most budgets. One should never measure for the sake of measuring or with the idea that the data may be useful sometime. I would approach the problem by first defining my objectives for the study and answering the following questions:

1. Why do particular environmental variables need to be measured? I must know enough about the organism and disease epidemiology to make an intelligent guess about what aspects of the environment are important. One should concentrate on the biology of the organism at this stage.

2. Which sensor will give the most useful information for each variable I want to record? One must be familiar with the available instruments and

Table 1. Recommended criteria for reporting meteorological data collection

Investigation	Site	Measurements	Data report
Full description, including equipment used	Location, including latitude, longitude, and elevation Description Gradient and exposure Type and height of vegetation	Description Heights at which made Unit of measure in which numerical value recorded Significant digits in recorded data	Complete description of units of measure in all results, including tables and diagrams Formulas used in data reduction expressed as symbolic equations wherever possible, so that units of measure do not matter

methods of operation and understand the potential effects from use of varied techniques of exposure and recording. This is a good time to consult other researchers with experience in the field and to talk to industry representatives.

3. How accurate must the measurement be? It is important to remember that in most instances physical measurements can be made with greater precision than biological ones, and that the decision on accuracy must be based on the precision of the biological measurements. Accuracy requirements will determine the cost, frequency of maintenance, and environmental limits of the sensors. Accuracy is sometimes overemphasized in relation to other aspects of the data collection.

4. How often must the measurement be made? I must decide the time scale for comparing physical and biological measurements and set the recording scan accordingly. To obtain the minimum data necessary for describing the parameter in question, data can be averaged before they are recorded. For example, 1-minute scans could be expressed as a 1-hour average or 10-second scans could be expressed as a 1-minute average. The average of a variable can be described completely by sampling at two times the time constant of the sensor. To obtain a mean value, the time constant can be made deliberately large to eliminate "noise" from the data. It is very important not to collect information at the maximum rate possible on the assumption that unwanted detail can be eliminated later. This leads to more frequent equipment failure as well as to problems and inefficiency in analysis of the data.

5. How will the data be collected, stored, and analyzed? If a large project is planned, I will need help from a statistician, a computer programming specialist, and equipment manufacturers to plan data collection. Automation of data collection and analysis has made money the most limiting factor for collecting data on most parameters, and studies must be planned so that the data can be analyzed and reported in a timely fashion.

Table 1 lists the criteria recommended for reporting meteorological data collection.

Sources of Error

The many sources of possible error need consideration before data collection begins because incorrect measurements are worse than no measurements. Smith (12) described four categories of error: instrument, observer, instrument exposure, and sampling. Instrument error may be the easiest to control, and one can avoid systematic error by regularly checking, calibrating, and standardizing the instruments. The only safe correction of observer error is by the observer at the time of observation. Training of observers is essential, and using the same observer throughout a particular study improves consistency of data. Errors resulting from incorrect or altered instrument exposure may be more frequent but less obvious than instrument and observer errors. Sampling errors may result when spatial variability in the meteorological variables is large within short distances or when sampling frequency is not properly matched to temporal meteorological variations. If multiple sampling is not possible, the degree of reliability for the single sample needs consideration. Sampling problems cannot be solved by taking only one sample and ignoring the possible error.

General Considerations in Selecting Instruments

Six performance specifications should be considered in making a final decision about sensors and recording equipment (15):

Range—the difference between the two extreme measurable signal readouts as indicated by the highest and the lowest scale values.

Limitation—the capability of the instrument to give accurate readings only within certain states of the environment. Relative humidity sensors, for example, detect only a certain range of the scale accurately.

Accuracy—the closeness with which the measured value approaches the unknown true value or standard, for example, those of the National Bureau of Standards. The measured value is equal to the true value plus or minus an error that may be either systematic (an unchanged error caused by the instrument or observer) or random (an error that varies and is usually reduced in magnitude by repetition of the measurement). Accuracy is usually expressed as uncertainty, for example, 10 ± 5. The range of error should be included in all reports of data; when only single observations are made, error limits should be estimated.

Representativeness—the degree to which the measurement describes the variable being measured for a particular use. Some causes of unrepresentativeness are interaction with environmental conditions other than that being measured, interaction with the sensor's supporting structure or vehicle, time and space differences between a measurement and its intended application, and underestimation of the cumulative error when the value of one variable is calculated from the measurement of another, as in calculating relative humidity from vapor pressure (3,6).

Sensitivity—the change in the output to a given change in the input signal.

Time response—the time required for the instrument sensor to respond maximally to the input.

All parts of a sensing and recording system should be reliable, accurate over a long period of time, simple in design, convenient to operate and maintain, and strong in construction. The World Meteorological Organization provides specifications for standard instruments (16). When one has defined the operational requirements for the instruments and is ready to select equipment, manufacturers will be anxious to promote the outstanding features of their wares. A manufacturer's performance specifications are not always reliable, and it is worthwhile to consult current users of the particular instrument. Regardless of a manufacturer's assurances about precalibration and stability, equipment must be calibrated and tested before it is used.

Evaluation of the specific instrumentation available for environmental monitoring is not possible within this article. Sutton et al describe the instrumentation they consider useful for monitoring microclimate in studies of plant disease (13) and include numerous photographs and diagrams of the instruments as well as practical considerations for their use.

Fritschen and Gay (2), Monteith (5), Pennypacker (8), and Unwin (14) are other useful references on instrumentation.

Deployment of the Sensor and Associated Problems

Measurement of temperature. Temperature can be measured more accurately than is necessary for most studies. Placement of the sensor is critical because it must be in thermal equilibrium with the environment. Temperature can fluctuate rapidly, so the sensor must have an appropriate time response. The major sources of error are radiation effects, thermal mass of the sensor (may cause failure to respond fully and rapidly to fluctuating temperature), conduction, and wind velocity. Sensor choice may depend on available recording equipment, which in turn may affect the accuracy as much as the sensor does. For measurement of air temperature profiles, all sensors must be identical in construction and exposure. Sensors should be calibrated in liquid if possible, and self-heating should be checked. Temperature meters should be regularly checked against good-quality mercury-in-glass thermometers.

Measurement of radiation. Radiation is the process of energy transfer from one body to another by electromagnetic waves. Data collected at standard stations are sparse and inadequate and the equipment to measure radiation is expensive. The major sources of error are related to the spectral sensitivity of the sensors (14). One must use the right instrument for the spectral sensitivity of the organism. The sun angle must be considered (whether horizontal or normal incidence). Substantial errors result if surfaces are not kept clean or the site has obstructions. Calibration of a sensor may change suddenly, as from shock in transit, or from slow drift. A radiation instrument should be calibrated by comparison with an instrument that has been calibrated against a standard, using the radiation source appropriate to the instrument. Instruments calibrated at different times of the year agree less well with each other than those calibrated with a common outdoor exposure.

Measurement of moisture and precipitation. The moisture content of the atmosphere is difficult to measure. In measuring relative humidity, all sensors usually modify their environment to some degree and those involving air movement may actually modify temperature. Calibration of sensors is tedious and time-consuming and must be done by comparison with instruments of known performance. It is difficult to obtain an air source with a specified temperature and vapor content. The collection of precipitation data by the NOAA network appears to be satisfactory for many uses, but the network needs to be denser where convective storm activity is common.

Measurement of leaf wetness and dew has always been very difficult, although recent advances have improved accuracy. Sutton et al (13) describe their firsthand experience with this measurement. Variation between leaves and plants owing to exposure differences continues to be an important consideration when one is extrapolating from leaf-wetness measurements.

Measurement of wind. Wind speed and direction may be difficult to measure within the plant canopy. Thermal anemometers are accurate but are also fragile, expensive, and not suited for extended field use. Calibration of sensors requires wind tunnels and turntables or similar equipment. A large problem with wind measurement is how to express in a simple way a quantity with such a large variance.

Data Collection Equipment

Sensor selection is accompanied by selection of data collection equipment. Fritschen and Gay (2) present an overview of the data collection process, and Sutton et al (13) describe the necessary equipment and important considerations for recording data in the field. The trend toward automated data collection by data loggers is a great convenience if one knows what to measure and is familiar with the pitfalls of automated data collection. A readout in analog or physical units in the field facilitates checking the operation and the calibration of the sensors. Where possible, collection of data should be monitored by comparing data as they are collected with those collected by other equipment or with the synoptic weather conditions for the area. Visual printouts of data (e.g., graphs) are valuable tools for finding errors. On-site storage and transfer of data require a data logger with a reliable memory.

The field of data collection is developing rapidly and new options are becoming available faster than they can be integrated into the design of the units. For collection of valid data, a basic understanding of the monitoring equipment is necessary. Unfortunately, the specification sheets for much of the available equipment stress how little knowledge is needed to run the equipment. The data logger may be "heatproof, coldproof, floodproof, foolproof," but the sensors most likely are not—and the entire system is certainly not "scientist-proof." You may be able to "turn on, start taking data, and use without reading a lengthy instruction manual," but the validity of the data collected may be questionable.

Simple instruments with specific uses are available and reliable for their intended uses but may not be applicable for wider uses. Instruction manuals and specification sheets tend not to comment on the limitations of, or expected problems with, the equipment. The ease of training and use is often unrealistically stated. Verification of data is never mentioned. In all cases, communication with the manufacturers of the equipment is essential and may be valuable if they can provide the solutions to some of the problems encountered.

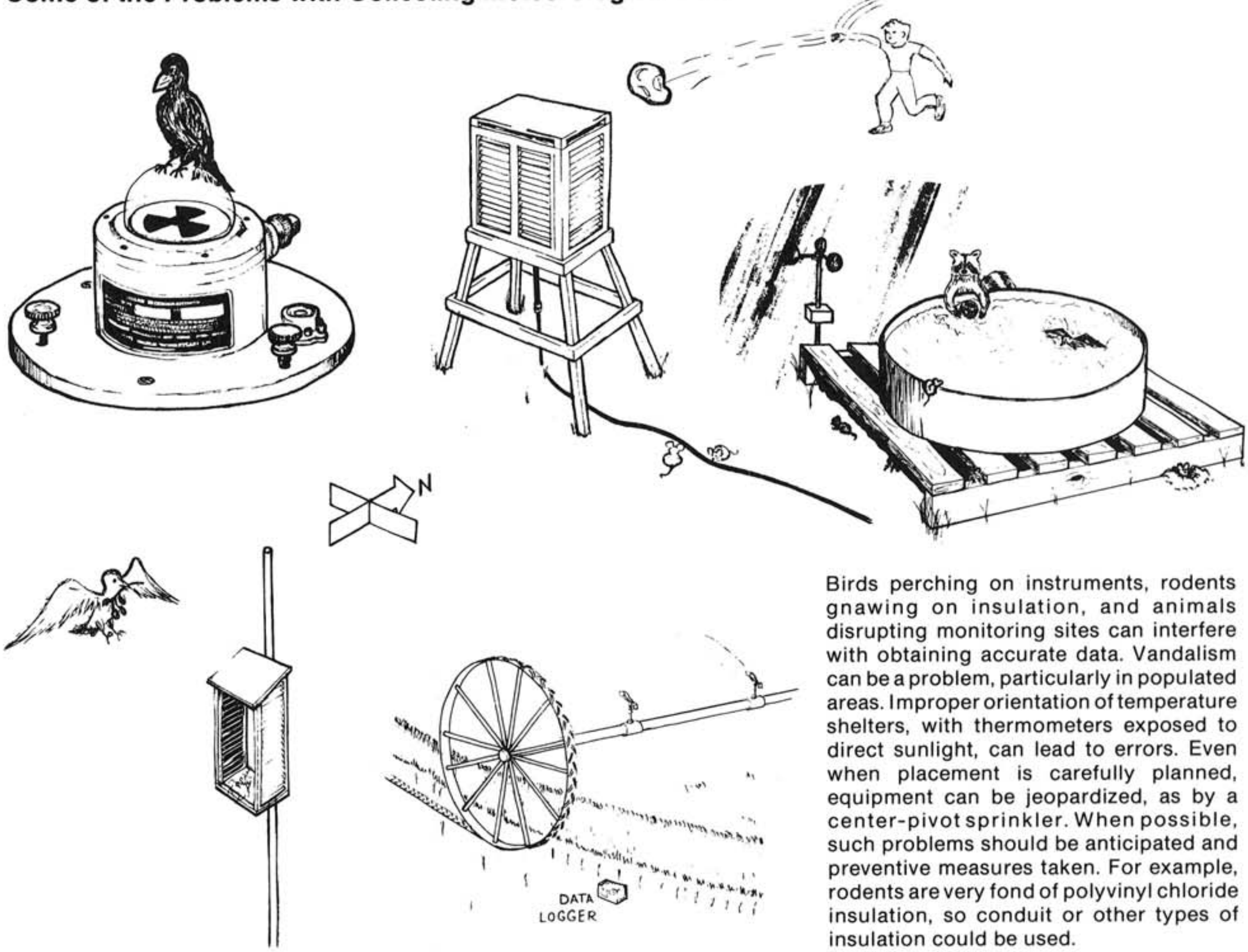
Problems to Anticipate

A variety of factors can hamper collection of accurate data, with the human factor perhaps the greatest limitation. Vandals or animals may damage equipment, and inappropriate exposure or positioning may lead to mishaps or erroneous results. Equipment requires calibration before and after each experiment and at least every 6 months for continuous monitoring, and the

Stella Melugin Coakley

Dr. Coakley is associate research professor in biological sciences at the University of Denver but maintains her research location at the National Center for Atmospheric Research in Boulder, Colorado. She investigates the effects of long-term and short-term climatic variations on plant disease occurrence. Other interests include improving the collection of meteorological data for use in plant pathology research. She has B.S., M.S., and Ph.D. degrees from the University of California, Davis.

Some of the Problems with Collecting Meteorological Data



Birds perching on instruments, rodents gnawing on insulation, and animals disrupting monitoring sites can interfere with obtaining accurate data. Vandalism can be a problem, particularly in populated areas. Improper orientation of temperature shelters, with thermometers exposed to direct sunlight, can lead to errors. Even when placement is carefully planned, equipment can be jeopardized, as by a center-pivot sprinkler. When possible, such problems should be anticipated and preventive measures taken. For example, rodents are very fond of polyvinyl chloride insulation, so conduit or other types of insulation could be used.

operation needs to be checked directly at least weekly or by remote access at more frequent intervals. Operator-induced failures include not switching on the equipment, setting the wrong date, and using the wrong multiplier in the micrologger. In one long-term monitoring project in California vineyards, field cultivation equipment pulled up wires and displaced or disconnected probes, chemical sprays coated sensors, the plant canopy entangled wind sensors, birds landed on or upset probes and probe shields, electrical storms caused changes in probe readings, irrigation water seeped into equipment shelters, unexplained negative values were recorded from probes, salt air corroded sensors on the relative humidity recorders, and low battery power resulted in recording errors.

Low temperatures may influence performance of equipment in the field by affecting, for example, cable insulation, soldered joints, or magnetic tape tolerance. Battery voltage needs to be maintained above a threshold constant, and a backup battery supply should be provided. Response of the system to voltage decline must be established before field use, and voltage should be monitored in the field along with other inputs. If voltage to chart or tape drive motors is reduced, data are recorded at an increased density and may not be properly translated. Dust accumulation in naturally aspirated radiation shields may cause temperature errors. Humidity exceeding 75% in equipment shelters may reduce accuracy and reliability of electrical components; a desiccant should be included. High temperature caused by direct sunlight may shut down liquid crystal displays on data loggers without affecting their recording. The large errors in electronic humidity sensors at high humidity limit their usefulness to plant pathologists. Condensation reduces the accuracy of sulfonated polystyrene sensors over time.

Needs for Better Monitoring of the Environment

Given all the concerns about and limitations to the collection of accurate data, what are the needs for better monitoring of the environment? Money would resolve many of the problems; more instrumentation does not necessarily mean fewer people and may even mean more people to successfully analyze and report the research. Needs expressed by the research community include a denser network for standard measurement of solar radiation and a denser network for measurement of the agricultural environment. More records of onset, intensity, and duration of precipitation would be useful. Many individuals have mentioned the need for improved training of graduate students in collecting environmental data and understanding the instrumentation.

We need to spend more time on determining when and where to make measurements. Little guidance in the form of quantitative data exists on how to decide what variable to measure, how to measure it, how often to measure it, and how accurate and precise the measurement must be. Replication of measurements may be necessary to obtain representative data.

Even though my focus on the many requirements for collecting meteorological data may make the task sound overwhelming, my intention is not to be discouraging but rather to encourage the collection of accurate data that will be useful for the intended purpose. I think all of us who collect or use environmental data should keep in mind the words of Smith (11): "All too often published meteorological data are accepted at their face value, with a blind faith that is rarely justified by the facts. . . . the main unforgivable effect of incompetence is the trouble it causes for other people."

Note: A copy of a more complete bibliography compiled for a symposium at the 1983 annual meeting of The American Phytopathological Society may be obtained by sending a self-addressed legal-sized envelope to Dr. Stella M. Coakley, NCAR, P.O. Box 3000, Boulder, CO 80307.

Acknowledgments

I wish to thank Lee Fortier of the NCAR Graphics Department for the drawings depicting some of the problems that can arise in collecting data; Nancy Mielinis for obtaining, compiling, and typing the original bibliography and for useful suggestions for this paper; and R. G. Grogan for valuable comments on the manuscript. Research was supported by the National Science Foundation, Climate Dynamics Program Grant ATM 82-11253.

Literature Cited

1. Dale, R. F. 1981. Existing meteorological networks. Pages 56-76 in: Computer Techniques and Meteorological Data Applied to Problems in Agriculture and Forestry: A Workshop. A. Weiss, ed. American Meteorological Society, Boston. 386 pp.
2. Fritschen, L. J., and Gay, L. W. 1979. Environmental Instrumentation. Springer-Verlag, New York. 216 pp.
3. Giraytys, J. 1970. Can instruments be designed to be both accurate and representative? A summary of a panel discussion. Pages 437-443 in: Meteorological Observations and Instrumentation. Meteorol. Monogr. Vol. 11, No. 33. American Meteorological Society, Boston. 455 pp.
4. Jones, A. L., Fisher, P. D., Seem, R. C., Kroon, J. C., and Van DeMotter, P. J. 1984. Development and commercialization of an in-field microcomputer delivery system for weather-driven predictive models. Plant Dis. 68:458-463.
5. Monteith, J. L. 1972. Survey of Instruments for Micrometeorology. Blackwell Scientific Publications, Oxford. 263 pp.
6. Nappo, C. J. 1983. Methods of estimating meteorological representativeness. Pages 246-251 in: Preprints of Fifth Symposium on Meteorological Observations and Instrumentation. American Meteorological Society, Boston. 572 pp.
7. Pedro, M. J., Jr., and Gillespie, T. J. 1982. Estimating dew duration. II. Utilizing standard weather station data. Agric. Meteorol. 25:297-310.
8. Pennypacker, S. P. 1978. Instrumentation for epidemiology. Pages 97-118 in: Plant Disease. An Advanced Treatise. Vol. 2. How Disease Develops in Populations. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York. 436 pp.
9. Russo, J. M. 1983. Reference agrometeorological data for the northeast region. Pages 136-140 in: Extended Abstracts, 16th Conference, Agriculture and Forest Meteorology. American Meteorological Society, Boston. 244 pp.
10. Sierchio, J. M., and Hatfield, J. L. 1983. Relationship between the microclimate of canopies and observed data from climatological stations. Page 53 in: Extended Abstracts, 16th Conference, Agriculture and Forest Meteorology. American Meteorological Society, Boston. 244 pp.
11. Smith, L. P. 1972. Processes in micrometeorology. Pages 300-305 in: Agricultural Meteorology. No. 310, World Meteorological Organization, Geneva. 357 pp.
12. Smith, L. P. 1975. Methods in Agricultural Meteorology. Developments in Atmospheric Science 3. Elsevier Scientific Publishing Co., Amsterdam. 210 pp.
13. Sutton, J. C., Gillespie, T. J., and Hildebrand, P. D. 1984. Monitoring weather factors in relation to plant disease. Plant Dis. 68:78-84.
14. Unwin, D. M. 1980. Microclimate Measurement for Ecologists. Academic Press, London. 97 pp.
15. Wang, J. Y., and Felton, C. M. M. 1979. Instruments for Physical Environmental Measurements. Vol. 1. Milieu Information Service, Inc. 379 pp.
16. World Meteorological Organization. 1981. Guide to Agricultural Meteorological Practices. 2nd. ed. World Meteorological Organization, Geneva.